PROCEEDINGS

OF THE

LUX EUROPA 2017

European Lighting Conference

September 18-20, 2017

Ljubljana Slovenia

Lighting for modern society

Organised by

SLOVENSKO DRUŠTVO ZA RAZSVETLJAVO / SDR
LIGHTING ENGINEERING SOCIETY OF SLOVENIA

PROCEEDINGS

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Lighting for modern society

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LUX EUROPA 2017
Lighting for modern society

Sponsors

Monday, September 18

8:00-18:30 Conference registration/Foyer

9:30-10:30 Opening Session

Moderator: **Grega Bizjak,** Slovenia

Room: White Hall (I+II+III)

- **Transnational Lighting Detectives**
  Aleksandra Stratimirović

11:00-12:30 Plenary session

Moderator: **Andrej Orgulan,** Slovenia

Room: White Hall (I+II+III)

- **"European Lighting Expert" - the European standard for knowledge in lighting**
  Matthias Hessling

- **Does higher illuminance encourage reassurance that it is safe to walk? Comparing different methods of analysis**
  Steve Fotios

- **Effective radiant flux for non-visual effects – is the illuminance and the melanopic irradiance at the eye really the right measure?**
  Kai Broszio

- **TM-30-15 and CIE-CRI-Ra: Investigation of colour rendering of white pc LEDs**
  Karin Bieske

13:30-15:30 Standards and regulation

Moderator: **Peter Dehoff,** Austria

Room: White Hall (II+III)

- **The International Lighting Vocabulary (ILV) – yesterday, today, tomorrow**
  Peter Zwick

- **The new EN 15193-1 to calculate the energy performance for lighting in buildings: analysis and application to reference building types**
  Chiara Aghemo | Laura Blaso | Simonetta Fumagalli | Valerio R.M. Lo Verso | Anna Pellegrino

- **Lighting role in green building rating systems: comparison between different assessment criteria in an Italian building**
  Laura Bellia | Francesca Fragliasso | Maria Maddalena Egger | Marina Mazza

- **The Interreg Project Dynamic Light**
  Axel Stockmar

- **Outdoor Adaptive Lighting in the new UNI 11248 Italian standard and results of experience**
  Paolo Di Lecce

- **Comparison of Different Methods of Distribution Factor Calculation**
  Peter Raynham | Peter Thorns

- **Documentation of Lighting Design**
  Dionyz Gasparovsky | Roman Dubnicka

13:30-15:30 Exterior lighting

Moderator: **Dionyz Gasparovsky,** Slovakia

Room: White Hall (I)

- **Mainstreet of Waldenburg (CH) "A non-everyday lighting solution"**
  Mario Rechsteiner

- **Multi-variable light distribution in road lighting increases safety and reduces the energy demand**
  Stephan Voelker | Juri Steblau

- **A New Dimming Control Scheme of LED Based Streetlighting Luminaires Based on an Embedded LED Model Implemented on an IoT Platform to Achieve Constant Luminous Flux at Different Ambient Temperatures**
  János Hegedüs | Péter Horváth | Tamás Szabó | András Szalai | András Poppe

- **A urban lighting renovation project to optimize environmental performance and reduce energy consumption: results of a measurement campaign**
  Anna Pellegrino | Gabriele Piccablotto | Rossella Taraglio | Dario Fisanotti | Alessandra Paruzzo | Gianpaolo Roscio

- **Metrology of road surface for smart lighting**
  P. Iacomussi | G. Rossi | P. Blattner | C. Chain | G. Gallee | T. Kubarsepp | M. Lindgren | F. Manoocheri | C. Van trang | P. Zehntner

- **Vertical illumination requirements for pedestrian gaze estimation**
  M.A.H Donners | L. Crommentuijn

- **Limiting disturbance of bats by adapting the spectral composition of road lighting**
  Maurice Donners | Roy van Grunsven | Elmar Veenendaal | Marcel Visser | Kamiel Spoelstra

16:00-17:00 Poster presentation

Moderator: **Peter Zwick,** Austria

Room: White Hall (II+III)

PPM01
- **Measuring Sustained Attention and Mood: Effects of Correlated Color Temperature**
  Rengin Kocaoglu | Nilgün Olguntürk

PPM03
- **Comparison of the measurement methods of road lighting**
  Roman Dubnicka | Lukas Lipnicky | Dionyz Gasparovsky

PPM04
- **Measurement of luminaires for road lighting**
  Lukas Lipnicky | Roman Dubnicka | Dionýz Gašparovský

PPM05
- **Problems identified during measurement and assessment of blue-light hazard from arc welding process**
  Andrzej Rybczyński | Agnieszka Wolska | Janusz Pikuła | Tomasz Pfeifer

PPM06 • **Improvement of monitor calibration using other than CIE 1931 Color Matching Functions**
Steffen Goerlich, Lev Bakhrakh

PPM07 • **Review of state of the art and new measurement methods for the determination of the reflection properties of road surfaces**
Sandy Buschmann

PPM10 • **Results from Monitoring the Energy Certification of Lighting in Buildings**
Dionyz Gasparovsky | Jana Raditschova | Peter Janiga

PPM11 • **Lighting Culture**
Károly Zsolt Molnár | Renáta Rebeka Szabó | József Nádas

16:00-17:00 Poster presentation

Moderator: **Stanislav Darula,** Slovakia

Room: White Hall (I)

PPM12 • **Beleuchtungstechnik 4.0 - The 4th Edition of a Lighting Education Book**
Dirk Seifert | Meike Barfuß | Alexander Rosemann

PPM16 • **Visual comfort evaluation methods in residential buildings: a simulation-based study**
Mandana Sarey Khanie | Milena Ślipek | Anders Thorseth | Daria Zukowska | Jakob Kolarik | Toke Rammer Nielsen

PPM17 • **First outcomes of an investigation about Daylighting knowledge and education in Europe**
Federica Giuliani | Natalia Sokol | Valerio R.M. Lo Verso | Federica Caffaro | Raquel J. A. V. Viula

PPM18 • **What's the matter with multi-layers facades?**
Bernard PAULE | Marine BERGES | Robert CELAIRE

PPM21 • **Advances in daylight simulation – validation and applications**
David Geisler-Moroder | Wilfried Pohl

PPM22 • **Tubular light-guide under broken cloud array – working plane illumination**
Ladislav Kómar | Miroslav Kocifaj

PPM23 • **Measuring daylight properties with five TCS230 sensors**
Klemen Zalokar | Matej B. Kobav

17:00-18:30 Poster viewing

Room: Foyer

Poster Number	**Paper & Authors**
PM01	Simplified model of spectral distribution of daylight in interior of the building Roman Dubnicka | Lukas Lipnicky
PM02	Preliminary experimental evaluation of electrotropic windows in a full scale test facility

	Sergio Sibilio
PM03	The optimal luminous intensity curves of luminaries for roadway lighting Jan Škoda
PM05	Lighting for cyclists: An eye tracking study in natural settings to investigate where they look Hussain Gasem | Jim Uttley | Steve Fotios
PM06	The role of ambient light level in accidents at pedestrian crossings Steve Fotios | Jim Uttley
PM07	A novel method for demonstrating that light encourages pedestrian activity Steve Fotios | Jim Uttley | Scott Fox | Hussain Gasem
PM08	Spectral reflectance of Argentinean road surfaces Pablo Ixtaina
PM09	Refurbishment of Lighting Systems in Kindergardens – Case Studies for Bratislava Dionyz Gasparovsky | Jana Raditschova
PM10	Concept of lighting system for experimental studies in interiors Piotr Pracki | Michal Dziedzicki
PM11	Indoor lighting: how a reflector can improve performance and how to assess it Simonetta Fumagalli | Laura Blaso | Giuseppe Leonardi | Adriano Antonelli | Diego Diaz Sanudo
PM12	Effects of high-purity LED light colors on time-sense perception Hiroshi Takahashi | Hayato Kikuchi
PM13	On the correlation between SQM data and zenith brightness Jaromír Petržala | Miroslav Kocifaj

20:30-22:00 Light Guerrilla - opening

Location: Trnovo park/Gradaščica, a park between Riharjeva, Finzgarjeva and Barjanska cesta
GPS: N46 02.604 E14 29.952

20:30 Opening of Light Guerrilla
21:30 Dance Performance: Liza Šimenc & Urša Rupnik: Meduza

Tuesday, September 19

8:00-18:30 Conference registration/Foyer

9:30-10:30 Plenary Session

Moderator: **Axel Stockmar,** Germany

Room: White Hall (I+II+III)

- **SenCity – Evaluating users' experiences of intelligent lighting for well-being in smart cities**
  Henrika Pihlajaniemi | Eveliina Juntunen | Anna Luusua

- **An Evaluation Method for Façade Renovation Strategies in Residential Buildings Using Gaze Responsive Visual Comfort Assessments**
  Mandana Sarey Khanie | Ślipek, M. | Zukowska D. | Kolarik J. | Nielsen T.R.

- **Exploring interaction with office lighting: a case study**
  Daria Casciani | Maurizio Rossi | Fulvio Musante | Simonetta Fumagalli

10:30-11:00 Coffee Break

11:00-12:30 Energy efficiency

Moderator: **Alexander Rosemann,** Netherlands

Room: White Hall (II+III)

- **Estimation of the Energy Efficiency Potential in Street Lighting in Serbia**
  Sabine Piller | Siegfried Brenke | Zoran Kapor

- **Experimental investigation of the correlation between power consumption and luminous flux of LED luminaires in adaptive road lighting**
  Dimitris Panagiotis T. Nikolaou | Constantinos A. Bouroussis | Frangiskos V. Topalis

- **DALEC – evaluation tool for an integrated planning approach**
  Oliver Ebert | David Geisler-Moroder | Matthias Werner

- **Energy Efficient Lighting in University Buildings**
  Dorin BEU | Calin CIUGUDEANU | Andrei CECLAN

11:00-12:30 Measurements and photometry

Moderator: **Denan Konjhodžić,** Germany

Room: White Hall (I)

- **Luminance maps from High Dynamic Range imaging: calibrations and adjustments for visual comfort assessment**
  PIERSON Clotilde | WIENOLD Jan | JACOBS Axel | BODART Magali

- **"FluxGage" A Photometric Test System for LED Luminaires Based on Solar Panels**
  Christian Dini | Simon Rankel

- **Influence of measuring equipment parameters on recorded luminance values in context of glare measurements**
  Sebastian Slominski

- **On site photometric characterisation of concrete pavements with COLUROUTE device**
  Valérie Muzet | Joseph Abdo

- **Mobile methods of rated lighting parameters of illumination measurement - luminance and illuminance**
  A.B. Kuznetsova | M.A. Fedorishchev | A. Sh. Chernyak | A. G. Shakhparunyants

13:30-15:30 Lighting for human and their needs

Moderator: **Laura Bellia,** Italy

Room: White Hall (II+III)

- **Exploration of light-induced variations in cognitive task performance in real life**
  Karin Smolders | Yvonne de Kort

- **The impact of dynamic lighting on cognitive processes**
  Oliver Stefani | Liselotte Ilg | Achim Pross | Herbert Plischke

- **The myth of Baker-Miller pink: Effects of colored light on physiology, cognition and emotion**
  Oliver Stefani | Susanne Reithinger | Christoph Grabmaier | Achim Pross | Anke Huckauf

- **Illumination needs of patients with low vision**
  Kazim Hilmi Or

- **Artificial vision patients' illumination needs**
  Kazim Hilmi Or

- **Acute Diurnal Non-image Forming Effects of Light in Middle-aged Participants**
  Laura Huiberts | Karin Smolders | Yvonne de Kort

- **Health effects of biodynamic lighting in a clinics**
  Wilfried Pohl | Markus Canazei | Katrin Tanzer | Johannes Weninger

- **Influence of light condition on medication care in a hospital**
  M.P.J. Aarts | H.S.M. Kort | A.L.P. Rosemann | E.J.van Loenen

13:30-15:30 Exterior lighting

Moderator: **Péter Schwarcz,** Hungary

Room: White Hall (I)

- **Determination of veiling luminance for peripheral visual objects**
  Carolin Tatulla | Oliver Maak | Stefan Wolf | Christoph Schierz

- **Discomfort Glare caused by several LED sources**
  Joffrey Girard | Céline Villa | Roland Bremond

- **The treatment of light scattering in a volume and application to foggy traffic situations**
  Michael Marutzky

- **Disability and discomfort glare caused by today's automotive headlamps in interaction with road conditions**
  Kleinert, B. | Bogdanow, S. | Marutzky, M.

- **Investigating impediments to drivers' hazard detection ability: fog and sudden switch-off**
  Steve Fotios | Jim Uttley | Chris Cheal | Scott Fox

- **Urban environment illumination impact on user priorities and respond**
  Melita Rozman Cafuta

- **Does pedestrian useful visual field change at night?**
  Navaz Davoudian | Peter Raynham

- **Does lighting affect pedestrian flows? A pilot study in Lund, Market Harborough and Dublin**
  Jemima Unwin | Phil Symonds | Thorbjorn Laike

16:00-17:00 Poster presentation

Moderator: **Dorin Beu,** Romania

Room: White Hall (II+III)

PPT01
- **The effect of daylight on the elderly population**
  Lorna Minu Flores Villa | Jemima Unwin | Peter Raynham

PPT03
- **Gender- and age-related preferences of the lighting conditions for activity and recovery**

Susanne Schweitzer | Clemens Schinagl | Gordana Djuras | Matthias Frühwirth | Hans Hoschopf | Friedrich Wagner | Birgit Schulz | Wolfgang Nemitz | Vincent Grote | Sybille Reidl | Paul Pritz | Maximilian Moser | Franz Peter Wenzl

PPT06 • **Daylight dependent, seasonal patterns in industrial incident data**
Jan Krüger | Holger Reyhl | Jens Kinne

PPT07 • **Age Difference in Comfortable Lighting -The Evaluation of the Lighting Environment in Real Space**
Oe Yuki | Inoue Youko

PPT10 • **An investigation on lighting matter in design guides of educational buildings**
Kasim ÇELIK | Rengin UNVER

PPT11 • **The Relationship Between Energy Saving and Visual Comfort in Different Lighting Sources**
Banu Tabak Erginöz | Yavuz C

PPT13 • **Optimization of lighting power consumption in buildings**
Tomaž Novljan | Janez Rihtar

PPT14 • **Illumination Levels for Office Work in Thailand: Standards vs Occupants' Perspective**
Tharinee Ramasoot | Satta Panyakaew

16:00-17:00 Poster presentation

Moderator: **Mario Rechsteiner,** Swiss

Room: White Hall (II+III)

PPT15 • **BIM and Lighting Design**
Robert Heinze

PPT17 • **An Expo Box for flicker**
Matjaž Colarič | Matej B. Kobav

PPT18 • **The engineering assessment of floodlighting designs**
Krzysztof Skarżyński

PPT19 • **Smart design of thin direct-lit luminaires**
Christian Sommer | Claude Leiner | Ladislav Kuna | Frank Reil | Paul Hartmann | Franz Peter Wenzl

PPT20 • **Using adjustment to evaluate discomfort glare**
Michael Kent | Sergio Altomonte | Steve Fotios

PPT21 • **Color characteristics of two-crystal LEDs for dynamic lighting**
Anna Savitskaya | Ruzana Delyan

PPT22 • **Research Progress on AlGaN-based Ultraviolet Light Emitters**
Jianchang Yan | Junxi Wang | Jinmin Li

PPT23 • **LED and HPS luminaires in Russian greenhouses**
L.B. Prikupets | V.G. Terehov

17:00-18:30 Poster viewing

Room: Foyer

Poster Number	**Paper & Authors**
PT02	Reducing of blue light hazard Jaroslav Štěpánek | Jan Škoda | Michal Krbal
PT03	Digital Light: Perception of projected visual signal from different perspectives Michael Marutzky
PT04	Realization of a Test Setup for a Smart Light Guiding System with Assistance Functions for Elderly People Christian Eßelmann | Kristin Gabel | Eva Schwenzfeier-Hellkamp
PT05	Experimental LED Luminaire for Investigation of Non-visual Effect of Light to Human Circadian System Mikuláš Parma | Petr Baxant | Jan Škoda
PT06	Study of LED Modulation Effect on the Photometric Quantities of Public Lighting? Karel Sokansky | Tomas Novak | Petr. Koudelka | Radek Martinek
PT07	Possibility of Bandwidth-widening with Luminescent Layer in LED Structures József Nádas | Vilmos Rakovics | István Réti
PT09	Distortion electrical power in the measurement of electrical parameters of luminaires Lukas Lipnicky | Roman Dubnicka | Peter Janiga
PT10	The implementation of the measurement system for measuring the luminous intensity distribution using the imaging luminance measuring device (ILMD) Piotr Michalek
PT11	The Comparison of different types of Spectroradiometers in terms of Uncertainty of measurement Martin Motyčka
PT12	Uncertainty of luminous intensity measurement with short photometric distance Marek Bálský | Petr Žák
PT13	Practical assessment of photobiological safety of light sources based on requirements of standard EN 62471 Andrzej Pawlak

Wednesday, September 20

9:00-10:30 Lighting for human and their needs

Moderator: **Arnaud Deneyer,** Belgium

Room: White Hall (II+III)

- **Office lighting hierarchies – lit surfaces contributing to visual appearance**
  Raphael Kirsch

- **Digital Lighting: A macro-economic view**
  Péter Schwarcz

- **Decision schemes for lighting controls - how to apply the TR 222**
  Peter Dehoff

- **Indoor lighting design with included non-image forming effects**
  Katja Malovrh Rebec | Marta Klanjšek Gunde

- **Environmental effects of wall colours in offices and user preferences**
  Fazila Duyan | Şensin Yagmur | Rengin Ünver

- **The effect of short exposure to coloured light on thermal perception: a study using Virtual Reality**
  Giorgia Chinazzo | Kynthia Chamilothori | Jan Wienold | Andersen Marilyne

9:00-10:30 Measurements and photometry

Moderator: **Karel Sokansky,** Czech republic

Room: White Hall (I)

- **The evaluation of measurement uncertainty of LED luminaire for industrial applications**
  G. Rossi | P. Iacomussi | M. Radis

- **Photometric and colorimetric testing of colour-tunable LED lighting products**
  Leloup Frédéric | Desnouck Pieter-Jan | Lootens Catherine

- **Research Progress on GaN-based LEDs and Solid-state Lighting in China**
  Jianchang Yan | Junxi Wang | Jinmin Li

- **Investigation of Wavelength Changes of the Leds Used for Illumination**
  Vedat ESEN | Bülent ORAL | Şafak SAGLAM

- **Inter Laboratory Comparison of LED Measurements Aimed as Input for Multi-Domain Compact Model Development within an H2020 R&D Project**
  András Poppe | Gábor Farkas | Ferenc Szabó | Julien Joly | Joël Thomé | Joan Yu | Karel Bosschaart | Eveliina Juntunen | Emmanuel Vaumorin | Alessandro di Bucchianico | Thomas Merelle

- **Application of Stray Light Corrected Array Spectroradiometers**
  Denan Konjhodžić

11:00-12:30 Lighting for human and their needs

Moderator: **Peter Thorns,** United Kingdom

Room: White Hall (II+III)

- **Human-centric Lighting**
  Gašper Čož
- **Important aspects of serious HCL – design**
  Klaus Bieckmann
- **Investigating a dose-response curve for daytime**
  Samantha Peeters | Karin Smolders | Ingrid Vogels | Yvonne de Kort
- **Impact of spectrum and illuminance on alertness – a quasi-field study in a lecture hall**
  Inga Rothert | Martine Knoop | Stephan Völker
- **Measurement of the effect of dynamic lighting on alertness, mood and sleepiness**
  Maria Nilsson Tengelin | Stefan Kallberg | Per Olof Hedekvist

11:00-12:30 Daylighting

Moderator: **Marta Klanjšek Gunde,** Slovenia

Room: White Hall (I)

- **A new standard for Daylight : Towards a daylight revolution**
  Arnaud Deneyeer
- **New daylight solutions for energy and health**
  Wilfried Pohl | David Geisler-Moroder | Christian Knoflach
- **Key learnings about daylight performance in demonstration buildings and potential outcomes**
  Jens Christoffersen | Nicolas Roy | Katarzyna Stefanczyk | Neza Mocnik
- **Daylight transmission via hollow light pipes with Fresnel (directional) reflection**
  František Kundracik | Ladislav Kómár | Miroslav Kocifaj | Ágnes Bazsó
- **Electrochromic glazings: Integrated dynamic simulation with DIAL+**
  Bernard Paule | Eloise Sok | Samuel Pantet | Julien Boutillier

13:30-15:00 Lighting for human and their needs

Moderator: **Piotr Pracki,** Poland

Room: White Hall (II+III)

- **Ledification: Revisiting Quality of Light**
  Pieter Seuntiens

- **Study of overhead glare discomfort from downlight luminaires**
  Lou Bedocs | Peter Thorns

- **Receptive field mechanism and pupillary light reflex for the assessment of visual discomfort**
  Gertjan Hilde Scheir | Peter Hanselaer | Wouter Rita Ryckaert

- **Testing Colour-Matching Functions - Perception of luminous color differences of white LEDs in relation to ambient luminous color and age of observers**
  Karin Bieske | Johannes Kolmer | Nicole Stubenrauch | Christoph Schierz | Anja Frohnapfel | Alexander Wilm

- **Office lighting characteristics determining occupant's satisfaction and health**
  Juliëtte van Duijnhoven | Mariëlle Aarts | Alexander Rosemann | Helianthe Kort

13:30-15:00 Daylighting

Moderator: **Tomaž Novljan,** Slovenia

Room: White Hall (I)

- **Metrics to predict visual discomfort in a daylit classroom**
  Raquel Viula | Truus Hordijk

- **Modelling the Luminance Coefficient Uncertainty using a Bidirectional Goniophotometer Facility**
  Alaaeldin Abdelmageed | Stefan Gramm | Stephan Völker

- **The new generation of an artificial sky: Simulating various overcast sky conditions**
  Stanislav Darula

- **High-resolution tilted surface illuminance/irradiance spectral model applicable to arbitrary sky conditions**
  Miroslav Kocifaj | Chris Gueymard

Oral presentations

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Posters

"European Lighting Expert" – The European Standard for Knowledge in Lighting

Matthias Hessling
President
European Lighting Expert Association (ELEA)
Olten, Switzerland
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***Abstract* — Due to the increased pace of technological developments in lighting, requirements for know-how are becoming more complex, and customers have to rely on so-called "experts" for their conceptual design, planning and operational needs. A common standard, however, to define and measure the level of know-how, such "experts" should have, did not exist so far. For that reason, the lighting societies of Germany (LiTG), Austria (LTG), the Netherlands (NSVV) and Switzerland (SLG) created such an educational standard. A "European Lighting Expert" has to prove his/her competencies in an examination, testing sufficient know how related to a wide-ranging catalogue of topics, and being supervised by an independent body. After an examination on national level, successful candidates are eligible to be registered as European Lighting Expert by the "European Lighting Expert Association", which was founded in August 2016 and it is open for membership by lighting societies from other European countries.**

***Index Terms* — educational standard, European standard, examination, know-how, lighting expert**

Background

Due to the increased pace of technological developments in lighting, requirements for know-how are becoming more complex, and customers have to rely on so-called experts for their conceptual design, planning and operational needs. A common standard, however, to define and measure the level of know-how, such "experts" should have, did not exist so far. While there are specific, lighting related examinations possible at universities on a top level, those who focused on practical planning, product sales or operational tasks, and did not choose the comprehensive, but time consuming university education, an internationally accepted education and examination was missing, allowing them to prove their know how.

While there are many training programmes being offered, and well sounding titles being available after short training already, it is difficult to judge their quality. This is even more so, if a title was acquired in a foreign country and is not known in others. Moreover, some training courses are offered by manufacturers or developers of luminaires, systems or software programmes, and while they might be of sufficient quality, they might also lack the independence required to develop the optimal solution for the customer e.g. in conceptual and planning tasks.

Against this background, there is a need for an independent and transparent qualification, examination and a related title, guaranteeing that the candidate has a defined level of competencies, regardless where in Europe the examination to acquire this title has taken place.

Development of the "European Lighting Expert" concept

Based on above analysis, the lighting societies of Germany (Deutsche Lichttechnische Gesellschaft, LiTG), Austria (Lichttechnische Gesellschaft Österreichs, LTG), the Netherlands (Nederlandse Stichting voor Verlichtingskunde, NSVV) and Switzerland (Schweizer Licht Gesellschaft, SLG) few years ago started a project to create such an educational standard. Until autumn 2016, they had finished a process of thorough consultation, to define exactly the requirements to pass the examination as "European Lighting Expert (ELE)", and to fix all details about the standard and execution of the examination, its independent supervision by a special body, as well as the administration of this title.

In addition to the basic requirements mentioned above, such as independence, transparency and clearly defined competencies, the lighting societies worked out the following principles:

- publication of a catalogue of educational objectives, defining the required competencies of a European Lighting Expert
- differentiation of required competencies in different levels per topic (according to Bloom's taxonomy)
- differentiation between interior and exterior lighting in the examination and in the acquired title
- national examination to be carried out under responsibility of national lighting societies

- compulsory oral examination, in order to evaluate the candidate's ability to apply the acquired knowledge, optionally with an additional written part
- homework (specific planning task) to be presented in the examination
- independent supervision of the examination
- training for such examination not compulsory and not restricted to offers from national lighting societies (can be offered by other institutions too)
- registration as European Lighting Expert requiring such national examination, as well the compliance with a specific code of conduct
- publication of the register of European Lighting Experts in a specific website
- re-registration after 5 years, requiring proof of sufficient further education (e.g. by conference participation)
- administration of the examination's supervision, the registration, the register and the further development of the concept and all corresponding documents by a specific association, the "European Lighting Expert Association (ELEA)"

Target audience

The target audience of the "European Lighting Expert" concept consists of persons interested to qualify as experts in indoor and/or outdoor lighting, such as:

- employees and entrepreneurs of all business areas of the lighting branch (technology, planning, design, installation, facility management, marketing & sales, operations etc.)
- newcomers in lighting with a solid education in a different field (e.g. electricians, wholesalers, energy consultants, auditors etc.)
- people involved in lighting technology and design looking for further education (e.g. architects, engineers, planners, builders, employees in technical offices, testing/certification institutes etc.)

Persons intending to be registered need profound knowledge about relations between perception, generation and effects of light as well as the related electrical engineering. They have to be able to apply this knowledge considering the relevant laws, standards and rules as well as ecological and economical aspects. They need to know up-to-date lighting equipment and lighting controls and how to use them. Proficiency about interfaces to adjacent fields like architecture, electrical engineering, ergonomics and ecology is mandatory. This enhances the ability to recognise lighting as being multidisciplinary and embedded in the environment.

The capability to think discretely and conceptualise interdisciplinary is essential to take proper decisions and act conveniently. Candidates who have passed an examination enabling their registration as European Lighting Expert are qualified to independently work in the fields of surveying, analysing, planning, designing, consulting, selling, installing and operating lighting installations in indoor or outdoor environments.

Definition of required competencies

It is not sufficient to only repeat memorized knowledge to succeed in an examination qualifying for the European Lighting Expert in indoor or outdoor lighting. The educational objectives must be worked out by individual thinking and studying to achieve the necessary level of competence.

The educational objectives are classified into three levels of competence (after Bloom's taxonomy), which are necessary for the qualification as European Lighting Expert, with increasing difficulty:

C1: Knowledge Exhibit memory of learned materials by recalling facts, terms, basic concepts, and answers:

- knowledge of specifics – terminology, specific facts used in lighting
- knowledge of ways and means of dealing with specifics – conventions, trends and sequences, classifications and categories, criteria, methodology
- knowledge of the universals and abstractions in lighting – principles and generalizations, theories and structures

C2: Comprehension Demonstrate understanding of facts and ideas by organizing, comparing, translating, interpreting, giving descriptions, and stating the main ideas. Coping with issues and problems in lighting praxis with calculations, graphical presentations and explanations.

C3: Application Using acquired knowledge. Solve problems in new situations by applying acquired knowledge, facts, techniques and rules in an unknown and new situation. Coping with complex problems as found in typical working routines, finding optimal solutions.

EXECUTION OF THE EXAMINATION

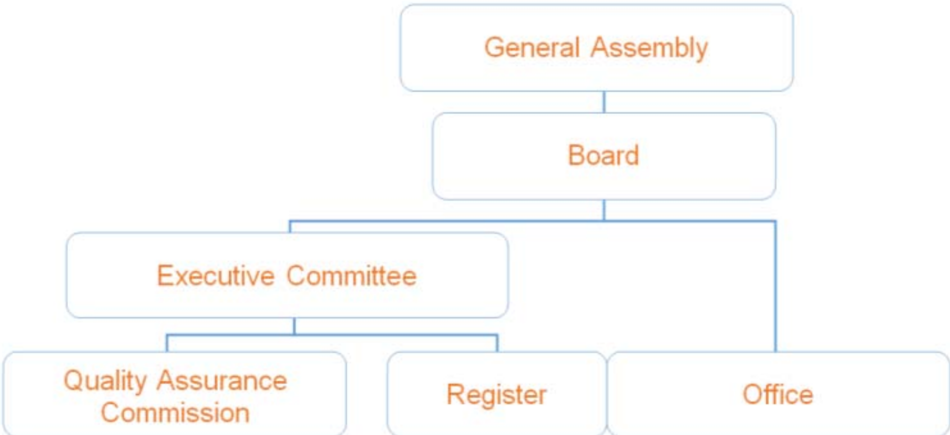
In the examination, the candidate has to prove sufficient know how related to a wide-ranging catalogue of topics from basic knowledge in lighting technology, electrical engineering, light sources and luminaires, via lighting design, execution, operation and renovation of exterior and/or interior lighting to photometric measurements. There is a total of some 150 sub-topics, each one of which requiring a different, specific level of knowledge, understanding and ability to apply the acquired knowledge (C1 to C3, as described above), and differentiated between exterior and interior lighting. In addition to a compulsory oral examination and possibly a written part, the examination contains the presentation and discussion of a planning task, which the candidates have worked on prior to the examination. This approach allows to test candidates according to the defined educational objectives with a differentiated level of competencies up to C3 (ability to apply acquired knowledge), which would be impossible – or at least very difficult – with a written test, or even a multiple-choice test only.

The examination can be done under responsibility of any of the national member societies of the "European Lighting Expert Association (ELEA)". In several countries, corresponding training is provided by the lighting societies. For the examination, however, the participation in these training courses is not mandatory. Also, any voluntary preparatory courses may be provided by other institutions as well. After an examination on national level, successful candidates are eligible to be registered as European Lighting Experts by the ELEA.

ADMINSTRATION OF THE "EUROPEAN LIGHTING EXPERT" CONCEPT

The ELEA was founded in August 2016 by its four founding members LiTG, LTG, NSVV and SLG, and it is open for membership by additional lighting societies from other European countries, who are invited to realize the ELE concept in their respective countries. The ELEA is responsible for all documents related to the educational concept and its further development, for the independent supervision of the examinations, the registration, the certificates, the register itself, the publication of that register in a specific website (www.europeanlightingexpert.org), as well as all administrative tasks within the association with its growing number of members.

The organizational structure of the ELEA looks as follows:



The ELEA is a society registered in Switzerland. Its office is located in Olten (Switzerland), where also the register is managed. Office and register are run by the Schweizer Licht Gesellschaft (SLG). Each of the current members of the ELEA is represented in the Board – with Matthias Hessling (LiTG) as President, Jan Meutzner (NSVV) and Manfred Mörth (LTG) as Vice Presidents and Albert Studerus (SLG) as Treasurer and Secretary – in the Executive Committee, which is responsible for the operative tasks, and in the Quality Assurance Committee, the independent body, not bound by instructions from other ELEA bodies, controlling the compliance with the examination regulations and the defined educational objectives in the national examinations.

Candidates who have passed a national examination and have committed themselves to comply with a particular code of conduct, can apply via their national lighting society for a registration as European Lighting Expert. In addition, they have to pay a registration fee, which currently amounts to 150 €. For member associations of the ELEA, there is a yearly membership fee to be paid. In addition, national lighting associations from other countries are asked for a one-time admission fee, which should be regarded as contribution towards the costs associated with the preparation of the ELE concept by the four founding members.

Outlook

The ELEA is happy that several parties already have expressed their strong interest to join the association, and invites all others to ask for any information they might need. By the end of May 2017, 24 European Lighting Experts already were registered by the ELEA, and the ongoing training courses, examinations and applications for a registration from several countries – an additional 25 in the next round – will lead to a constantly growing number.

Customers and companies working together with European Lighting Experts can be sure to have partners with a comprehensive and clearly defined level of lighting know how, and for European Lighting Experts, it has become much easier to prove their competencies, to be recognized in an international context, and to get easier access to attractive lighting jobs.

Responses from registered European Lighting Experts are very positive and promising – it seems that the concept is well balanced and does satisfy existing needs, and that it did come at the right time with its enormous developing speed and customers increasingly relying on qualified support. A European Lighting Expert for sure can provide this!

Does Higher Illuminance Encourage Reassurance That it is Safe to Walk? Comparing Different Methods of Analysis

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***Abstract*—This article describes two field studies carried out to investigate how changes in lighting affect the reassurance evaluations of pedestrians – lighting that promotes reassurances means pedestrians have greater confidence to walk alone after dark. The studies were carried out in Rome and Sheffield, using the difference between daytime and after-dark ratings of reassurance to investigate the effect of changes in lighting. While both studies suggest that higher illuminance reduces this difference, and that this benefit reaches a plateau, there was a slight disagreement in the optimum illuminance: for similar day-dark differences these were 7 lux in Sheffield and 10 lux in Rome. One difference between these studies was the choice of independent samples or repeated measures: analysis of this difference using a resampling technique did not suggest it to be a significant factor**.

***Index Terms*—illuminance pedestrians, reassurance.**

I. INTRODUCTION

Reassurance describes the feeling of confidence a pedestrian might gain from road lighting to walk along a road, in particular if walking alone after dark. It is used here to encompass the terms commonly used in previous work - perceived safety and fear of crime. While a lit road is likely to offer more reassurance than an unlit road [1] it is not yet established how much light (or, other criteria) is optimum.

Many studies have used rating scale questionnaires to compare feelings of safety or fear in roads lit to different illuminances, with surveys carried out after dark. In the quest for an optimum absolute illuminance, this approach is doomed. It is doomed for two reasons. First, there will likely be a range bias, meaning that the higher of the illuminances examined in a survey will be placed at the higher (safer) end of the rating scale, regardless of the actual illuminances examined [2]. This means that different studies, surveying roads of different ranges of illuminance, will draw trivial conclusions about the effect of absolute illuminances, typically demonstrating only that higher illuminances are better. Second, comparing surveys of different roads to say something about illuminance is confounded if the locations surveyed have different underlying levels of reassurance. There is an alternative approach that may provide a better analysis, which is to record evaluations of reassurance in both daytime and after dark (at nighttime in these two cities), for the same locations, and to plot the difference between day and dark ratings against illuminance [3]. Using this approach it has been shown that an asymptote illuminance is likely to be reached.

This article reports two surveys of reassurance. These surveys used the day-dark approach to compare subjective evaluations against illuminance, with one survey carried out in the UK (Sheffield) using repeated measures and the second in Italy (Rome) using independent samples.

II. STUDY 1: SHEFFIELD

A. Method

Ten locations were evaluated, comprising eight roads, a pedestrian underpass and a footpath running through a park, all located in an urban residential area of Sheffield, UK. Preliminary measurements suggested mean horizontal illuminances ranged from approximately 5 lux to 60 lux, this range being chosen to test the day-dark method of analysis. Road lighting was provided by High Pressure Sodium (HPS) lamps in six locations, with LED arrays and fluorescent lamps used in two locations each, in all cases being post-mounted lighting along the side of the road.

Three photometric values were recorded; horizontal illuminance, hemispherical illuminance and semi-cylindrical illuminance. The semi-cylindrical illuminance sensor was mounted on a post so that it measured illuminance in the vertical plane at a height of 1500 mm above floor level, and facing parallel with a pedestrian direction of travel on the path. The horizontal and hemispherical sensors were placed flat, in the horizontal plane, and were 150 mm above floor level, being mounted upon a trailer. Measurements were taken for ten evenly spaced locations between the two lamp posts of each test location, in accordance with BS EN 13201-3:2015. For the eight roads, these measurements were taken along the centre of the footpaths on both sides of the road, giving 20 measurement points; for the park pathway and the underpass, only a single row of measurements were recorded, giving 10 measurement points. Light measurements were carried out after-dark on two occasions, with both sets of measurements commencing at 19:00. Table I shows the mean and minimum illuminance at each location, these determined from the mean of the measurements captured on the two days.

TABLE I. TEST LOCATIONS IN THE SHEFFIELD AND ROME STUDIES OF REASSURANCE

	Sheffield				Rome			
Location	**Road Type**	**Light source**	**Horizontal illuminance (lux)**		**Road Type**	**Light source**	**Horizontal illuminance (lux)**	
			mean	*min*			*mean*	*min*
1	Residential	Fluorescent	7.5	1.3	Residential	HPS	10.5	2.5
2	Residential	HPS	4.2	0.5	Residential	HPS	18.1	8.5
3	Residential	HPS	10.6	3.2	Residential	HPS	21	5
4	Residential	HPS	9.1	3.1	Residential	HPS	24	17
5	Residential	LED	8.5	3.5	Residential	LED	16.1	7
6	Residential	LED	7.3	4.1	Residential	LED	11.9	6
7	Residential	HPS	6.9	1.8	Residential	HPS	12.4	3.65
8	Residential	HPS	5.0	1.2	Residential	HPS	18.3	9
9	Park pathway	HPS	7.7	1.1	Residential	HPS	12.0	6
10	Underpass	Fluorescent	58.2	28.5	Residential	HPS*	35.0	20

*Note: road 10 in the Rome study also had Metal halide on the façade of adjacent buildings.

Separate but near-identical questionnaires were used to evaluate each location. For daytime, this was nine questions relating to reassurance and the general environment, with a further question to check attentiveness. For the after dark version, five questions regarding road lighting were added. Responses to all questions were captured using 6-point scales. In this article we present analysis of the responses to one of these questions: *How safe do you think this street is?* (1=very dangerous and 6=very safe).

Twenty-four participants were recruited for the experiment, aged between 18 and 38 years, with a mean age of 24 years, and included an equal balance of males and female. Following Boyce et al [3] a repeated measures design was used in which all participants provided ratings on all streets, during daylight and after-dark. The participants were divided into four groups of six, with each group being taken to the ten locations together. This allowed the day-dark order (i.e. daytime or after dark evaluation first) and the location order (i.e. forward or reverse) to be counterbalanced. The tests were conducted between the 18th and 30th November 2016. The typical time for the morning sessions was 10.30 am and 4.45 pm for the after-dark sessions following a sunset time of approximately 4pm. A test session took approximately two hours. At each location the evaluation point was close to a lamp post. Before completing the questionnaire the test participants were asked to walk a set distance, usually between the two lamp posts used for the lighting measurements, then cross and walk back to the evaluation point. They were asked to face towards this same area when responding to the questions. The timing of each participant in the group was staggered so that they walked this route alone.

B. Results

Fig I shows the Day-Dark difference plotted against mean horizontal illuminance. This relationship appears to be best explained by a logarithmic trend. When all ten locations are considered, $R^2=0.61$. Within these data, the illuminance of the underpass is extreme (58 lux against <11 lux for all other locations) and the Day-Dark difference for the park does not appear to follow the same trend as for the other locations: if only the eight road locations are considered, $R^2=0.60$, but the trend does not reach an asymptote. Fig II shows the day-dark difference plotted against uniformity (minimum/average illuminances). This also appears to give a reasonable explanation of the effect of lighting on reassurance, with the logarithmic relationship suggesting R^2=0.70. Taken together, these suggest that both higher illuminance and higher uniformity raise reassurance.

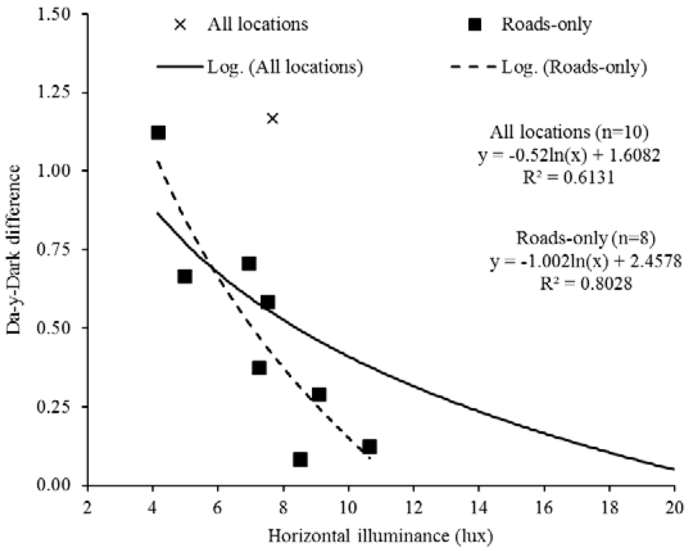

Figure 1. Results of Sheffield study: Day-dark difference plotted against mean horizontal illuminance.

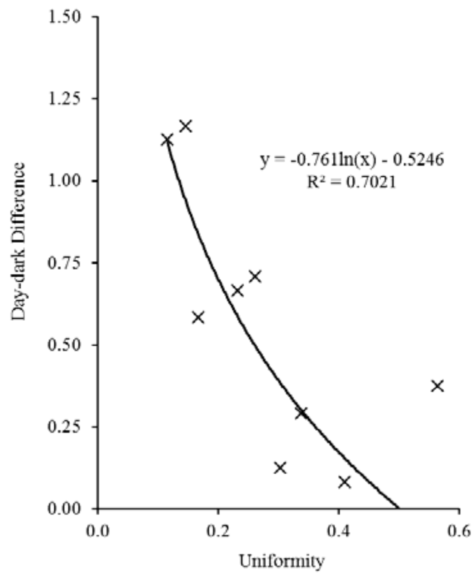

Figure 2. Results of Sheffield study: Day-dark difference plotted against uniformity ($E_{mean}/E_{minimum}$)

STUDY 2: ROME

Method

Ten locations were evaluated, with all ten being roads of similar physical features located in the same district of the city centre of Rome, Italy. All ten roads were lit using HPS road lighting, mounted in the centre of the road with a catenary system. Mean horizontal illuminances ranged from 11 to 35 lux (Table I). Evaluations were sought using two similar questionnaires for the daytime and after dark surveys. These included eight questions about the street, the visual comfort and the quality of lighting with responses given using an 11-point response scale. In the current article we consider responses to one question which directly addressed reassurance: *Please rate how safe you would feel to walk alone along this road* (10 = very safe and 0 = very unsafe). The remaining questions included four related to perceptions of street characteristics, answered in daytime and after-dark, and three about street lighting which were asked only in the after-dark surveys.

In this study an independent samples approach was used. While many other studies associated with pedestrian reassurance use an independent samples approach (typically for before-and-after evaluations of a change in lighting e.g. [4], [5]) Boyce et al [3] used repeated measures. Independent samples require a larger sample but each participant is required to attend for only one session: this may be of practical advantage to the experimenter. The 40 test participants (aged 20-30 years old; equal balance of male and female) each evaluated all ten locations but each was evaluated in daytime or after dark but not both. Test participants were randomly allocated to the two groups (Day or Dark conditions). The ten locations were divided into two routes, A and B. Half of the test participants evaluated route A in daytime and route B after dark, and the other half evaluated route B in daytime and route A after dark. The mean reassurance rating for each street was calculated for the day and after-dark surveys and the day-night difference for a street determined from these mean values.

Results

Fig III shows the Day-Dark difference plotted against mean horizontal illuminance. This relationship can be explained using a logarithmic trend (R^2=0.69, n=10). Fig IV shows the day-dark difference plotted against uniformity (minimum/average illuminances). A logarithmic relationship is illustrated here for consistency with other plots, but the low degree of correlation (R^2=0.25) is improved using an exponential relationship (R^2=0.40). These results again suggest that both higher illuminance and higher uniformity raise reassurance.

A. RE-SAMPLING

In both studies the results indicate that the Day-Dark difference is reduced with higher illuminance and higher uniformity, but there is slight disagreement as to the magnitude of light needed. In the Sheffield study and illuminance of 7.0 lux is associated with a day-dark difference of 0.5 on their 1-6 rating scale. The Rome study used a 0-10 rating scale and a difference on this scale of 1.0 represents the same scale proportion as 0.5 in the Sheffield study: this difference is associated with an illuminance of 10 lux. There are three key differences between these studies that might explain part of this difference. First, the studies were carried out in different countries where the expectations of lighting may be different. Second, there were differences other than illuminance between these studies.

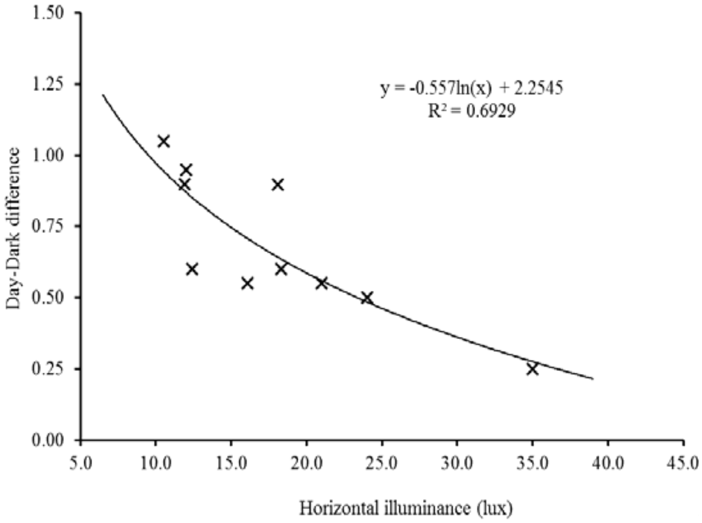

Figure 3. results of rome study: day-dark difference plotted against mean horizontal illuminance

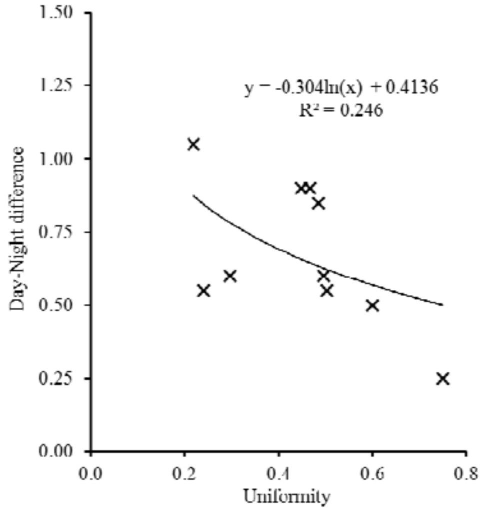

Figure 4. Results of Rome study: Day-dark difference plotted against uniformity ($E_{MEAN}/E_{MINIMUM}$)

A third difference is the sampling technique, whether repeated measures (Sheffield) or independent samples (Rome). This difference was explored using a re-sampling technique.

Resampling compares two groups of data to determine if they are statistically different by repeatedly shuffling and randomly allocating the data into two new resampled groups and calculating the difference between the means of these two groups. These multiple group differences from the resampled data are combined to create a sampling distribution. This is effectively a distribution of group differences that might be found if the two groups of original data were not statistically different. If there are a very low proportion of values in this distribution that are more extreme than the original difference between the two groups (0.05 or less, representing the conventional alpha used in most statistics) it can be concluded that the original groups of data are significantly different [6] .

Here we use this resampling method to determine whether the mean day-dark difference values produced from independent-samples (IS) and repeated-measures (RM) approach are significantly different. A mean day-dark difference based on an IS approach was estimated from the Sheffield data by only using the ratings provided by participants in their first session. As the order of the sessions (day followed by dark, or vice versa) was counterbalanced between participants, this resulted in 12 participants who provided day ratings and 12 participants who provided after-dark ratings in their first session. The mean dark ratings were subtracted from the mean day ratings for each road to give a mean day-dark difference based on an IS approach (Table II). The day-dark difference for all 24 participants using responses from both sessions provided a mean day-dark difference for the RM approach, also shown in Table II. To carry out the resampling procedure, IS day-dark differences were calculated from 24 random pairings of first session day and first session after-dark ratings, for each road. These IS day-dark differences were randomly shuffled with the RM day-dark differences from all 24 participants, and allocated into two equal-sized groups. The difference between the means of these two new resampled groups was calculated. This process was repeated 10,000 times to create a distribution of differences between the resampled groups; Fig. V shows an example distribution for Sheffield road 1.

The proportion of these distributions that were more extreme (either positive or negative) than the original difference between IS and RM day-dark values are shown in Table II for all 10 roads. For all ten roads, the proportions are larger than 0.05, which does not indicate that the RM and IS methods produce significantly different day-dark differences.

A. CONCLUSION

This study described two field surveys carried out to investigate the influence of road lighting on pedestrian reassurance. Specifically, a key aim was to use the Boyce et al Day-Dark approach to seeking an optimum illuminance for reassurance. In both studies there is a clear association between the day-dark difference in ratings of safety and road lighting as characterised by mean horizontal illuminance or illuminance uniformity. While more light helps to raise reassurance, these data suggest a limit to the benefit of increasing illuminance, and also that spatial variation in the amount of light matters. The studies suggest different illuminances for a set value of the day-dark difference: for a value of 1.0, the associated horizontal illuminances are 4 lux in Sheffield and 10 lux in Rome. Our resampling analysis does not suggest this difference is due to the sampling method.

In on-going work we are evaluating the impact of a principal components analysis to establish the reassurance rating, using eye tracking and involuntary physiological response as alternative to subjective ratings, considering alternative photometric quantities (with caveats [7]), ratings captured using immersive virtual reality, and the responses of older aged test participants.

TABLE II. DAY-DARK DIFFERENCES FOR RM AND IS APPROACHES, AND PROPORTION OF RESAMPLED DISTRIBUTIONS MORE EXTREME THAN DIFFERENCE BETWEEN THESE ORIGINAL RM AND IS VALUES.

Road Number	Mean day-dark difference (RM); N = 24	Mean day-dark difference (IS); N = 12	Difference between mean values from IS and RM	Proportion of resampled distribution more extreme than original RM and IS difference
1	0.58	0.33	±0.25	0.44
2	1.13	1.25	±0.12	0.61
3	0.13	-0.17	±0.3	0.31
4	0.29	0.00	±0.29	0.43
5	0.08	-0.25	±0.33	0.23
6	0.38	0.25	±0.13	0.66
7	0.71	0.58	±0.13	0.61
8	0.67	0.58	±0.09	0.71
9	1.17	0.75	±0.42	0.21
10	-0.38	-0.50	±0.12	0.67

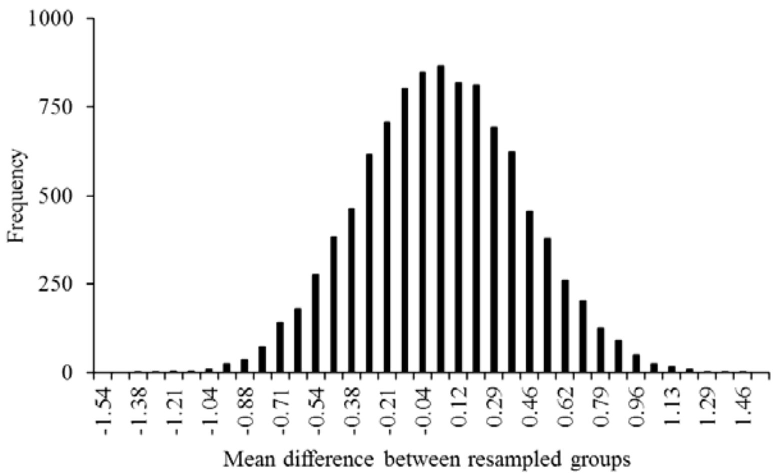

Figure 5. distribution of differences in group means for road 1, following permutation testing with 10,000 repetitions

B. ACKNOWLEDGEMENT

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Effective Radiant Flux For Non-Image Forming Effects – is The Illuminance and the Melanopic Irradiance at The Eye Really the Right Measure?

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Abstract — **Research indicates that intrinsically photosensitive retinal Ganglion Cells are not evenly distributed or evenly sensitive throughout the retina. Still, most research looking into non-image forming (NIF) effects uses an integral measured quantity, illuminance or melanopic weighted irradiance, to represent the amount of light at the participants' eye level. This paper describes a theoretical approach to define the effective radiant flux for stimulating the ipRGCs, taking into account a spatially resolved sensitivity. Research on retinal sensitivity is scares and not yet substantial, but the methodology can easily be adopted when areas of specific sensitivity are set. Preliminary results indicate that, with similar vertical illuminances and spectral power distribution, typical office lighting solutions might have a lower NIF effectiveness than settings with higher luminances in the central part of the field of view. This could explain why research on NIF effects is inconclusive, even though reported lighting conditions are similar.**

Index Terms – **inferior light exposure, nasal light exposure, NIF effects, office lighting, retinal sensitivity**

INTRODUCTION

Since the discovery of the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) in 2002, non-visual effects or non-image forming (NIF) effects of light have become increasingly important in lighting research, development and design of lighting solutions. In this, lighting is, for example, used to increase alertness or sleep quality, to reduce desynchronization of the circadian rhythm or to treat seasonal affective disorders. The majority of the research looks into dependencies of amount, spectral power distribution, length and temporal distribution of light stimuli. Not in focus but also of interest seems to be the dependency on directionality and position of the light source, as only a small number (less than 1%) of the retinal Ganglion Cells are photosensitive [1], and they are not evenly distributed throughout the retina (review in [2]).

Only a few publications on the impact of spatial light distribution include the description of lighting conditions in the experimental set-up. The majority of these studies were conducted between 1992 and 2005 (review in [3]). The offered lighting conditions differed greatly from one study to another. They ranged from 5 to 1000 lux, vertical illuminance at eye level, with varying colour temperature from warm white to cool white, realized by polychromatic light sources; fluorescent lamps, halogen lamps or LEDs. Partial retinal exposure was realised by using light boxes at defined positions in the field of view, or applying modified eye shields on subjects looking into a uniformly lit half dome. All studies took place at night time, sometime between 22:00 and 3:30. The lighting conditions were offered for 60 - 240 minutes and melatonin suppression was used to study the impact of light source size and / or position. The number of participants per study ranged from six to 32, with varying age.

The studies suggest that large sources are more effective than small sources [4]. Binocular light exposure realises a higher melatonin suppression than monocular light exposure (spatial summation in [5]-[6]). Additionally to that, the studies indicate that, in human beings, nasal exposure is more effective than temporal exposure [7]-[8]. Inferior retinal light exposure seems to induce a greater response than superior exposure [9]-[11]. Piazena et al. partly confirmed these findings [12]. Superior warm white light exposure (800 lx, 2666 K) resulted in a reduced and delayed melatonin suppression in comparison to inferior exposure realising the same lighting level at the eye. However, similar cool white light levels (6060 K) caused comparable NIF responses for both inferior and superior light exposure.

Considering the above mentioned, it is questionable if illuminance levels or melanopic irradiance levels, currently referred to in studies with respect to NIF effects of light, are adequate parameters in terms of comparability, being integrally measured values of the full visual field. Retinal illuminance would respect human anatomic restrictions [13], and can be measured with adjusted illuminance sensors (e.g. [14], [15]). Nonetheless, a more distinct subdivision within the human field of view might be required. Whereas the number of studies is too small to define areas with different ipRGC sensitivities, a suggestion for approximate areas of “no”, “little” and “good” effectiveness is given by FGL (Fördergemeinschaft Gutes Licht) (2014) (Fig. 1) [16].

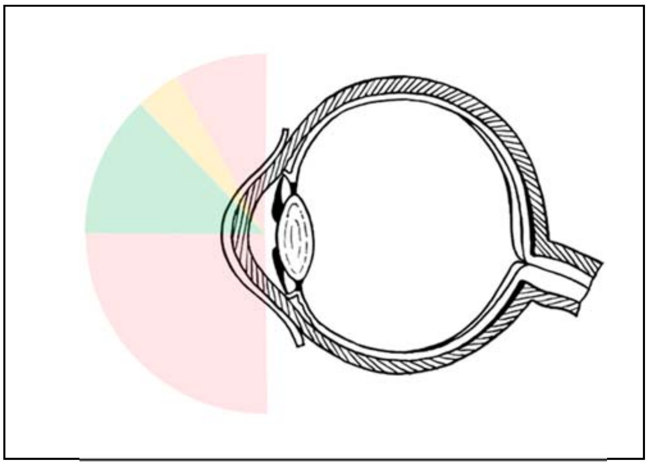


Figure 1. Approximation of spatial sensitivity due to ipRGC density or sensitivity as found in a small number of studies (based on [16] with areas of “little” (yellow) and “good” (green) response to induce NIF effects.

The aim of the presented study is to look into the range of the, spatially resolved, effective radiant flux stimulating the ipRGCs for different distribution of the incident light under a constant (full visual field) illuminance level at the eye.

METHODOLOGY

The study described in this paper uses a theoretical approach to evaluate the impact of higher sensitivity for nasal and inferior light exposure. For this, a methodology to evaluate the spatially resolved illuminance contribution of defined areas in the field of view to the overall vertical illuminance at the eye was defined. Luminance images are converted into matrices containing luminance values for each pixel. Using another matrix that holds the opening angle ω_s and an additional matrix with the tilt angle ϑ of each pixel, it is possible to calculate the illuminance contributions. Generally, the following equation applies:

$$E_p = \int \quad L(\theta, \psi) \cos(\vartheta) \, d\omega_s \qquad (1)$$

E_p	illuminance
L	luminance of each pixel, which position is determined by θ, ψ
ω_s	solid angle
ϑ	tilt angle

The resulting matrix comprises the illuminance contribution of each pixel to the integral vertical illuminance. Hence it is possible to define regions of interest in the field of view and to calculate the illuminance at eye-level caused by each region.

A. Test room

A complete LED backlit test room with typical cell-office dimensions (5 m width, 4 m length and 2.8 m height) at the Chair of Lighting Technology of TU Berlin was used for this study. This test room is equipped with 1470 individually addressable LED panels with a size of 18 cm x 18 cm, covered by a diffusing material. Each panel holds 36 mid-power, cool white or warm white, LEDs. The correlated colour temperature (CCT) of the LED panels behind the diffusing material was measured with a ‘specbos 1201’ spectrometer by Jeti Technical Instruments. The cool white setting has approximately 5900 K, the warm white setting 2800 K. Mixed settings have 4400 to 4500 K, depending on the used lighting scenes. The cool and warm white LED panels are arranged in a checkerboard pattern to ensure good uniformity and mixing characteristics if used together as well as separately. With this installation, it is possible to set specific luminance distributions for separate fields of the walls and ceiling with different CCTs. Twelve luminaires in the middle part of the ceiling are designed to optimise NIF effects; offering a range between 2000 – 20 000 K.

B. Settings

Within this study, eight different luminance distributions, some very similar to typical electric lighting solutions for offices, some very different, were set to realize a constant vertical illuminance of 500 lx (+/- 2.5 %) at eye level. This was measured at 1.20 m above floor level by a luxmeter MX-ELEKTRONIK Mini-Lux with a V(λ)- and cosine-corrected Si-photometer head. Additionally the horizontal illumination at 0.85 m, at a fixed position on the desk was measured with a cosine-corrected luxmeter LMT Pocket-Lux 2. CCT of the lighting scenes ranged from 3900 K to 4900 K.

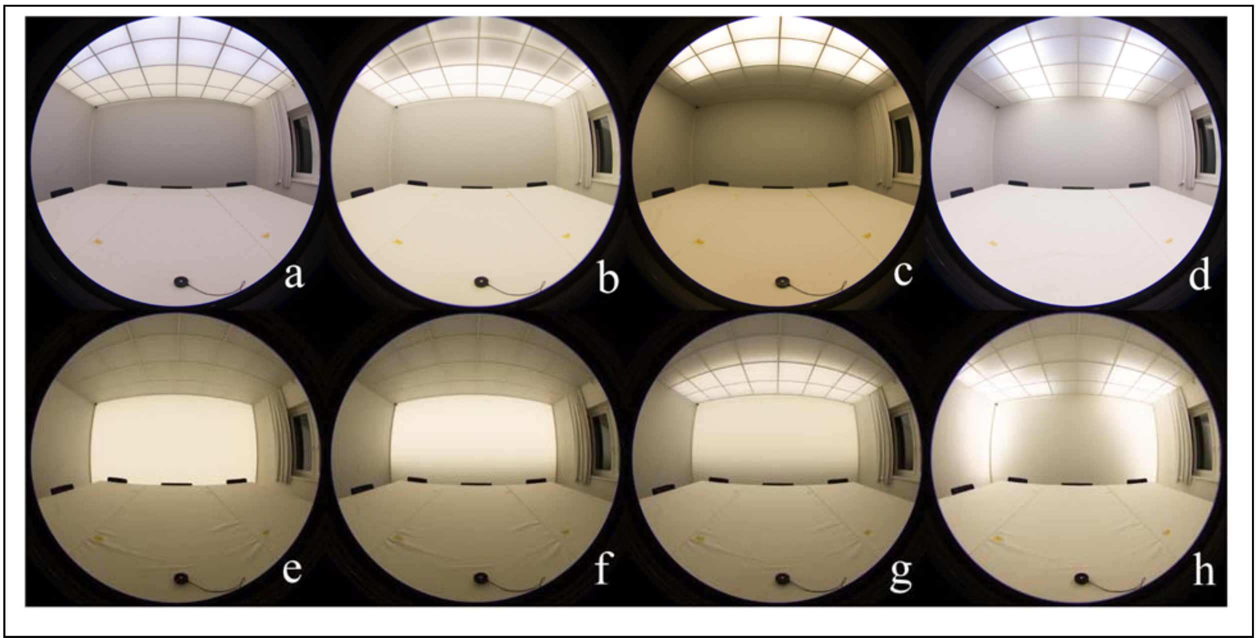


Figure 2. Lighting scenes (a – d typical office like; e – f non-typical like)

a. Measurement and processing

The variable in this study, the luminance distribution of the eight chosen scenes, was measured by a luminance camera 'LMK mobile advanced' based on a CANON EOS 550D by TechnoTeam GmbH equipped with a 4.5 mm object lens (circular fisheye lens) with an angle of coverage of 140°. For each setting HDR luminance images were taken.

Based on the approximation of spatial sensitivity by FGL (Fördergemeinschaft Gutes Licht) (Fig. 1), and the anatomic restrictions (e.g. light shielded by the nose), following areas of interest were chosen to demonstrate the potential and the consequences of a spatial differentiation (Fig. 3 and Fig. 4):

- ☐ = 0° to 45° and 45° to 60°
- φ = 0° to 55° and 0° to −55° (to both sides of the direction of gaze)

Light coming from region 1 (Fig. 4) illuminates only the nasal part of the right eye's retina. Light in region 2 causes illumination of the lower part of both retinas. Light from region 3 illuminates the nasal part of the left eye. These angles are believed to have a good impact on NIF effects, while angles between ϑ = 45° to 60° are supposed to have only weak effect and higher angles have no effect [16]. Moreover, region 2 is of special interest since the illumination of both retinas is found to cause a higher melatonin suppression [5]-[6].

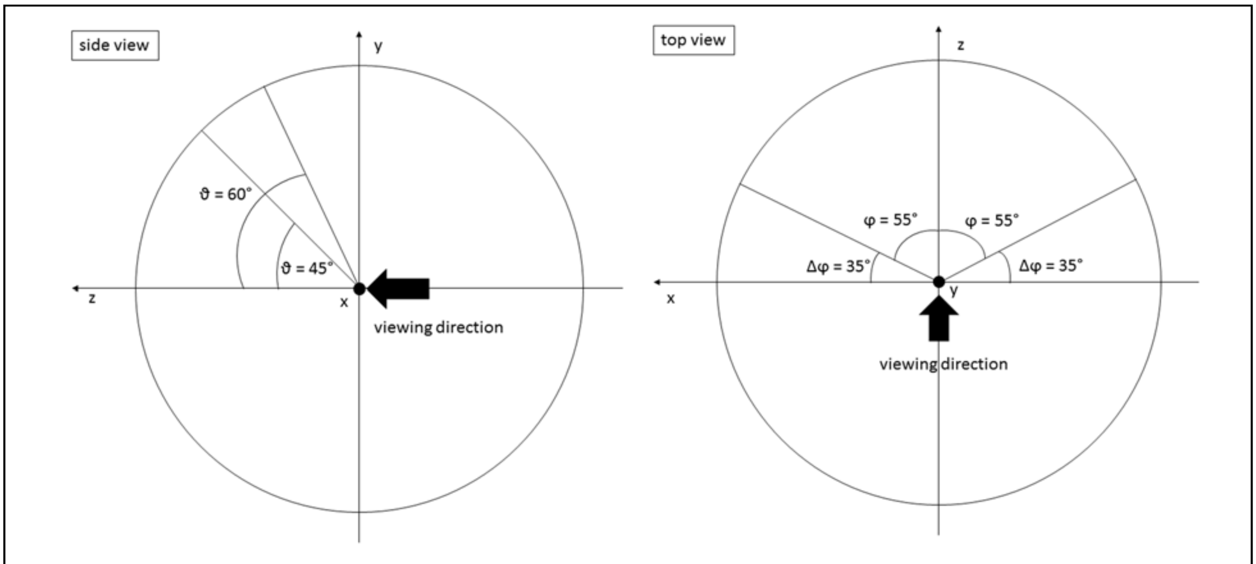


Figure 3. Schematic of the angles in the visual field (based on [13] and [16])

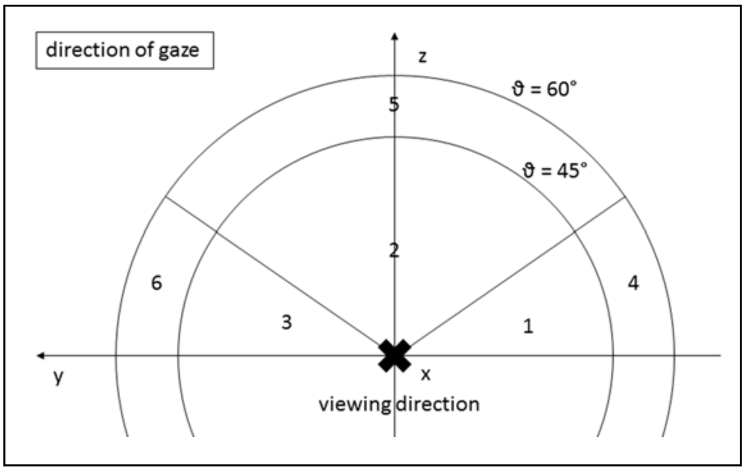
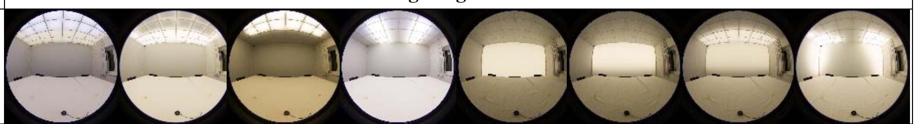


Figure 4. Overview of the region in the field of view

RESULTS

The methodology was applied to the eight lighting scenes shown in Fig. 2. For each region, the illuminance contribution was calculated. Table 1 holds this value represented as percentage of the measured vertical illuminance for better comparability. The lighting scenes a – d with light mostly coming from the ceiling show in general low values. The ϑ=0° to 45° region contributes only with 10 to 26 % to the integral illuminance. If extended to ϑ=0° to 60° this increases up to 44 %. On the other hand, lighting scenes e – h, with light mostly coming from the opposite wall, have relatively high values. The ϑ =0° to 45° region contributes with 35 – 51 %, in the extended ϑ =0° to 60° region up to 58 %. In case region 2 gets a higher weighting, taking the findings of Wang [5] and Brainard [6] into account, the differences between lighting scenes a – d and e – h become even larger.

TABLE III. ILLUMINANCE VALUES

regions		**Lighting scenes**							
									
		a	b	c	d	e	f	g	h
Illuminance	E_v [lx]	506	511	504	500	497	500	507	496
	E_h [lx] [a]	657	694	619	640	263	276	329	338
	E_v [%] [b]	2.8	3.2	2.0	2.8	9.5	10.6	7.5	8.5
	E_v [%] [b]	15.1	19.2	5.6	17.3	24.3	29.2	28.6	19.1
	E_v [%] [b]	2.8	3.1	1.9	2.6	9.9	11.1	7.7	7.3
	E_v [%] [b]	20.7	25.5	9.5	22.6	43.7	50.8	43.8	34.9
	E_v [%] [b]	1.5	1.7	1.0	1.3	1.2	1.3	1.5	2.1
	E_v [%] [b]	14.0	11.0	18.6	18.4	4.2	4.2	9.0	10.5
	E_v [%] [b]	1.5	1.7	0.8	1.2	1.6	1.6	1.8	5.4
	E_v [%] [b]	37.7	39.9	30.0	43.6	50.7	58.0	56.1	52.9

a. horizontal Illuminance at 0.85 m

b. vertical Illuminance in percent of the luxmeter-measured value

CONCLUSSION AND DISCUSSION

A luminance camera based evaluation method to determine the spatially resolved partial illuminance values was developed. Here regions were chosen to fit illumination of the lower left and right eye's nasal part of the retina and the illumination of the lower halves of both retinas simultaneously. Typical and non-typical office lighting scenes were investigated. Data showed that the more standard-like office lighting scenes cause only weak illumination of the defined regions. Logically, lighting of the opposite wall leads to much higher contributions from these regions. With comparable spectral power distribution and vertical illuminances, typical, electric, lighting solutions for offices will result in a lower efficiency to induce NIF effects than settings with higher vertical luminances in the central part of the field of view, such as daylit rooms or lighting solutions with wall washers.

It needs to be pointed out, that there are only few studies indicating differences in melatonin suppression if superior or inferior halves of the retina are illuminated and even fewer showing differences in nasal and temporal parts of the retina. For now, an exact determination of regions and their respective sensitivity weighting cannot be made. Furthermore, these studies were executed at night time looking into the resulting suppression of melatonin levels. Rüger et al. already showed that suppression of melatonin does not per se lead to reduced sleepiness when only parts of the retina are illuminated [17]. Additionally to that, these results are not directly applicable for daytime responses. During daytime, the mode of action for NIF effects is still not well enough understood. Cones, with their incidents mostly in the centre of the visual field, are considered to influence NIF effects as well [18]. Resulting, it could be that, at least under daytime conditions, the distribution and spectral sensitivity of more than one receptor has to be taken into account.

In this respect, this method is a theoretical approach. Nonetheless, it is an aspect of interest, as it could explain why some studies do find NIF effects, and others do not, even though vertical illuminances and spectral power distribution of the light sources applied are similar. In order to compare these studies and to allow future adjustments to areas of interests and their specific sensitivities, it is proposed to look into the representation that accounts for the origin of light (e.g. by means of light incidence according to [19]-[20]).

Spectral power distribution was not considered in this study. Future research will look into spatially and spectrally resolved measurements, using a luminance camera that includes colorimetric filters and a melanopic filter, to evaluate the consequences of spatial sensitivity on NIF effects of typical lighting conditions with varying spectral power distributions in laboratory studies as well as field studies.

ACKNOWLEDGEMENT

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TM-30-15 and CIE-CRI-Ra: Investigation of Colour Rendering of White Pc LEDs

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***Abstract*— The colour rendering properties of 21 phosphor converted LED light sources (pc LED) with different R_f and R_g values as in the Fidelity Index and Gamut Index of the TM-30-15 have been investigated. Scenarios illuminated by pc LEDs, a fluorescent lamp (FL) and a tungsten halogen lamp (THL) were presented to 34 subjects. An assortment of coloured objects was arranged identically in two adjoining booths and participants rated the test scenarios in comparison with the reference illuminant (THL). For colour quality, both indexes are reflected in the observer's ratings. The Fidelity Index strongly correlates with the colour difference and colour shift perceived; the Gamut Index with the subjects' ratings of the colour saturation. Participants found the best match with the fluorescent lamp (R_f = 80/ R_g = 100) to be the pc LEDs with R_f = 75/ R_g = 105 and R_f = 80/ R_g = 105.**

***Index Terms*-- colour rendering, pc LED, TM-30-15.**

INTRODUCTION

Nowadays, Light Emitting Diodes (LEDs) are used more and more in indoor lighting applications. In the first years, white light was produced by combining differently coloured LEDs (RGB-LEDs). Nowadays, phosphor converted LEDs (pc LEDs) are used. The light emitted by a blue LED is down-converted to light with a longer wavelength, using phosphors. This is then added to the original blue LED light, making white light. Commonly, the converter is a mixture of different types of phosphors to achieve a certain LED spectrum, which will affect the colour rendering properties. Correct description of these properties is a prerequisite to target setting in light source development. The current standard method of calculating these properties is the CIE colour rendering index (CRI) R_a, recommended in 1995 as CIE 13.3 [1]. Studies have revealed inconsistency between this method and its rating by subjects especially in LED lighting [2]. Attempts to improve on it go back many years. On one hand, the method of calculation has been improved in reliance on new colorimetric discoveries; on the other, the spectral power distribution (SPD) of the light sources has been optimised, for instance by using different types of phosphors, as this is what largely defines colour quality. In 2015, the Illuminating Engineering Society (IES) published the Technical Memorandum TM-30-15, a new calculation method for colour rendering of white light sources [3]. There is international consensus that a single criterion is insufficient to describe colour quality for this includes many aspects. TM-30-15 combines colour fidelity, rated with the R_f index, and the colour gamut, rated with R_g index: this describes the area enclosed by the average chromaticity coordinates in each of 16 hue bins. THORNTON has shown that the larger the colour gamut, the better is the colour discrimination because the chromaticity coordinates are further apart in the colour space. There is also an assumption that light sources with larger gamut enable colours to be perceived as more saturated, more brilliant and more natural [5]. XU assumes that the size of the area enclosed is proportional to the maximum possible number of colours that can be represented [6]. RGB-LEDs are an example of LEDs with narrow SPD. They may have a large gamut index but the rendering of certain colour may be inexact. It therefore makes sense to combine the two indices.

ROYER has carried out an initial study of LED illumination in a test room with coloured objects. The illumination produces white light from seven types of tuneable, coloured LEDs with varying R_f and R_g values. The conclusion is that observers prefer LED light sources with Fidelity R_f > 75 and Gamut Index values $R_g \geq 100$ [7]. In the present work, this result is examined in respect of pc LEDs.

RESEARCH ISSUES AND HYPOTHESES

It is hypothesised that the ROYER requirements are fulfilled for white pc LEDs and that the R_f and R_g values in TM-30-15 reveal high correlation with subjective evaluation of colour rendering properties on the part of observers. The present work tests whether pc LEDs with identical CIE R_a values improve on the subjective evaluation of fluorescent lamps.

EXPERIMENTAL SETUP AND METHODOLOGY

Two adjoining booths with two sections, one for the illumination unit with diffuser and another for test objects, were used (Figure 1, left). In one booth, the light sources installed were a tungsten halogen lamp (SoLux) and a fluorescent lamp (OSRAM Sylvania with CIE $R_a = R_f = 80$ and $R_g = 100$), together with three types of blue LED and seven different fully converted LEDs incorporating a variety of green and red phosphors. Combining a variety of LEDs enabled various SPDs to be produced which were identical to those of white pc LEDs. 21 combinations of LED with R_f values between 66 and 94 and R_g values between 92 and 114 were investigated in comparison with a reference, as were the FL and the THL. The reference lighting in the second booth was provided by a THL (SoLux, $R_f = R_g = 100$). All lighting conditions had identical luminous colours ($CCT = 3800$ K) and the same illuminance level in the centre of the floor of the booth ($E = 400$ lx). This experimental setup reflects the fact that both the CIE CRI R_a and the TM-30-15 are reference-based methods. Figure 1 right shows the relative SPDs of the light sources.

a) 

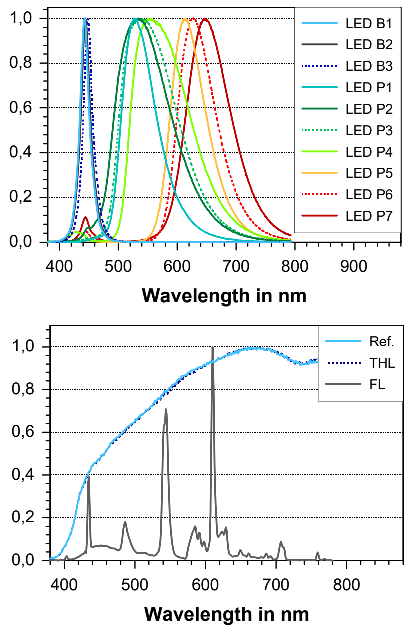
b) 

Figure 1: a) Experimental setup with two booths (width: 46 cm, depth: 48 cm, height: 96 cm), at the top the lighting units, curtained and exposed, and below the test objects; b) relative SPDs of the light sources: B stands for blue LED, P for fully converted LED with different types of phosphors, Ref. for reference illuminant (SoLux THL), THL for the Solux tungsten halogen lamp, FL for the OSRAM Sylvania fluorescent lamp

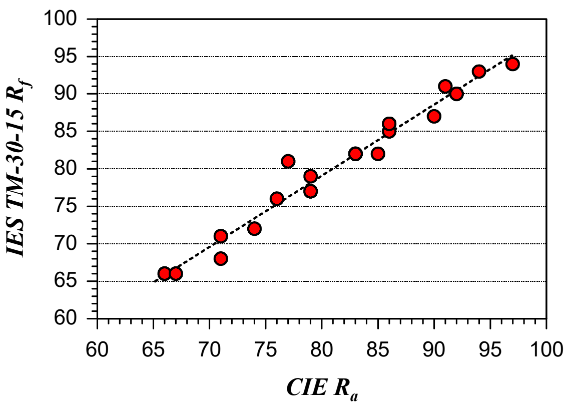


Figure 2: Correlation between the R_a and R_f values, coefficient of determination $R^2 = 0.98$

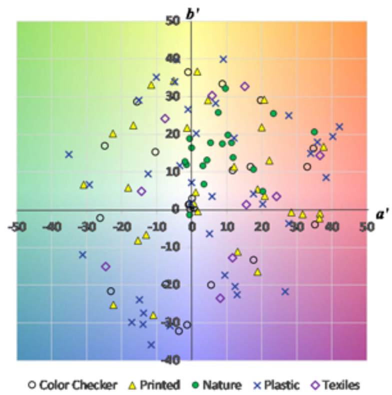


Figure 3: Chromaticity coordinates of the test objects in the CIE CAM02-UCS when illuminated with a Planckian radiator at $CCT = 3800$ K

The R_a values are almost identical with the R_f values, differing by an average of only one point with a maximum of four. The coefficient of determination for the lighting conditions tested is $R^2 = 0.98$ (Figure 2).

An assortment of identical coloured objects was arranged equally in the two booths. The choice of objects ensured that a wide range of hue, saturation and lightness was covered. The chromaticity coordinates of the objects are shown in Figure 3. They were objects from daily life: they included plants, food, consumer goods, office and printed materials, and colour rendition charts (Color Checker). The SPDs of selected LED scenarios and the R_f-R_g combinations are shown in Figure 4.

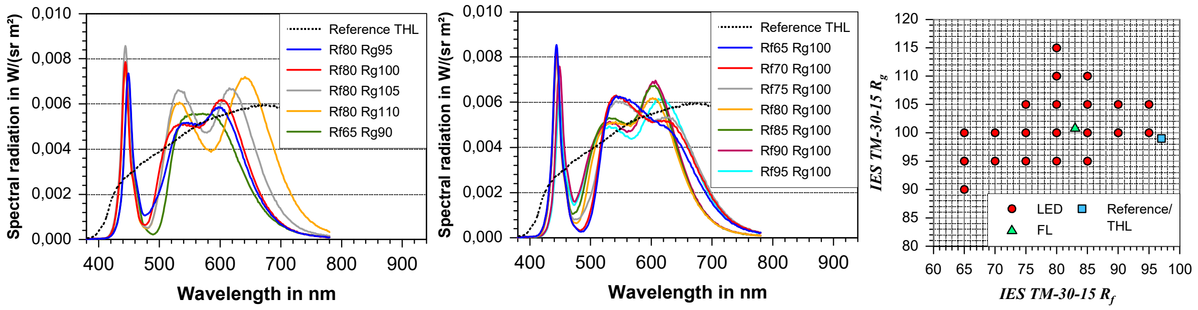


Figure 4: Spectra of selected scenarios (left and centre); R_f-R_g combinations for all scenarios in the experiments (right)

There were 34 participants between 23 and 48 years old (∅ 35 ± 7 years), 10 of them women. They filled in a questionnaire, firstly evaluating the colour rendering properties experienced simultaneously in the two booths. This evaluation was of differences in object colour perceived under the test and the reference light source according to the criteria of colour difference (CD), saturation (S), brightness (PB), temperature (T), colour shift (CS), likeability (LA) and naturalness (NN). In addition, the subjects were asked which of the object colours matched their expectation (EP) for the objects and how they rated the overall colour quality (CQ) of the objects independently of the reference. The questionnaire is shown in Figure 5.

Do you perceive a colour difference between the objects in the left booth and those in the right booth?					
Colour difference (CD)	1 = none	2 = small	3 = moderate	4 = great	5 = very great
How do you find the colours of the objects in the left booth in comparison to those on the right hand side?					
Saturation (S)	1 = very saturated	2 = somewhat saturated	3 = no difference	4 = somewhat unsaturated	5 = very unsaturated
Brightness (PB)	1 = very bright	2 = somewhat brighter	3 = no difference	4 = somewhat darker	5 = very dark
Temperature (T)	1 = very warm	2 = somewhat warmer	3 = no difference	4 = somewhat cooler	5 = very cool
Colour shift (CS)	1 = none	2 = small	3 = moderate	4 = large	5 = very large
Likeability (LA)	1 = very nice	2 = somewhat nicer	3 = no difference	4 = somewhat less nicer	5 = much less nice
Naturalness (NL)	1 = very natural	2 = somewhat more natural	3 = no difference	4 = somewhat less natural	5 = very unnatural
In which booth do the colours of the objects better match your expectation?					
Expectation (EP)	1 = left	2 = right	3 = both	4 = neither	
Ignoring the right hand side, how do you rate the colour quality of the objects in the left hand booth?					
Colour quality (CQ)	1 = very good	2 = good	3 = moderate	4 = bad	5 = very bad

Figure 5: Items in the questionnaire (translation from the German version)

The differently lit scenarios were presented in random order. There was a repeat of the test for four scenarios. The mean values and intervals of confidence ($CI_{95\%}$) were calculated in respect of the subjects' responses and of the experimental parameters R_a, R_f and R_g. The coefficient of determination (R^2) was established for the linear regression across the mean of the ratings. Analysis of variance and post-hoc tests were carried out for the comparison between LED light sources and the FL.

RESULTS

There is a diagrammatic summary of the questionnaire results in Figure 6. The figures used are mean values and bares are intervals of confidence across all subjects (N = 34).

It can be seen in the diagrams and from the coefficients of determination for the linear regression R^2 in Figure 6 and from Table I, that subjective colour quality rating is indeed a multi-dimensional problem and that both indices, R_f and R_g, are important aspects. While the R_f value gives a good description of colour difference, colour shift and the perception of colour as warmer or cooler in comparison with the reference light source, the R_g value is an explicit reflection of saturation rating. Whether a scenario is perceived to be likeable depends very much on how saturated the colours appear. Both indices are important in the rating of naturalness. At constant R_f value, pc LEDs have a more likeable and saturated effect the higher the R_g value up to a certain point. As the R_f value rises, so does the subjective colour rendering rating. The fidelity index R_f correlates very strongly with the CIE R_a value, so that here both indices are similarly applicable. Responses to the question on expectation of the colour of objects related to those seen under the test and reference light sources are shown on the left Figure 6. The diagram shows the absolute frequency with which the object colours seen match those expected. Responses were given as to whether this was true for a single scenario in one of the booths (either the test or reference booth) or for both or for neither. Represented is the "both" response has been shared in the Figure 7 between the test and reference scenario.

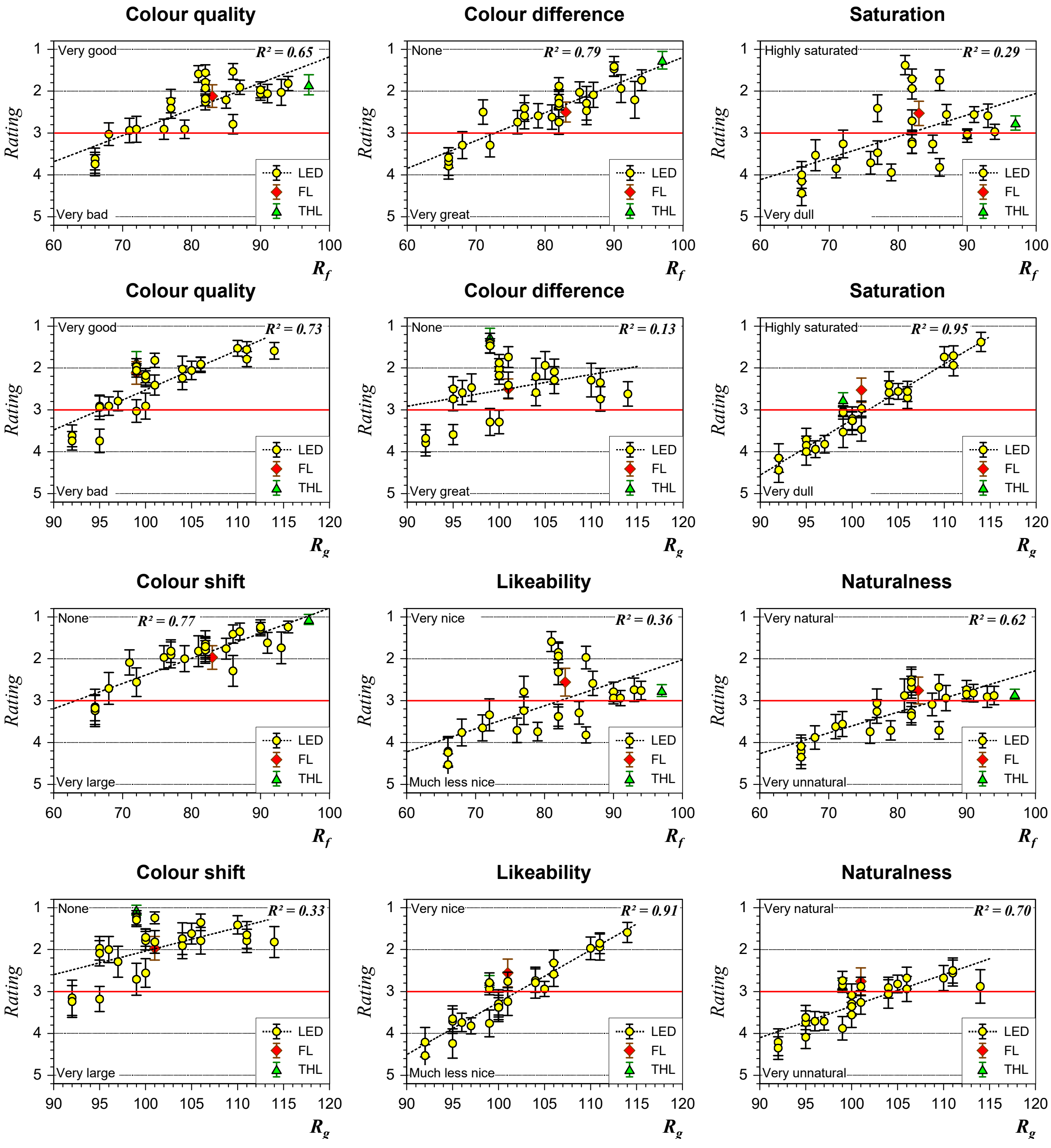


Figure 6: Subjective ratings (mean values and intervals of confidence) (*CI* 95%) for R_f and R_g. The linear regression was determined for the LED scenario ratings. The coefficient of determination R^2 for this is shown.

TABLE I. COEFFICIENT OF DETERMINATION R^2 OF THE LINEAR REGRESSION

Item	R^2 for R_a	R^2 for R_f	R^2 for R_g	R^2 for CQ
Colour quality CQ	0.62	0.65	0.73	1.00
Colour difference CD	0.80	0.79	0.13	0.58
Saturation S	0.25	0.29	0.95	0.77
Colour shift CS	0.77	0.77	0.33	0.79
Perceived brightness PB	0.01	0.01	0.41	0.17
Temperature T	0.55	0.63	0.06	0.52
Likeability LA	0.32	0.36	0.91	0.85

Naturalness NN	0.61	0.62	0.70	0.92

As shown in the diagram, the colours of the objects are not better than the subjects' expectation when the LED light source tested has values $R_f < 90$ and $R_g \leq 100$. LED light sources with $R_f \geq 80$ and $R_g = 110$ are rated as better than the reference illuminant. The FL ($R_f = 80$, $R_g = 100$) investigated is greatly preferred to the reference and adjudged better than the LED lighting with the same R_f and R_g values.

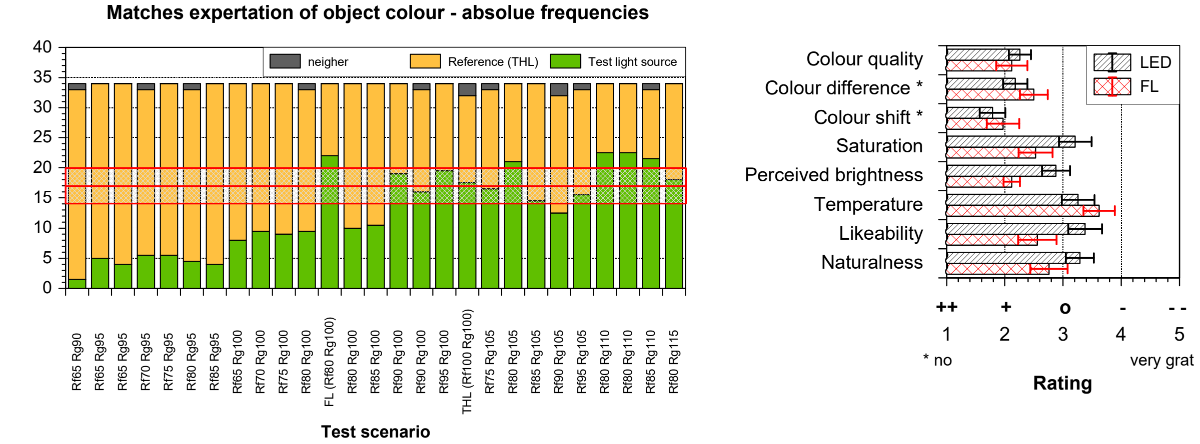


Figure 7: Absolute frequencies of responce that object colours match expectation (left); responces for LED ($R_f = 80$, $R_g = 100$) and FL ($R_f = 80$, $R_g = 100$) – mean and intervall of confidence (CI 95%), N = 34 (right)

Table II gives a summary of the comparison of ratings for LED types compared with FL (R_f 80, R_g 100). The figures given are the probability p with a level of significance of $\alpha = 0.05$. At the same R_f and R_g values the general colour quality was rated identically, but the colours of the objects are perceived to be less saturated, less natural and less likeable than under the FL (Figure 7, right). There is no significant difference in the rating of LED types R_f 75, R_g 105 and R_f 80, R_g 105 as compared with the FL. This leads to the assumption that it would be possible to compensate for slight differences in R_f value by a slight increase in saturation.

TABLE II. SUMMARY OF COMPARISON BETWEEN LED AND FL (values given are probability p; statistical significance is denoted by italices)

R_g	95			100					105		
Item/ R_f	**75**	**80**	**85**	**75**	**80**	**85**	**90**	**95**	**75**	**80**	**85**
Colour quality CQ	*0,000*	*0,000*	*0,000*	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Colour difference CD	1,000	1,000	1,000	1,000	0,082	0,277	*0,000*	*0,000*	1,000	1,000	0,622
Colour shift CS	1,000	1,000	0,910	1,000	1,000	1,000	*0,000*	*0,002*	1,000	1,000	*0,030*
Saturation S	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*	*0,002*	*0,037*	0,303	1,000	1,000	1,000
Likeability LA	*0,000*	*0,000*	*0,000*	*0,026*	*0,000*	*0,009*	1,000	1,000	1,000	1,000	1,000
Naturalness NN	*0,000*	*0,000*	*0,000*	0,185	*0,036*	1,000	1,000	1,000	1,000	1,000	1,000
Colour coding:	*FL significantly better*			*LED significantly better*				no significant difference			

SUMMARY

The likeability of the colour of an object (as compared with the reference) cannot be predicted solely on the basis of the value in the Fidelity Index R_f. This index, like the CIE CRI R_a, serves to describe the difference in colour only in relation to colour appearance as compared with that under reference illuminant, which means that the reference spectrum will always be the criterion. There is no statement as to which of the colours' appearance, under test or reference light source, is better. It makes sense to incorporate the fidelity index with the gamut index into the evaluation and to set targets for the development of light sources. The present investigation indicates that $R_f \geq 80$ and $R_g \geq 100$ are useful prescriptive values. The perceived naturalness of the object colour correlates with both the R_f value and the R_g value, in that the subjects evaluated scenarios illuminated at $R_f \geq 80$ and $R_g \geq 100$ as similar to or better than the reference. This result tallies with ROYER [7]. The high correlation between the R_a and R_f value, see Figure 1, indicates the experimental results are also applicable to the R_a colour rendering index.

ACKNOWLEDGMENT

The cooperation of OSRAM Opto Semiconductors GmbH was indispensable for the experimental setup and the investigation.

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The International Lighting Vocabulary (ILV) – Yesterday, Today, Tomorrow

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***Abstract*—The International Lighting Vocabulary (ILV) is an indispensable source for everyone working in the field of light and lighting. The aim of the ILV is to promote international standardization in the use of quantities, units, symbols and terminology related to the science and art of science and art of light and lighting, colour and vision, photobiology and image technology.**

In order to end the unfortunate situation that the latest version of the ILV (2011) and the version of the ILV included in the International Electrotechnical Vocabulary (IEV) (1987) are different, at least in some definitions, a joint project of CIE and IEC was initiated to revise the ILV, which will conclude in a new edition of the ILV as much as a revised Section Area 845 of the IEV.

The paper includes details of the harmonization and approval process of the ILV and its inclusion in the IEV, and highlights new features.

***Index Terms*-- colour, light, lighting, terminology, vision.**

INTRODUCTION

The first edition of the ILV was published in 1938, the current version (CIE S 017) was published in 2011 as a CIE International Standard [1], also available online as eILV (http://eilv.cie.co.at/). Before this latest version was issued, the ILV had been published in 1987 as CIE Publication 17.4. That version of the ILV also formed part (as subject area 845) of the International Electrotechnical Vocabulary (IEV), published by the IEC as IEC 60050-845 [2] and, in its online version, as part of Electropedia (http://www.electropedia.org/).

Currently, we have the unfortunate situation that the latest version of the ILV (2011) and the version included in the IEV (still of 1987) are different, at least in some definitions. For that reason intensive negotiations have been undertaken between CIE and IEC with the aim to harmonize the content of the current ILV and subject area 845 of the IEV.

The paper includes details of the harmonization and approval process of the ILV and its inclusion in the IEV, highlights new features, points to possible conflicts with regional documents currently being developed, and finally gives an outlook on future developments.

HARMONIZATION AND APPROVAL PROCESS

In order to use the expertise of CIE and IEC as efficiently as possible, the work was split such that IEC was supposed to care about the terms and definitions related to lamp and luminaire equipment, whereas CIE was assigned the responsibility for all other terms and definitions. While CIE installed a joint technical committee (JTC 8) "Terminology in light and lighting", in IEC a maintenance team (MT 2) within IEC/TC 34 "Lamps and related equipment" was set up for the purpose of this revision work and future maintenance work in terminology.

With the purpose of making the ILV entries suitable for the inclusion in the IEV, all terms and definitions needed to be reviewed with regard to the rules for drafting definitions given in the ISO/IEC Directives Part 2 [3] and the respective IEC supplement [4]. In addition the existing definitions were checked for their technical correctness. Harmonization efforts with ISO/TC 12/WG 19 (working, among other things, on a revision of ISO 80000-7 [5]) were considered in this work. A number of entries that proved to be not light and lighting related were removed, new entries were added, partly in coordination with ISO/TC 274.

The efforts to prepare a revised version of the ILV, which would be suitable for incorporation into the IEV, resulted in a CIE Draft International Standard (DIS) [6] that was circulated to CIE National Committees, Divisions and Board of Administration, to IEC/TC 34 and ISO/TC 274 for comments in December 2016 (with deadline in March 2017).

After the comments have been addressed by CIE JTC 8, the ILV entries will become part of a Committee Draft for Vote (CDV) for commenting and voting in IEC, before it will be circulated as Final Draft International Standards (FDIS), both in CIE and IEC, for parallel approval in the two organizations.

The finalization of this process and the inclusion in the IEV is scheduled for the middle of 2018.

New Features

One of the main achievements in the new edition of the ILV is the introduction of new definitions of the basic quantities (e.g. illuminance/irradiance, luminance/radiance). These definitions have been discussed not only within CIE, but also in ISO during the revision work on ISO 80000-7, so that they are now based on a wide acceptance in the lighting community.

Most changes have been performed in terms of editorial aspects. While the current edition of the ILV is sorted alphabetically (according to the English entries), the ILV is now back to section-wise assignment as this is the requirement of IEC (to include the ILV terms and definitions in the IEV) and as this has been proven as more reasonable than an alphabetical order (which only works for one language).

The new entry numbers have been created as follows:

- The section titles of the current IEV have been left as they are, an additional section was created for “Imaging”.
- The section numbers of the current IEV (845-01 through 845-11) have been replaced by new numbers, adding 20 to each of the section numbers, so that the sections in the IEV will now have the numbers “845-21” through “845-32”. For the ILV the number for the IEV subject area “845” has been replaced by the number of the CIE Standard (“17”). (See also Table 1.)
- All entries have been assigned to one of these sections, considering existing assignments of entries that had already been present in the current version of the IEV. Anyhow, as entries have been re-sorted considering similar subject fields within one section, the entry numbers have changed in most cases compared to those in the current IEV.
- Entries are sorted accordingly by sections and within the sections by their term numbers.

TABLE I. Numbering of IEV/ILV sections

IEV 1987 Section	*New IEV Section*	*New ILV Section*	*Title*
845-01	845-21	17-21	Radiation, quantities and units
845-02	845-22	17-22	Vision, colour rendering
845-03	845-23	17-23	Colorimetry
845-04	845-24	17-24	Emission, optical properties of materials
845-05	845-25	17-25	Radiometric, photometric and colorimetric measurements: physical detectors
845-06	845-26	17-26	Actinic effects of optical radiation
845-07	845-27	17-27	Light sources
845-08	845-28	17-28	Components of lamps and auxiliary apparatus
845-09	845-29	17-29	Lighting technology, day lighting
845-10	845-30	17-30	Luminaires and their components
845-11	845-31	17-31	Visual signaling
	845-32	17-32	Imaging

In addition to the renumbering of the entries the following formal changes were taken care of:

- All terms and synonyms relating to one concept are now in the same entry. Thus synonyms and abbreviations have been transferred to the entry of the preferred term and are not listed as separate entries anymore. The respective entries for synonyms (called “Equivalent terms” in CIE S 017:2011) and abbreviations have been deleted.
- Deprecated term(s) are now placed on a new line below the term name (and synonym(s), if any) and are identified by the text "DEPRECATED:".
- The indication of the national variant “US” for synonyms was deleted in the CIE-responsible part because the relevant terms are not only used in the US (though they may have their origin there). The entries under IEC responsibility still use the indication of “US” in some cases. This is still under discussion.
- Grammatical information for terms that are not nouns or for terms that are used in their plural form was added, e.g. “bright, adj”, “cones, pl”.
- Parentheses are not used anymore to show alternative terms. If parentheses had been used to indicate more than one alternative for the presentation of a term, this is now indicated by synonyms.

- If a term is used to represent several concepts, the specific use or subject to which each concept belongs is indicated between angle brackets, e.g. "colour difference, <psychophysical>". Each concept received a separate entry.
- Symbols have been transferred to a dedicated field. They are not presented in square brackets on the same line as the term anymore.
- NOTES have been renamed "Note X to entry" or in case where they represent an example "EXAMPLE".
- Units are now specified in a note to entry.

The following deletions of entries have been performed:

- Entries that were transferred as synonyms to other entries (including abbreviations)
- Entries that were not explicitly related to light and lighting (e.g. road-related terms)
- Entries with definitions of acronyms for organizations, e.g. CIE and PIARC

The following entries have been added:

- Terms and definitions that had been under discussion in CIE TC 1-64
- Terms and definitions of CIE S 017-SP1
- Terms and definitions that have been agreed in ISO/TC 274
- Terms and definitions of CIE TN 002
- Entries which proved to be reasonable during revision work

POSSIBLE CONFLICTS WITH REGIONAL DOCUMENTS

Currently the European standard EN 12665 "Light and lighting - Basic terms and criteria for specifying lighting requirements" is in revision. The standard includes a number of entries that have been adopted from the ILV. Unfortunately the revised version, which will probably be published shortly before the revised ILV, will still include terms and definitions from the ILV versions of 1987 and 2011. This should be adjusted by a new revision as soon as possible after publication of the new edition of the ILV.

FUTURE WORK

The new edition of the ILV will form an excellent basis for further revisions in the context of international standardization and harmonization. On CIE side it is intended to continuously work on new revisions of the ILV within JTC 8, taking into account new terms arising from new technologies and the need to revise existing definitions due to respective requests by the stakeholders. This will lead to a much more robust maintenance of terms and definitions as was the case in the past.

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The New EN 15193-1 to Calculate the Energy Performance for Lighting in Buildings: Analysis and Application to Reference Building Types

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***Abstract*— The standard EN 15193 is part of a set of standards developed to support the implementation of EPBD directives. The EN 15193 provides a simplified method for the estimation of the energy consumption for lighting through the index LENI. The calculation method introduced in the original standard (2007) has been revised in 2017, especially on the approach to calculate the daylighting contribution. In this paper calculation method of the LENI is analysed and the results obtained for a reference buildings, representative of the Italian building stock, are presented. The LENI values found for the building stock were then compared to the LENI of four retrofitting scenarios, based on different combinations of relampling with LED systems, use of dimming sensors and automated shades. All together, these interventions allowed a reduction in the energy consumption for lighting up to -58.1% compared to the existing buildings.**

***Index Terms*—energy demand for lighting, EN 15193-1, energy conservation measures, simplified calculation methods.**

INTRODUCTION

Lighting of indoor as well as outdoor spaces is one of the key factors that concur to determine the total consumption of primary energy at a large scale and the subsequent CO_2 footprint. In the building sector, the strategies to reduce the energy demand for lighting are concerned with different aspects: energy efficiency of products; energy efficiency of systems; energy saving oriented behavior of users. Increasing the energy efficiency of each component of a lighting systems is crucial (and many important innovations have been introduced in this field) but may be not sufficient to actually achieve energy saving, as shown by the studies carried out on the "rebound effect" [1].

At a building scale, the energy performance of lighting systems needs to be evaluated accounting for all interconnected factors such as the efficiency of components, the presence of control systems for lights and shades, the user behavior and, last but not least, the daylight availability inside indoor spaces. This is the approach implemented in the European Standard EN 15193 "Energy performance of buildings. Energy requirements for lighting" [2], which is part of the Energy Performance of Building Directives EPBD and defines a simplified method to assess the lighting energy demand of a building and the indicator to express it (Lighting Energy Numerical Indicator LENI, in [kWh/m^{2}yr]). The procedure to calculate the LENI accounts for the complex integration between building, lighting systems, light controls and user behavior: in detail, factors such as the daylight amount in a space, which depends on the architectural features of a building, how the various spaces are used (in terms of target illuminance and occupancy profile etc), the characteristics of the lighting systems and associated controls are included in the calculation.

The calculation method originally introduced in the standard EN 15193:2007 has recently gone through a revision, especially focusing on the approach to calculate the daylighting contribution. In the new version of the standard (EN 15193:2017) [3] the calculation of the daylighting contribution does not only rely on the calculation of the daylight factor but it also accounts for the climate, the orientation of openings, as well as for the presence of mobile sun shades for glare and thermal control. The differences included in the new version of the standard to calculate the LENI, compared to the previous standard, were analyzed in a previous paper from the same Authors, especially focusing on the approach to calculate the daylight availability [4].

In this frame, this paper critically analyses the characteristics of the new simplified method to estimate daylighting and to calculate the LENI, highlights how influencing factors are considered, and which are the main differences with respect to other calculation approaches, such as software based on dynamic climate based simulation.

Furthermore, the new simplified calculation approach is applied to estimate the LENI of a reference educational building (a high school), defined so as to be representative of the Italian school building stock. The aim of this part was to show the magnitude and variation of LENI values for typical Italian educational buildings. The results that were obtained allowed some considerations on the lighting energy demand of the existing building stock to be carried out and some possible energy conservation measures related to electric lighting to be defined.

CALCULATION OF THE LIGHTING ENERGY DEMAND ACCORDING TO THE STANDARD EN 15193:2017

The standard EN15193 describes the methods to estimate the amount of electric energy required for lighting in buildings. The calculation methods are based on the following formulae:

$$LENI = \frac{W}{A} = \frac{W_{L,t} + W_{P,t}}{A} \qquad \left[\frac{kWh}{m^2 year}\right] \tag{1}$$

$$W_{L,t} = \sum \frac{(P_n \times F_c) \times [(t_D \times F_O \times F_D) + (t_N \times F_O)]}{1000} \left[{kWh}/{t_s}\right] \qquad W_{P,t} = \sum \frac{P_{pc} \times [t_y - (t_D + t_N)] + (P_{em} \times t_{em})}{1000} \left[{kWh}/{t_s}\right] \tag{2}$$

where: W = total annual energy required for lighting [kWh]; $W_{L,t}$ = total energy for illumination [kWh]; $W_{P,t}$= total energy for standby [kWh]; A = total useful area of the building [m^2]; P_n; P_{pc}; P_{em} = total power respectively for: luminaires, controls standby and emergency battery recharge [W]; F_C = constant illuminance factor [-]; F_D = daylight dependency factor [-]; F_O = occupancy dependency factor [-]; t_D; t_N; t_y; t_{em}= daylight time; daylight absence time; number of hours in a standard year; battery charge time [hrs].

Daylight contribution is taken into account through the daylight dependency factor (F_D), which in turn depends on two other factors: $F_{D,S}$, or daylight supply factor, and $F_{D,C}$, or lighting control factor. The first one is the factor that estimates the “daylight autonomy” of the zone under consideration, the second one accounts for the effectiveness of the type of lighting control system in exploiting daylight. For the calculation of $F_{D,S}$ two different façade states are considered: with activated and not-activated solar and/or glare protections. $F_{D,S}$ is therefore calculated as weighted average of two partial $F_{D,S}$ value ($F_{D,S,SNA}$; $F_{D,S,SA}$), one for each state, using the relative time of each state (shades activated and shades not-activated) as weigh (both times are a percent of the total annual occupancy time of the building). The relative time during which the shades are not activated and the corresponding partial daylight supply factor ($F_{D,S,SNA}$) are determined as a function of: site location (latitude); climate (through the ‘luminous exposure’, that is the ratio of direct to global illuminance - H_{dir}/H_{glob}); façade orientation; daylight availability without shading (Daylight Factor - D); target maintained illuminance E_m. Instead, the $F_{D,S,SA}$ for activated shades depends on the type of shading and the daylight availability class (D_{class}), as a function of the daylight factor of the carcass opening (D_{CA}).

As for the lighting control factor $F_{D,C}$, this is determined as a function of the D_{class}, the type of control system and the maintained illuminance required for the zone.

The occupancy dependency factor (F_O) is determined considering the proportion of the time the space is unoccupied and the type of control system, and finally, the constant illuminance factor (F_C) is introduced to estimate the reduction of energy consumption that can be achieved with control systems designed to maintain the target illuminance during the overall lighting plant life.

Compared to more advanced lighting analysis approaches, based on simulation tools such Radiance, Daysim or DIVA-for-Rhino, it is worth pointing out that the method to calculate the LENI considers, with different levels of detail, the main factors affecting the buildings’ energy consumption for electric lighting: the power of the lighting systems, including the parasitic power of control systems and the power for recharging the emergency lamps; the type of control system (manual or automatically controlled according to daylight availability or spaces’ occupancy); the daylight penetration into the indoor spaces through both vertical glazing and roof lighting systems; the building usage and the corresponding lighting requirements; the occupancy profile (occupancy time and probability). The daylight amount in turn accounts for parameters such climate and latitude of the site, orientation of windows, presence of obstructions and of fixed or mobile sun shades. On the other hand, all these factors are simplified compared to an advance simulations: the daylight penetration is accounted based on discrete ranges (“none”, “low”, “medium” and “strong”) and a similar approach is used for the target illuminance values; the number of climates that are available is limited, as well as the number of shading systems or the lighting control systems. Basically, the method is tabular, while the most advanced simulations tools allow, in principle, any value of above variables (climate, geometries, light and control sensors) to be implemented in the calculation of the energy demand for lighting.

CASE STUDY: APPLICATION OF THE LENI CALCULATION METHOD TO A REFERENCE EDUCATIONAL BUILDING

A reference educational building, hosting a high school, was defined to be representative as much as possible of Italian stock of secondary schools. A number of studies and reports were consulted to define the most recurring characteristics of the reference building [5], [6]: for instance, according to [5], the number of floors is mostly in the range 3-5 (53% of cases), with a predominance of double pane glazing (64%) with shading systems that are most commonly shutters and venetian blinds. The study by Enea [6] highlights that in the regional area around Turin the surface of schools is in mainly the range 3000-5000 m^2 (21% of cases) or over 11000 m^2 (15%).

The reference building was defined also based on the requirements for architectural projects of educational building currently available in Italy. The resulting building has the following features: the building was sized to host 500 students in 20 classrooms and consists of 3 floors, each measuring around 1300 m^2 (rectangular base of 77 m * 19 m, with a floor-to-floor distance of 3.5 m; total surface: 3900 m^2). Each floor has a central corridor and rooms on two sides of this, with opposite orientations. The ground floor hosts the administrative functions and other functions such as the library and the teachers' room, while the classrooms and laboratories take the second and third floor. Each window is equipped with a double plane glazing (with a visible transmittance T_v = 70%) and with a moveable blind for glare protection. The building was assumed to be located in three different urban settings, labelled "low density" (suburban areas), "medium density", "high density" (urban areas). Furthermore, different sites and orientations were also considered to represent more widely the existing stock: as for the site, the building was assumed as located in Turin (latitude L = 45.1°N, H_{dir}/H_{glob} = 0.43) and in Catania (latitude L = 37.4°N, H_{dir}/H_{glob} = 0.56), while as for the orientation, the building was assumed with windows facing north-south and east-west.

Figure 1 shows the plan views of the reference building as well as the distribution of the various hosted functions.

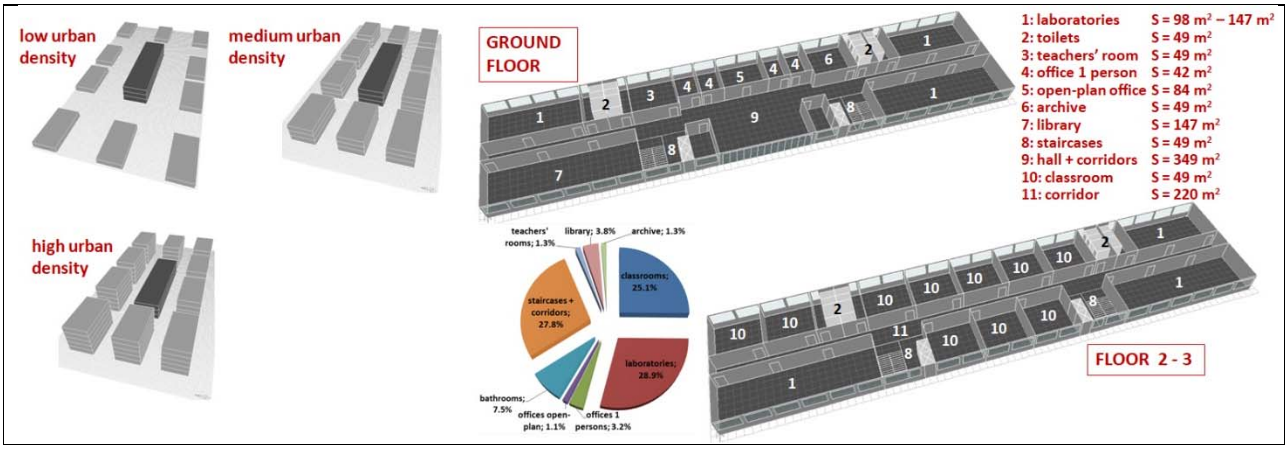

Figure 1. Visualization of the 3 urban settings considered and of the plan views of the reference educational building.

The study, carried out in two steps, was aimed at calculating the LENI values of each floor and of the whole building:

- Step 1: calculation of the LENI values for the existing educational buildings in Italy: for this purpose, fluorescent lighting systems were assumed, with manual shadings ("glare protection")
- Step 2: calculation of the LENI values for different retrofitting scenarios, based on a progressive replacement of fluorescent luminaires with LED systems (re-lighting), of manual controls with photo-dimming controls, of manual shading with automated shading. In detail, the following scenarios were defined:
  - 50% fluorescent, 50% LED (re-lighting fluorescent luminaires with LED luminaires in all teaching spaces - classrooms and laboratories, corresponding to half of the total surface)
  - 100% LED luminaires, with a manual control
  - 100% LED luminaires, associated with photodimming controls (that is "systems which are daylight-responsive and dim the electric lighting but do not switch it off nor turn it on again; the electric lighting system is not turned on again automatically" [3])
  - 100% LED luminaires, like the previous one, with the replacement of manual shadings with automated shadings (labelled "auto glare protection").

The LENI values were calculated using a software that was purposely developed by ENEA and in which the calculation method of the standard is extensively implemented.

RESULTS

The results that were obtained for the two steps of the study are presented in the following subsections.

A. Results For Existing Educational Buildings

Figure 2 summarizes the main results which were found at this stage of the study on the educational building located in Torino.

A first result of interest to characterize the existing school building stock is that the orientation does not seem to be a significant variable (Fig. 2a): the average relative difference for the same building oriented with windows facing north-south or east-west was 1.2%, with no value > 6.8% (floor 2 in the high urban density setting). Similarly, a little role is played by climate and locations: the LENI values obtained for Catania, southern Italy, were found to be constantly higher than their corresponding LENI values for Turin, northern Italy, but with small relative differences (6.3% on average, but in any case > 8%).

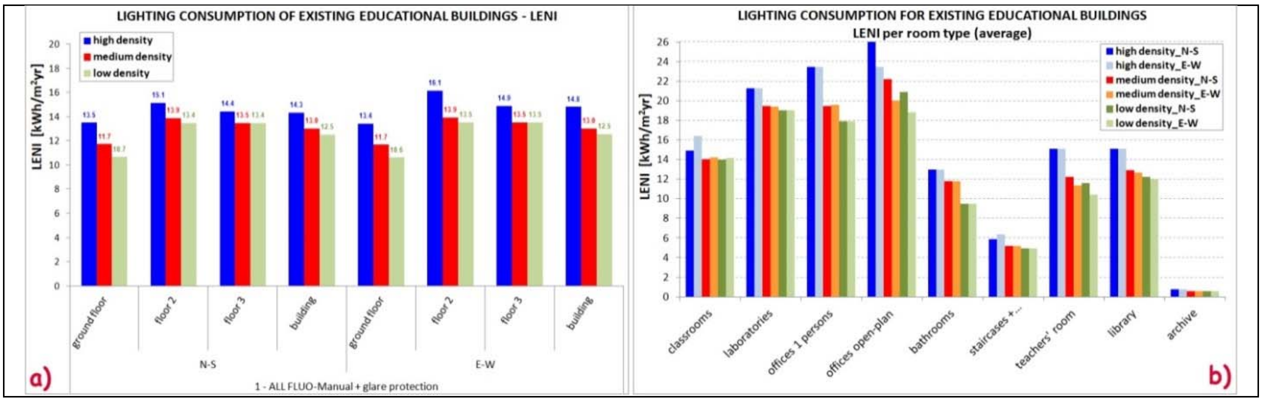

Figure 2. LENI values obtained for the reference building representing the existing heritage.

Differently, the following factors showed to have a significant influence on the LENI values:

- The urban context: compared to buildings located in a low density urban settings, the same buildings considered in a medium and in a high density context showed significantly higher LENI values: Δ = +9.2% as average, with higher increments, as expected, for the ground floor (average Δ: +18.2%, with a maximum value of +26.4% for the high density urban context) and lower for the top floor (average Δ: +3.6%).
- The floor: floor 2 showed the highest lighting consumption (LENI values). Floor 3 obviously has (slightly) lower LENI values as it hosts the same functions and suffers from a lower impact due to the surrounding context, while the ground floor shows the lowest LENI values. This is due to the specific functions (with different illuminance requirements and consequently different lighting power densities) that are located at this floor with respect to floors 2 and 3: the activities that require a maintained E_m = 100 lx occupy 45.7% of the floor area on ground level versus 32% on level 2 and 3, while the opposite trend applies for the activities that require an E_m = 300 lx (30.1% vs. 45.3%). The area devoted to activities with an E_m = 500 is comparable on the different floors (24.2% vs. 22.7%). The average relative difference between the ground floor and floor 2 is Δ = +18.9% (with a peak of +26.1% for the building located in the high density urban setting (Fig. 2a).
- The room usage (Fig. 2b): the highest LENI values were observed for open-plan offices and cellular offices for 1 person (average $LENI_m$ = 22.0 kWh/m^{2}yr and = 20.3 22.0 kWh/m^{2}yr, respectively, with peak values of 26.4 kWh/m^{2}yr and 23.5 kWh/m^{2}yr for the high density urban setting). This is due to a combination of two factors, that is the position (on the ground floor) and a higher illuminance requirement (E_m = 500 lx). After the offices, the highest consumption is due to the laboratories (some of them having a requirement E_m = 500 lx and being located on the ground floor. The classroom showed a $LENI_m$ of = 14.6 kWh/m^{2}yr, comparable to what observed for the library and the teachers' room.

In general terms, the energy consumption for lighting was quite high ($LENI_m$ = 13.4 kWh/m^{2}yr for all the configurations analyzed (with a peak of 14.8 kWh/m^{2}yr for buildings in high density context and windows facing east-west). The effect of four retrofitting interventions is showed in the next section.

B. Results For Different Possible Retrofitting Interventions

The LENI results that were obtained for the four retrofitting scenarios are reported in Figure 3a (scenarios 2 through 5), together with the results of the existing reference building presented in the earlier section (scenario 1), while Figure 3b shows how the average LENI values change as a function of the room type: in this case, the LENI values were averaged for the scenarios 2 through 5.

The results show a progressive reduction in the energy consumption for lighting for all the retrofitting interventions based on the re-lighting of luminaires with LED systems (scenarios 2 and 3) and on the introduction on photodimming and occupancy controls (scenario 4). Compared to scenario 1 (existing building stock), the average $LENI_m$ (averaged for all the urban settings and orientations) showed a reduction Δ_2 = -18.2% for the scenario 2, Δ_3 = -35.8% for the scenario 3, Δ_4 = -57.5% for the scenario 4, and Δ_5 = -58.1% for the scenario 5. It emerges that the light performance for scenarios 4 and 5 is practically the same: it seems thus that the introduction of an automated shade in replacement of a manual shade is not worthwhile for the reference educational building due to a combined effect of the obstructions (especially in the high and medium urban settings the ground floor and in some cases the floor 2 receive insufficient daylight) and of the exposition (in the case of north-facing rooms, for which the effect of a shading systems is typically negligible.

Analyzing the lighting consumption as a function of the room type shows similar trends to what observed for the existing buildings (Fig. 3b), with higher consumption for open-plan and single cellular offices, while the LENI values for the teaching spaces (classrooms and laboratories) became comparable.

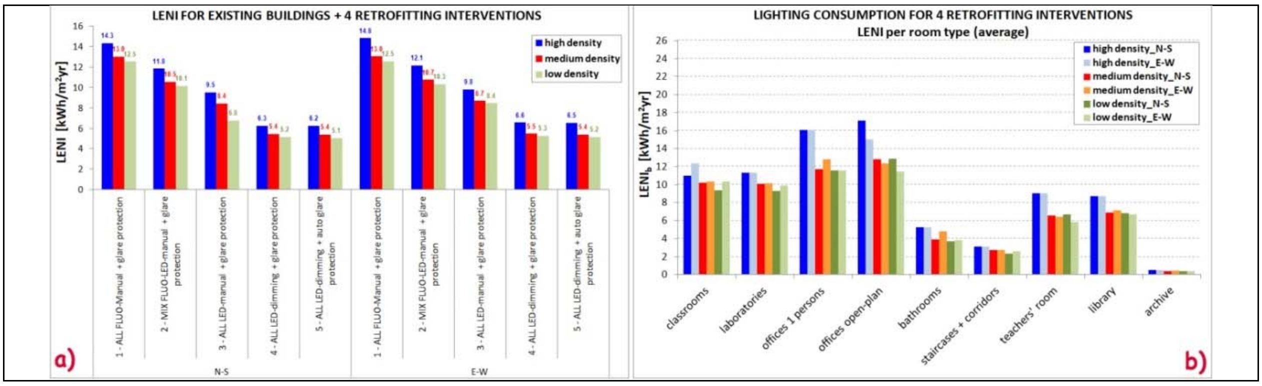

Figure 3. LENI values obtained for the different retrofitting scenarios that could be applied to the reference building.

CONCLUSIONS

In a context where the EBPD provide tools to calculate the total consumption of primary energy of a building, the new standard EN 15193:2017 provides the index LENI to quantify the energy demand for lighting. The LENI accounts for all the main factors that influence the energy demand, such as the power of lighting systems (including the parasitic power of controls and the power for recharging the emergency lamps), the type of control system, the daylight availability in a room, the lighting requirements and the occupancy time and behaviour.

The LENI was calculated for a reference high school, defined to be representative of the Italian educational building stock. As a second step of the study, the LENI was also calculated for four retrofitting interventions, based on different combinations of relampling with LED systems, use of dimming and occupancy sensors and automated shades. These scenarios were defined to be useful to provide building practitioners with LENI values and help them establish lines and priorities of retrofitting interventions in existing educational buildings.

In short, the main conclusions were:

- With regard to the existing building stock (fluorescent luminaires and manual shades), significant effect on the LENI was observed for the urban context (and therefore the obstruction angles for windows), the floor (top floor vs. ground floor) and the activity carried out in a room (offices, laboratories, classrooms etc). On the contrary, the site and the orientation did not show a significant influence on the LENI values. In absolute terms, the average LENI value of all the configurations analyzed was found to be $LENI_m$ = 13.4 kWh/m^{2}yr).
- With regard to the retrofitting interventions, compared to the existing building stock, the $LENI_m$ showed a reduction of -18.2% for a relampling of 50% of fluorescent with LED systems, of -35.8% for a re-lighting of all the fluorescent with LED systems, of -57.5% by equipping the LED systems with dimming and occupancy sensors, and of -58.1% by replacing manual with automated shades.

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Lighting Role in Green Building Rating Systems: Comparison between Different Assessment Criteria in an Italian Building

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***Abstract*—The paper investigates lighting role in green building rating systems. Specifically, it focuses on the Italian situation, analysing assessment criteria referred to light in ITACA protocol and in BREEAM and LEED international versions. Finally, it applies described criteria to a residential building located in Benevento (Italy) to highlight the differences of the considered certification systems.**

***Index Terms*—green building rating systems; lighting assessment criteria; residential buildings.**

Introduction

During the last two decades, the interest towards the impact of construction industry on the environment has determined the birth and the spread of the so-called green building rating systems. These standards contain a set of prescriptions that a building is supposed to fulfil, to be classified as *green*, i.e. as a building able to reduce its environmental impact and, at the same time, to maximize indoor quality and users' comfort.

Over time the importance of certification systems has become so strong, that nowadays more than 600 methods to assess the sustainability of a building exist [1]. To obtain an objective evaluation useful to compare building performances worldwide, the uniformity of assessment criteria in certifying systems is crucial; however, standards structure and the related evaluation method are different. This is due on the one hand, to the fact that companies and associations publishing certification systems are contending a position on global market and, on the other hand, to the fact that the assessment criteria must be tailored to the needs of regional climate [1]. Considering that the use of certification systems is not mandatory, that sometimes in the same country more than one certification system is available and that the choice between one available code or another is subjective, a building could obtain a different evaluation depending on the adopted assessment code.

Certification systems contain prescriptions related to lighting as well. As all the other design aspects, lighting is differently evaluated depending on the considered system. However, generally, the prescribed requirements are not so stringent, "which practically means that projects can achieve enough points for obtaining the certificate without improving lighting design in any way" [2].

Given these premises, the paper aims at analysing the role of lighting design in green building rating systems. It is divided in two sections: a) focus on rating systems available in Italy and description of lighting assessment criteria they contain; b) evaluation of lighting performance in a residential building located in Benevento (Italy). Results are discussed to highlight pros and cons related to the use of each rating system.

Lighting Role in Certification Systems Available in Italy

In Italy, the only one rating system completely Italian, i.e. conceived and published in Italy by Italian organizations is the ITACA Protocol. It was ratified in January the 15th 2004 by a task force for sustainable buildings composed of ITACA (Institute for innovation and transparency of tenders and environmental compatibility), iiSBE Italia (international initiative for a Sustainable Built Environment Italia) and ITC-CNR (Institute for buildings technologies-National Researches Council) [3]. In 2015, to update the protocol on the basis of new national technical regulations, it was substituted by the Reference Procedure UNI/PdR 13:2015 [4]. ITACA protocol contains a specific version for residential buildings and another one that can be applied to schools, factories, retail buildings, offices and accommodation buildings. Besides ITACA protocol, it is possible to certify buildings by adopting international versions of other rating systems. Two of the most spread are the BREEAM (Building Research Establishment Environmental

Assessment Method) originally developed in UK and the LEED (Leadership in Energy and Environmental Design) born in USA.

BREEAM is the first written certification system and it was published by the BRE (Building Research Establishment) in 1990 [5]. It can be considered the model for all the other certificates, that are based on its contents and assessment methods [1]. It contains five technical standards referred to 1) large-scale development plans; 2) infrastructures; 3) new construction 4) In-Use (to certify and improve the building performance during its use); 5) refurbishment or fit out projects [5]. For each standard, an international version, applicable to projects of other countries (Italy as well) exists. Moreover, besides UK, other countries, such as Spain or the Netherlands published their own versions of BREEAM, to adapt performance criteria to local specific environmental conditions. As for the international version, prescriptions related to residential buildings are reported in the Standard named BREEAM International New Construction [6].

LEED was written by USGBC (United States Green Building Council) [7] in 2000. It is inspired to BREEAM [1]. The current version is LEED v4 updated on April 14, 2017. As the BREEAM, it includes different Standards: 1) new constructions; 2) interior design; 3) building operations and maintenance; 4) homes design; 5) new land development projects or redevelopment projects. LEED Standards can be applied outside USA; indeed, the most important LEED documents are available in different languages: Chinese, German, Italian, Japanese, Korean, Portuguese, and Spanish. However, as it was already mentioned about BREEAM, Green Building Councils of some countries proposed a national version of LEED system. For example, GBC Italia (Green Building Council Italia) proposed an Italian version of LEED certification system called LEED 2009 Italia. However, this version is now available only for buildings for which the certification process started before the October, the 31st 2016 and, for new evaluations, it is substituted by the international v4 [8]. The standard referring to residential buildings is LEED v4 for Homes Design and Construction [9]. It considers different building typologies: single family homes, low-rise multi-family (one to three stories), or mid-rise multi-family (four to six stories).

Rating systems structures and assessment criteria are different, but considering that their goal is "to evaluate the environmental performance of a building against an explicit set of criteria" [10], the evaluation process always implies the definition of a set of performance criteria organized in a logical fashion and, for each performance issue, of a number of credits that can be assigned if a specific level of performance is achieved [10].

Given that, Tab. I reports for each of the three described certification systems the criteria categories, the criteria and the sub-criteria related to lighting. Moreover, it reports for each parameter the attributable score and the percentage incidence of the considered criterion both on the category of reference and on the total score. The score reported in Table I, is referred to residential buildings. Specifically, the case study is classified by the BREEAM as a fully-fitted single dwelling (i.e. a permanent residential building, detached from any other building where, in addition to the core, central and localised systems, additional fixtures and fittings have also been provided) and by the LEED as a single family home. ITACA protocol does not diversify evaluation criteria in case of the residential typology.

TABLE I. LIGHITNG WEIGHT IN ITACA PROTOCOL, BREEAM AND LEED CERTIFICATION SYSTEMS

Certification System	*Edition*	*Year*	*Criteria Category*	*Criterion*	*Sub-criterion*	*Score [n]*	*Incidence on category [%]*	*Incidence on total score [%]*
ITACA Protocol	Reference Procedure UNI/PdR 13.1:2015	2015	Indoor environment quality	Visual comfort	Daylighting	5	16.67	2.78
			Service quality	Practicality and efficiency	Automated systems	0.5[a]	5.00	0.28
BREEAM	International New Construction	2016	Health and wellbeing	Visual comfort	Daylighting	4	16.00	2.67
					View out	1	4.00	0.67
					Internal and external lighting levels, zoning and control	1	4.00	0.67
			Energy	Reduction of energy use and carbon	Energy efficient design features [b]	3	8.33	2.00
				External lighting	-	1	2.78	0.67
			Pollution	Reduction of night time light pollution	-	1	7.69	0.67
LEED	LEED v4 for Homes Design and Construction	2016	Energy and atmosphere	Indoor lighting	-	1.5	2.27	0.92
				Exterior lighting	-	0.5	0.76	0.31

a. Specifically, 1 credit can be assigned if two systems are automated (see Tab. II)

b. To account for building total energy consumptions, the Standard suggests evaluating the Energy Performance Ratio for International New Constructions and comparing it with provided benchmarks. It specifies that if internal lighting is not included within the modelling calculation tool used to evaluate it, the procedure reported in the table can be used

As it can be inferred by Table I, three distinct aspects linked to lighting design are considered: energy consumptions due to indoor and outdoor lighting, indoor comfort conditions, night time light pollution. BREEAM is the only system considering all these issues and the weight of lighting on total building score is 7.35%. In ITACA Protocol, lighting has a total incidence of 3.06%. Energy aspects are not considered, because the energy consumption evaluation is performed by means of the Renewable Global Primary Energy calculation procedure that does not consider lighting in residential buildings case. However, automated lighting systems allow the buildings to obtain credits in the Service Quality category. It is interesting to notice that daylighting has a relevant role in the evaluation process and that its weight is almost equal to the BREEAM one. LEED is the system attributing the lower weight to lighting in residential building evaluation (1.23% on the total score). Light is considered only in *Energy and atmosphere* category whereas visual comfort aspects and daylight are completely neglected.

Indoor lighting evaluation process is deepened in Tab. II. It reports for each criterion the method to assess the building and the corresponding assignable credits.

TABLE II. INDOOR LIGHTING EVALUATION METHOD REFERRED TO ITACA PROTOCOL, BREEAM AND LEED CERTIFICATION SYSTEMS

Certification System	*Criterion or Sub-criterion*	**Assessment Method**	**Assignable credits**
ITACA protocol	Daylighting	Calculate the average Daylight Factor (DF) for each space of the building according to the described calculation method[a]. Then average the results and compare the obtained value with the proposed benchmarks to establish the score.	DF<2.0 → -1 credit 2.0<DF<2.3 → 0 credit 2.3<DF<2.5 → 3 credits DF>2.5 → 5 credits
	Automated systems	Verify how many systems are automated and assign the relative credits.	No one → 0 credit 2 → 1 credit 4 → 2 credits 6 → 3 credits 8 → 4 credits 10→ 5 credits
BREEAM	Daylighting	· Calculate the average daylight illuminance and the minimum daylight illuminance at worst lit point during the entire year and verify they are equal to or higher than 100 lx and 30 lx respectively, for at list 3450 hours per year, in 100% of the relevant building areas (kitchens, living rooms, dining rooms, studies, including home offices)[b]	Up to 4 credits can be assigned if requirements are fulfilled.
	View out	· All positions within relevant areas must be within 5m of a wall which has a window or permanent opening providing an adequate view out. The window or opening must be ≥ 20% of the surrounding wall area.	1 credit can be assigned if requirements are fulfilled
	Internal and external lighting levels, zoning and control	· Internal lighting in all relevant areas of the building must be designed to provide an illuminance level appropriate to the tasks undertaken in accordance with national best practice lighting guides. · The uniformity of illuminance due to electric lighting must fulfil recommendations of the approved local standard. · Internal lighting is zoned to allow for occupant control.	1 credit can be assigned if requirements are fulfilled
	Reduction of energy use and carbon	Calculate the percentage of the fixed internal fittings as a percentage of the total number of fixed light fittings within habitable rooms that have been fitted with (Low Energy Lamps) LELs[c] and assign the corresponding credits.	Up to 75% → 2 credits 100% → 3 credits
LEED	Indoor lighting	Calculate the lighting power density, compare it with benchmarks and assign the related credits.	7.7 W/m^2→ 0.5 credit 6.5 W/m^2→ 1 credits 5.2 W/m^2→ 1.5 credits

a. The calculation method considers DF as a function of some factors, for example windows area, glazing transmittance, reflectance of indoor surfaces, etc.

b. The indicated method is suggested for hot or sunny locations with predominantly clear skies.

c. LELs are deemed as bulbs that have a luminous efficacy greater than 50 lumens per circuit watt and 40 lumens per circuit watt for LEDs.

As for electric light, the evaluation is performed by means of lamps efficiency in BREEAM case and of lighting power density in LEED case. As for daylight, the BREEAM proposes a more sophisticated method than the ITACA Protocol. It prescribes two different evaluation procedures the former based on Daylight Factor and the latter on the use of dynamic daylight simulations. It suggests choosing the second one when building is in a hot and sunny location. As regards electric light quality evaluation BREEAM considers average illuminance at the task area and illuminance uniformity. It bases the assessment on the compliance with local standard. Finally, it suggests accounting for lighting system zoning to allow for occupant control.

THE CASE STUDY

A. Description and method

The case study is a single residential building (about 72 m^2) located in Benevento (41°08′N 14°47′E), specifically in a city area close to the University of Sannio. The residential building is designed to host university students or visiting professors and its realisation is part of the SMART CASE research project [11], which aims at proposing innovative solutions for buildings energy performances optimization. The building was conceived to be a nZEB. It is composed of two bedrooms, a kitchen, a living room and a bathroom. South windows are shaded by a porch and the west one of the living room by a sliding shading device composed of tilted wooden slats that is considered open during calculations.

Reflectances of the architectural surfaces are the following: walls 50%, indoor and porch floor 24%, ceiling 70%, outside ground 20%. Windows are equipped with low-e double pane glazings characterized by a 59% visual transmittance.

As for the lighting system, 27 LED recessed spotlights were installed. They are characterized by 1200 lm luminous flux and by 10.6 W power (light efficiency higher than 100). In the bedrooms and in the living room, they are arranged to obtain two rows each composed of three luminaires, so that, considering a surface located at 0.85 m from the floor, the average illuminance is 200 lx and the uniformity is 0.4. Moreover, in the bedrooms, each desk is equipped with a table lamp (300 lm, 8 W), in order to increment the average illuminance to 500 lx and the uniformity to 0.6, requirements typical of offices. In the living, two floor lamps with movable arm (1531 lm, 31 W) are located close to the table and close to the couch to increment the illuminance to facilitate reading task, when occupants use the living room to study. The same number of spotlights is installed in the kitchen to assure 500 lx at the workplane. Finally, in the bathroom two spotlights are mounted and only one in the hallway.

Figure 1. The case study

All the parameters described in Tab. II were verified to evaluate lighting performances of the building according to the certification systems. Specifically, as for the DF calculation the procedure described in [4] was used. As for the BREEAM daylighting check, daylight simulations were performed with DIVA for Rhinoceros [12]. Calculation grids were set considering 0.5 m distance from the perimeter walls according to certification prescriptions. The distance from the floor is 0.75 m and that set between points is about 0.5 m. Calculation parameters were: ambient bounces 7, ambient divisions 1500, ambient super samples 100, ambient resolution 300, ambient accuracy 0.05. Considering that a weather data file related to Benevento is not available, Naples IWEC was used [13]. As regards internal and external lighting, BREEAM suggest designers freely choosing the assessment criteria relevant to the building type. In this case, the compliance with regulations (see Tab. II) in terms of average illuminance, uniformity, etc was considered, since rooms can be used also as office. Finally, both for LEED and BREEAM indoor lighting evaluation, only fixed luminaires are considered and table and floor lamps are not included in the evaluation as reported in the calculation procedure.

B. Results

Tab. III reports for each parameter described in Tab. II the credits that can be assigned to the building, according to considerations reported in *Comment* column. A focus on BREEAM Daylighting and View out calculation is reported in graphs of Fig. 2. In this figure, the black horizontal line represents the limit value of 3450 hours and of 20% indicated by the standard as limit to attribute the maximum score.

TABLE III. BUILDING EVALUATION ACCORDING THE THREE CERTIFICATION SYSTEMS

Certification System	*Criterion or Sub-criterion*	**Credits**	**Comment**
ITACA protocol	Daylighting	5	Average DF = 3.1
	Automated systems	0 of 0.5	Lighting system is not automated
BREEAM	Daylighting	4 of 4	As it can be inferred by Fig. 2 each relevant area fulfils requirements reported in Tab. II.
	View out	1 of 1	Rooms dimensions are all smaller than 5m, so all positions within relevant areas are within 5 m of a wall which has a window. Moreover, as it can be inferred by the Fig. 2, windows area is always equal to or higher than 20% of the surrounding wall area.
	Internal and external lighting levels, zoning and control	1 of 1	As it was explained in Section III. A, the lighting system was designed to fulfil required criteria.
	Reduction of energy use and carbon	3 of 3	As it was explained in Section III. A, 100% of the fixed internal fittings have been fitted with LELs
LEED	Indoor lighting	1.5 of 1.5	Not considering table and floor lamps the lighting power density is equal to 3.97 W/m^2

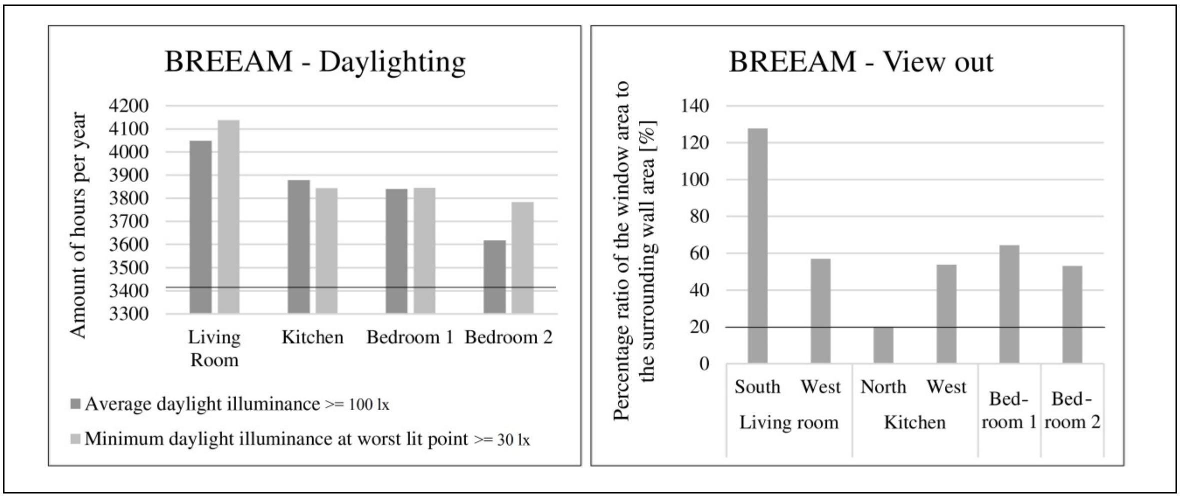

Figure 2. BREEAM Daylighting and View out evaluations

As it can be inferred by Tab. III and Fig. 2, irrespective of the applied certification (excluding the *Automated systems* criterion of ITACA protocol system) the building gained always the maximum score for each criterion.

CONCLUSIONS

The paper evaluated the lighting performances of an Italian residential building according to three different certification systems (ITACA Protocol, BREEAM, LEED). As it was demonstrated in III.B section, irrespective of the used system, the building gained always the maximum attributable score, despite the considered aspects of lighting design are very dissimilar: on the one hand ITACA protocol does not consider electric light consumptions, on the other hand LEED exclusively accounts for artificial lighting, completely neglecting daylight. Therefore, the most complete evaluation tool turns out to be BREEAM, accounting for both aspects. This demonstrates that, about lighting, the methodological approach to the building assessment is still confuse and lacking. This is especially true considering residential buildings and daylighting (as for artificial lighting the evaluation is simpler). ITACA Protocol still proposes a static daylight evaluation approach, based on DF, not considered sufficient by modern research. LEED, that does not includes daylight in residential building evaluation, prescribes a dynamic calculation approach based on sDA (spatial Daylight Autonomy) and ASE (Annual Sunlight Exposure) evaluation for other buildings typologies [14]. The difficulty to apply this method to residential dwellings depends on the fact that these parameters can be evaluated only by establishing a specific scheduling to define the occupied hours of a space, and residential spaces generally are not regularly occupied. BREEAM tries to solve this problem by proposing the alternative procedure described in Tab. II. This latter does not account for excessive light risks like ASE does, letting shadings design be based exclusively on thermal evaluations.

A clearer evaluation approach for daylighting in certification systems, especially in residential buildings case, should be found. The definition of performance parameters evaluating daylighting quality, independently from the way the building is occupied is then crucial. They would allow to classify an environment independently from its use, guarantying its quality even if its function is changed and would be applicable to buildings even if a precise occupancy scheduling cannot be identified.

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The Interreg Project Dynamic Light

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Abstract **In the European standard EN 13201-2:2015 "Road lighting - Part 2: Performance requirements" a lighting class is defined by a set of photometric requirements aiming at the visual needs of certain road users in certain types of road areas under specified environmental conditions. The selection of an appropriate lighting class for a given situation as well as the application of adaptive lighting as described in different national standards and/or recommendations are quite diverse across Europe. Furthermore, the options associated with the various parameters are not common in the different countries, or are not defined clearly and subject to interpretation. The importance of some parameters is regarded differently which leads to deviating lighting levels for the same type of road. Within the framework of the Interreg project CE 452 Dynamic Light it is the aim to harmonize the selection process and to elaborate a proposal for a further revision of the European standards on road lighting.**

Index Terms— **Adaptive lighting, harmonization of European regulations, road lighting, selection of lighting classes**

INTRODUCTION

In this european project, called interreg ce 452 dynamic light, dynamic lighting is defined as adaptive lighting, i.e. it is being provided where and when it is needed depending on different variable conditions, such as travelling speed, traffic volume and/or composition, ambient luminance, weather and other exterior factors in a way that it reduces light pollution as well as energy consumption; beyond that it recognizes varying human and social needs, such as aesthetics or feeling of safety.

In the European standard EN 13201-2:2015 "Road lighting - Part 2: Performance requirements" [1] a lighting class is defined by a set of photometric requirements aiming at the visual needs of certain road users in certain types of road areas under specified environmental conditions. In this European standard [1] which has to be implemented by the national standards organizations of the participating countries there are basically three different sets of lighting classes described: M classes for areas intended for motorized traffic, C classes for conflict areas, and P classes for pedestrian and low speed areas. Guidelines on the selection of an appropriate normal or adapted lighting class are given in the Technical Report CEN/TR 13201-1:2014 [2], but national standards organizations are not bound to implement CEN technical reports. The national standards organizations of four countries participating in this Interreg project CE 452, i.e. Croatia, Czech Republic, Slovakia, and Slovenia, have adopted the Technical Report CEN/TR 13201-1:2014 "Road lighting - Part 1: Guide-lines on selection of lighting classes" as national recommendation without specifying which of the two methods de-scribed in the report are to be applied. In the other three countries participating in this Interreg project the national standards organizations have elaborated or are elaborating national standards on the selection of lighting classes; namely in Italy the standard UNI 11248 "Illuminazione stradale - Selezione delle categorie illuminotecniche" [3] has been published in November 2016, in Austria a draft standard O 1055:2017 "Straßenbeleuchtung - Auswahl der Beleuchtungsklassen" [4] is under discussion, and in Germany a standard DIN 13201-1 "Straßenbeleuchtung - Teil 1: Auswahl der Beleuchtungsklassen" [5] is expected to be published in 2018.

Different fixed or (over time) variable parameters which are considered in the various selection processes could lead to deviating lighting classes for in principle the same type of road. Within the framework of this European project possibilities and limits associated with the different selection procedures will be described and discussed in view of a conceivable harmonization in the future taking into account normal and adaptive / dynamic lighting.

SELECTION OF LIGHTING CLASSES

In the Technical Report CEN/TR 13201-1:2014 "Road lighting - Part 1: Guidelines on se-lection of lighting classes" [2] two methods are presented for the selection of an appropriate lighting class, i.e. one method based on the Technical Report CIE 115:2010 "Lighting of roads for motor and pedestrian traffic" [6] given in the main text, and an alternative method proposed by the French standards organization included in an informative annex. The national standards organizations in Croatia, Czech Republic, Slovakia, and Slovenia have adopted the CEN Report [2] without giving guidance on the preferred application of one or the other method for the selection of a lighting class.

For the selection of a lighting class M for motorized traffic - following the method based on Technical Report CIE 115:2010 [6] - eight parameters are considered: design speed, traffic volume and traffic composition, separation of carriageways and junction density, parked vehicles, ambient luminance, and difficulty of navigational task. The same parameters, except junction density, are taken into account for the selection of a lighting class C for conflict areas. For the selection of a lighting class P for pedestrian and low speed areas in general five parameters are considered, i.e. travel speed, use intensity, traffic composition, parked vehicles and ambient luminance, and in addition, if necessary, facial recognition. For the determination of the lighting class M, C, or P to be applied to a given situation the appropriate weighting values associated with the options for the different parameters have to be selected and added. The sum of the weighting values leads to the number of the lighting class M, C, or P to be applied.

The alternative method for the selection of a lighting class, described in the informative annex B of the Technical Report CEN/TR 13201-1:2014 [2], is based on a functional or administrative classification of roads. For lighting classes M and C road designation ranges from interurban motorways (speed limit less equal 130 km/h) to dangerous sections of urban roads (speed limit less equal 30 km/h), for lighting classes P from low speed roads (speed limit less equal 40 km/h) to walkways and bicycle tracks. The five parameters considered, besides the road type, are in all cases the speed limit, the traffic composition and traffic volume, the ambient light, and the mental task load. For a given road category, from the multiplication of the five coefficients associated with the selected options per parameter results an overall coefficient. Transferring the overall coefficient on to the appropriate graphic presentation leads to an average luminance (for lighting classes M) or illuminance (for lighting classes C or P) to be applied to the given lighting situation.

In the Italian Standard UNI 11248:2016 “Illuminazione stradale - Selezione delle catego-rie illuminotecniche” [3] roads are categorized based on current legislation. The types of road classified range from interurban motorways to local urban streets predominantly used by pedestrians. For any type of road, associated with a given speed limit and traffic flow (in vehicles per hour), a lighting class M, C, or P as described in the European standard EN 13201-2:2015 [1] is specified as a starting point for the selection of an appropriate lighting class. Before a lighting class can be applied a risk analysis has to be carried out taking into account the parameters: normal complexity of the visual field, low density of conflict areas, and high conspicuity of traffic signs in conflict areas, presence of traffic lights, and lack of crime risk. Careful evaluation of these parameters for a given situation leads to a maximum reduction of two steps in term of the lighting class (M, C, or P) to be applied.

The selection of lighting classes M and P in the Austrian draft standard O 1055:2017 “Straßenbeleuchtung - Auswahl der Beleuchtungsklassen” [4] is based on the method described in the Technical Report CEN/TR 13201-1:2014 [2]. For the selection of a lighting class M for motorized traffic eight parameters are considered: substantial speed, substantial traffic volume (vehicles per day) and traffic composition, separation of carriageways and junction density, parked vehicles, ambient luminance, and difficulty of driving task. For the selection of a lighting class P for pedestrian and low speed areas in general five parameters are considered, i.e. speed, traffic flow, traffic composition, parked vehicles and ambient luminance, and in addition, if necessary, facial recognition. For the determination of the lighting classes M or P to be applied to a given situation the appropriate weighting values associated with the options for the different parameters have to be selected and added. The sum of the weighting values leads to the number of the lighting class M or P to be applied. For the selection of a lighting C for conflict areas the different Austrian standard O 1051 “Straßenbeleuchtung - Beleuchtung von Konfliktzonen” [7] has to be applied.

In the German draft standard (still under discussion) DIN 13201-1 “Straßenbeleuchtung - Teil 1: Auswahl der Beleuchtungsklassen” [5] roads are categorized based on common designations. For the selection of a lighting class M for motorized traffic different parameters are considered dependent on the road category, e.g. only speed, junction density, and luminance of environment for motorways. For major roads additional parameters like separation of carriageways, traffic flow and traffic composition, parked vehicles and/or increased demands (e.g. due to difficulty of driving task) are taken into ac-count. For the selection of a lighting class P further parameters are considered, i.e. traffic flow pedestrians, traffic flow cyclists and in addition, if necessary, facial recognition. For the determination of the lighting class M or P to be applied to a given situation the appropriate weighting values associated with the options for the different parameters have to be selected and added. The sum of the weighting values leads to the number of the lighting class M or P to be applied. The selection of a lighting C for conflict areas is linked to the lighting level of the roads leading to the conflict area using a table of comparable lighting levels for different values of the average luminance coefficient of the road surface or of the diffuse reflectance of the pavement of the area.

ADAPTIVE / DYNAMIC ROAD LIGHTING

According to the Technical Report CEN/TR 13201-1:2014 [2] the normal lighting class is defined as the class with the maximum value of luminance or illuminance at any period of operation, adaptive lighting is defined as temporal controlled changes in luminance or illuminance in relation to traffic volume, time, weather or other parameters. Here a more comprehensive working definition has been discussed by the partners of this Interreg project: Dynamic lighting is adaptive lighting, i.e. it is being provided where and when it is needed depending on different variable conditions, such as travelling speed, traffic volume and/or composition, ambient luminances, weathers and other exterior factors in a way that it reduces light pollution as well as energy consumption; beyond that it recognizes varying human and social needs, such as aesthetics or feeling of safety.

The adapted, usually reduced lighting level or levels should be average luminance or illuminance from a class or classes of the same type (M, C, or P) from which the normal lighting class has been selected [2] [6]. When applying adaptive lighting it is important that the changes in the average lighting level do not affect the other quality criteria outside the limits given in the system of lighting classes M, C, and P in the European standard EN 13201-2:2015 [1]. Reducing the light output from every light source by the same amount using dimming techniques will not affect the luminance or illuminance uniformity, diversity, or the object contrast, but the threshold contrast will increase. Reducing the average lighting level by switching off some luminaires will decrease uniformity while increasing glare, and will not fulfil the quality requirements and is therefore not recommended [2] [6]. The use of adaptive lighting can provide significant reduction in energy consumption, compared with operating the normal lighting class throughout the hours of darkness. Where the pattern of variation in parameter values is well known, such as from records of traffic counts on traffic routes, or can be reasonably assumed, as in many residential areas, a simple time based control system may appropriate. In other situations an interactive control system linked to real-time data may be preferred. Such a system would permit the normal lighting class to be activated in the case of e.g. roads works, serious accidents, bad weather or poor visibility [2] [6].

APPLICATION OF ADAPTIVE ROAD LIGHTING

In all technical reports [2] [6] and standards [3] [4] [5] considered in this European project the application of adaptive road lighting is described and recommended as a possibility to reduce energy consumption while keeping road safety and security at an appropriate level. In that part of the Technical Report CEN/TR 13201-1:2014 [2] which is based on the Technical Report CIE 115:2010 [6], all parameters considered in the selection process of a lighting class M, C, or P are regarded as time dependent. Re-determination of the lighting classes to be applied using different options associated with the parameters will result in different lighting levels per time interval. In the alternative method described in the informative annex B of the Technical Report CEN/TR 13201-1:2014 [2] the only parameter which is considered as time dependent for all road categories is the traffic volume. For lighting classes M or C (for some road designations), and for lighting classes P (for all road designations) also the parameters ambient luminance and mental task load are regarded as time dependent. In the Italian Standard UNI 11248:2016 [3] adaptive lighting is linked predominantly with traffic volume/flow. The categorized roads are associated not only with a design speed but also with a maximum traffic flow (in vehicles per hour). The comparison of the current traffic flow (measured real time) with the maximum traffic flow results in a reduction of the lighting level in one or two steps. The allowable reduction of the lighting level depends also on the outcome of the risk analysis carried out during the selection process for the normal lighting class. The application of adaptive lighting as describe in the Austrian draft standard O 1055:2017 [4] follows closely the method given in the Technical Report CEN/TR 13201-1:2014 [2]. All parameters are considered as possibly time dependent, but the parameters substantial traffic volume and ambient luminance are regarded most important. In the German draft standard (still under discussion) DIN 13201-1:2017 [5] not only roads are categorized but also parameters, as fixed or variable over time. In general, the parameters speed, junction density, and separation of carriageways are regarded as fixed. The other variable parameters could lead (when re-evaluated) to different lighting levels per time interval considered. No guidance is given how to link the (real time measured) traffic flow with an appropriate lighting level. The decision has to be taken from experience and knowledge.

COMPARISON AND CONCLUSION

The selection of an appropriate lighting class for a given situation as well as the application of adaptive lighting as described in different national standards and/or recommendations are quite diverse across Europe. Furthermore, the options associated with the various parameters, e.g. certain levels of design speed, are not common in the different countries, or are not defined clearly and subject to interpretation. The importance of some parameters is regarded differently which leads to deviating lighting classes/levels for the same type road. Within the framework of one of the work packages of the Interreg project CE 452 Dynamic Light a comparative analysis will discuss and make obvious current differences. It is the aim to harmonize the selection process for normal and adaptive lighting and to elaborate a proposal for a further revision of the European standards on road lighting taking into account the varying human and social needs.

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Outdoor Adaptive Lighting in the new UNI 11248 Italian Standard and Result of Experience

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Abstract—**In the world of Smart Cities and IoT, traditional pre-programmed both monitoring and adaptive (dimming) street lighting systems are considered obsolete. A new generation of sensors, that are capabled of measuring the three essential parameters, for correctly controlling lighting in outdoor areas, i.e. traffic and weather conditions, and road surface luminance, give opportunities for new approaches in design and maintenance of road lighting installations.. Both real time and closed loop configurations are possible today even in PLMS (Public Lighting Management Systems), at a reasonable cost .**

In Italy on November 2016 the new revision of the national standard UNI 11248, derived from EN 13201-1:2015 and CIE TR 115:2010, introduced a specific chapter about new approaches of *Adaptive Lighting*: both lighting designers and the Municipalities now can operate real time PLMS through sensors installed within their territories, with benefits in terms of energy saving and increased safety on the road. The new UNI 11248 sets a number of parameters (dimming speed, maximum dimming levels, number and periodicity of samples, calculation parameters, control strategies ,etc.), in order to ensure always maximum safety to the driver, depending on real time measurements.

UNI 11248 defines two different operating methods: a) TAI (Traffic Adaptive Installation), where only the traffic volume is measured; b) FAI (Full Adaptive Installation), where even meteorological conditions and road surface luminance are measured. When FAI is deployed, UNI 11248 allows a reduction of 3 lighting classes, correspondent often to 75% dimming, but only if safety conditions are guaranteed. This paper is entering into details about both parameters and the logic behind the rules set by the UNI standard, two of the authors being member of the GL5 (Road lighting) committee.

Besides, the paper will emphasize the results of this new technological frontline and specifically:
- **Data downloaded from LTM (Luminance, Traffic, Meteorological conditions) sensor operation in real installations;**
- **UNI 11248 Standard : Adaptive Lighting, prescriptions, limits of operation;**
- **"LIFE-Diademe" project co-financed by EU, supporting a new approach to Adaptive Lighting, making it more safe and efficient, but still coherent with the UNI 11248 standard.**

It seems that real time Adaptive Lighting is just behind the corner!

Index Terms--**adaptive lighting, public lighting, PLMS, monitoring system, energy efficiency**

I. INTRODUCTION

Road lighting installation dimming for energy conservation purposes has always been quite controversial, when applied specifically to large cities. The technology up to yesterday could only propose dimming systems that working through pre-set scheduling schemes. Local police and politicians refuse a so simple approach to dimming, because a city is somehow like a living body, and predicting what the traffic volume will be is not a simple task. For this reason some cities use dimming profiles which are activated very late in the night (i.e. 2 AM !), therefore the energy saving becomes negligible.

The only way to conciliate the need of safety and the energy conservation is to measure the parameters relevant to define the right lighting class and therefore the street light dimming level. Here comes then the possibility, offered by the best technologies available today, allowing complex systems operation, at a very low cost, both in term of initial investment and operating costs.

Anyway, technology should be able to take into account requirements stated by Standards, avoiding invention of further unreasonable approaches. During the last 10 years, a number of systems, based on occupancy sensors, has been advertised, but this approach could fit well to green areas, indoor, and in general restricted areas, not surely for motorized traffic roads. The only way to a guarantee a wide, accepted and smart approach to street light dimming is only coming from the real time knowledge of values of the parameters set by Standards and that influence the selection of the lighting class.

This paper is showing how the technology today is helping Adaptive Lighting to become the new standard for street and road lighting installations, and how the new Road Lighting Standard in Italy (UNI 11248, published in November 2016) sets specific rules in order to allow a wide and safe use of the new technologies.

Besides, new technological frontlines will be analysed

II. WHAT IS DYNAMIC LIGHTING

A. DimmingiIn The Last Two Decades

The need of dimming, when late at night, was coming out in the '70s, when the first energy crisis were obliging both citizens and governments to think and act towards energy conservation. The common feeling was that "all that light at night time, when nobody is there" would be a waste. During these years, in Italy, many municipalities decided to turn off one lamp out of two at midnight: a very simple technology, a good energy saving, but a much lower safety, considering that uniformity was altered and often lower than the minimum standard requirements.

In the late '90s, a study from The Netherland motorways (DYNO) was carried out, to understand how to correlate traffic and weather conditions to safety and energy conservation. The result was detailing that during low traffic hours, lamps should be dimmed down to 20% (-80%), but only when meteorological conditions are fair, while in case of high traffic and bad weather, the lighting level should be double when compared to standards in force. The analysis of the behaviour of the vehicles over a prolonged period did not show any increase in critical situations, during reduced luminance time.

While CIE 115 was starting to consider dimming for energy conservation, in Italy the standard UNI 10439 introduced for the first time in Europe a very simple criteria to dim: it is allowed to downgrade of one lighting class, if the traffic volume is lower than 50% of the nominal value, and two lighting class whenever the traffic is reduced more than 75%.

Anyway, the idea was to give simple rules to allow energy conservations when peculiar conditions were met, so that no one should invent and follow his own specific approach to street light dimming

B. The CEN 13201-1:2014

The CEN 13201-1 introduces the concept of Adaptive Lighting in paragraph 3.2

"Adaptive lighting: temporal controlled changes in luminance or illuminance in relation to traffic volume (e.g. vehicles/5 min), time, weather or other parameters"

In paragraph 4 the standard provides general indications about dimming:

*"*Where the pattern of variation in parameter values is well known, such as from a record of traffic monitoring stations (TMS) and weather stations (AWS) on traffic routes, or can be reasonably assumed, as in many residential areas, a simple time based control system may be appropriate. In other situations, an interactive control system linked to real-time data may be preferred. This approach will permit the normal lighting class to be activated in the case of road works, serious accidents, bad weather or poor visibility."

Therefore the CEN 13201-1 states that dimming should apply for energy conservation, if the other project quality criteria (for example uniformity) are not changed, preferably using real time information about traffic volume, weather and real lighting levels. The use of time-based systems should be limited to areas, which are easily predictable.

This is not the case of a city, where sudden and non-predictable activities might happen (events, sport related activities, security problems, weather, etc). As stated before, one main reason why municipalities in Europe are reluctant to dimming is because a pre-determined dimming program could not fit city's needs.

Another problem is the lack of statistical data about traffic conditions. In Italy these data are not often available, and therefore the technicians and the municipalities are founding their decisions about dimming programs just on personal evaluations.

Anyway, even if a good database is available, the common sense is that dimming based on statistics reduce safety. It is like concluding: traffic data and dimming programs are based on statistics, safety is related to traffic volume, therefore safety is strictly related to statistics. This kind of idea does not help the Mayors and the Police to go for dimming.

The only way to overcome this idea is to measure continuously the parameters that are defining precisely how to dim

III. THE ITALIAN STANDARD UNI 11248 AND LIMITS OF APPLICATION

A. UNI 11248 published in November 2016

The working group GL5 took the opportunity during the revision of the UNI 11248 Standard, given by the publication of the EN13201:2014, to establish some specific rules and requirements in order to:

- Grant a development of dynamic lighting in replicable safe conditions
- Incentivise the use of dynamic lighting, above all through LED sources, featuring the possibility to be dimmed up down to 10% of the nominal flux
- Prevent the abuse of Dynamic lighting when conditions are not met

The result of 2 years of discussions and case study evaluation (see paragraph 3) was the normative annex D, which set a number of operational parameters. First, the definition of Adaptive Lighting is being changed when compared to EN 13201:2014. Since GL5 wanted to give emphasis and advantages only to systems, which are based, on real time measurements, and not to pre-programmed time based systems, the definition clearly states that Dynamic Lighting is a type of dimming system where the variations of lighting parameters are performed in a continuous way, based on real time measurement of influence parameters, such as traffic and weather conditions.

Then UNI 11248 introduces two way of managing adaptive lighting:

- The Traffic Adaptive Installations (TAI)
- The Full Adaptive Installations (FAI)

TAI is a lighting installation with a luminous flux control system where only traffic is being measured in real time. In this case the UNI 11248 works as usual, that is only when traffic is lower than 50% of the nominal value, one lighting class can be downgraded and whenever traffic is less lower than 75% of the nominal value, light should be dimmed by 2 lighting classes.

The relevant difference to NON adaptive lighting is the possibility to follow the traffic volume variations in real time, allowing therefore dimming much earlier than average, if conditions are met, while giving full safety and light when traffic is for some reason “out of the statistics”.

It is clear as well that TAI represents a dimming “by step”: only when traffic volume is lower than 50% of its nominal value, dim is possible, if , in example, traffic volume corresponds to 48% only, dimming is not allowed.

UNI 11248 states as well that for TAI purpose, calculation of traffic volume should be measured every 10 min, and dimming is allowed only whenever two consecutive samples are below the limit, but is only one sample is higher, then the proper lighting level should be immediately applied.

FAI requires the real time measurement of three parameters: traffic volume, weather conditions, and road surface luminance. Since FAI allows higher dimming levels, the Working Group decided that, in order to reduce the light to the minimum, all influence parameters relevant to lighting have to be measured. The influence of weather conditions on lighting is very well known: wet roads increase non-uniformity of the road surface luminance and therefore dimming should not be allowed, fog reduces contrast and therefore the safety on the roads, snow on the contrary is causing even glare.

Besides, what is more important is to be sure that the road surface luminance corresponds to what required by the European standard EN 13201-2, and for many reasons this luminance may be variable: dirtiness of luminaire, ageing of the lamps, variability of road surface properties in reflection, etc. This is the reason why luminance should be measured and guaranteed, in order to run a FAI system, allowing higher dimming levels.

Only through measurement of these three parameters (traffic volume, weather and real luminance at that specific time), Municipalities are being allowed to dim according to FAI, that means:

- Possibility to dim up to three lighting categories, when traffic is lower than 12,5% of nominal value and weather is good.
- Possibility to dim continuously, that is for example, dimming 20% when traffic is reducing by 10%, following a straight line interpolating from the higher to the lower permitted luminous classes (max and min dimming level). The advantage compared to TAI is evident, because TAI can dim only in steps

In case of FAI, traffic volume has to be measured every minute, the value used for dimming should be the average over 10 reading (i.e.10 min). A mobile average should be used in the calculations. If three consecutives samples show a value greater than 20% of the last calculated value, an immediate variation of the dimming has to be activated.

The reason for such choices are:

- Average over 10 minutes is not being conditioned by specific traffic situations occurring, in example, when a traffic light is present along the installation.
- The lowest lighting level is acceptable only when all influence parameters are under control, including road surface luminance and weather

UNI 11248 also considers that today technology is limiting the number of sensors that can be reasonably installed in a city, for economic reasons. The limit coming from the investment cost is being solved by giving the lighting designer the possibility to consider homogeneous areas, therefore dimming according to a limited number of sensors, and using the same info for adjacent streets.

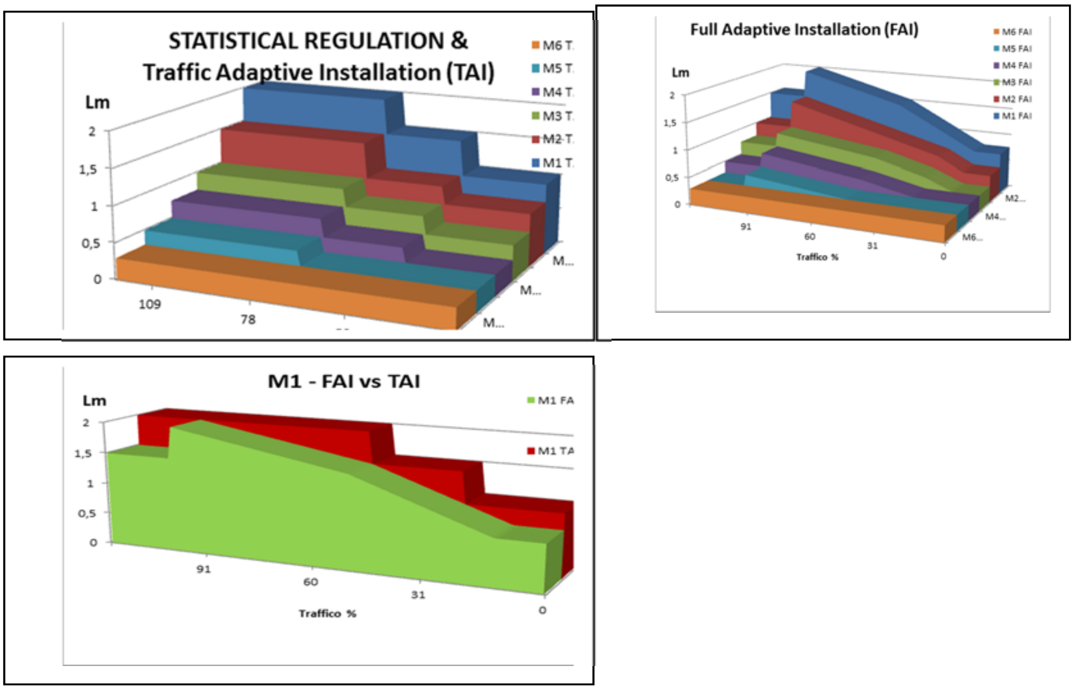


Figure 1 -2- 3 TAI, FAI dimming. Comparison between FAI and TAI for ME1 class

IV. RESULTS OF EXPERIENCES: BERGAMO PROVINCE, GALATINA

A. Bergamo Province, Highway

In 2011, thanks to Lombardy regional administration co-funding, a new research project in Adaptive Lighting was launched. Reverberi Enetec srl, a company having been working in dimming systems and PLMS for 20 years, has been leading the project. Both the Province of Bergamo and I.N.Ri.M., the Italian National Institute of Metrology were involved.

Bergamo Department of Roads took part in the working group actively and gave availability of two roads, one is the main highway around Bergamo (HPS lamps) and the second one is a minor road (MH lamps). I.N.Ri.M granted all the measuring equipment, specifically road surface luminance, uniformity and traffic counting.

The sensor used during the one year test was a prototype of Reverberi: a camera measuring traffic volume, environmental and road surface luminance and evaluating weather conditions.

The sensor was able only to record data, but not to dim the lighting instalaltion, in order to compare the dimming that would have been given by the FAI system and the real dimming ordered by a pre-programmed time system.

Comparing the dimming according to real time traffic and the pre-programmed dimming cycles, the average energy saving achieved over long periods would have been at least 30%.




Figures 4,5,6,7 – Testing site in Bergamo Province. Luminance measurements

Figure 8: example of graphs of measurements done in Bergamo. From the final report of the project

B. Galatina, Industrial Area

In 2016 the consortium of Industrial Activities of the city of Galatina, decided to renovate their lighting instalaltions by using the best technologies available.
Reverberi Enetec installed one LTM to measure the above mentioned influence parameters and dim the LED luminaires, according to the Italian standard FAI rules.
The influence of closed loop luminance dimming in this installation is quite negligible, because the luminance at full power is 1,05 cd/m^2 therefore in one year time the saving, considering dirtiness, source decay, etc, corresponds to around 2%
In a 6 months period, the energy saving of FAI Adaptive Lighting, compared to a pre-set dimming schedule, was, , 25%, while the energy saving compared to not dimmed consumption was 44%.
The reason of this nice result is easily understandable from one single figure: in 92% of lighting hours, the traffic volume was below 12,5% of the road capacity. This explains why the potential of Adaptive Lighting is quite important.


Figures 9, 10 – Testing site in Galatina

C. LTM Sensor

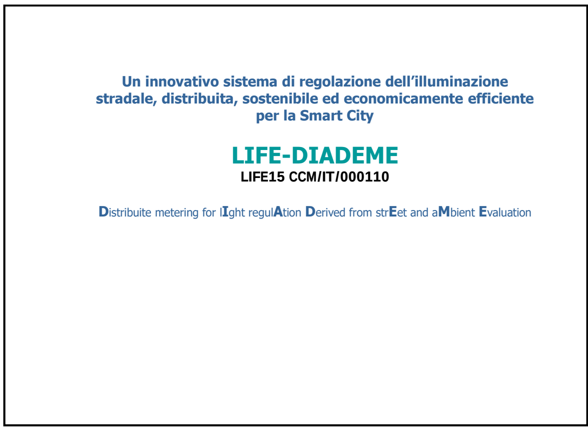
LTM sensor is a camera, able to evaluate the 3 parameters relevant to UNI 11248, featuring state-of-the-art techniques of computer vision and image processing.
LTM is able to count the vehicles running across a virtual line, with an accuracy of about 10%. The vehicles are counted per each lane and per each carriageway, since UNI 11248 specifies that the traffic volume should be measured in the lane where the highest traffic volume is present.

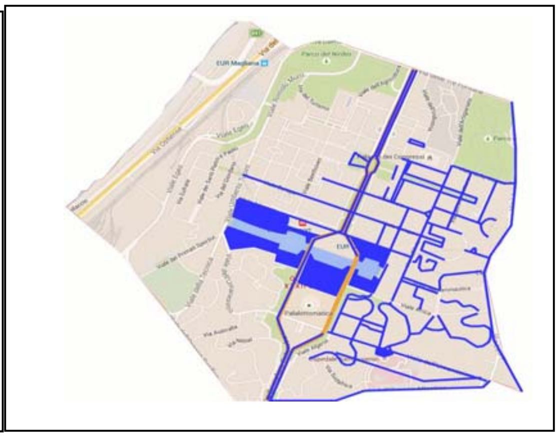
Every minute, LTM takes a peculiar picture of the road, and using this picture calculates the luminance of the area under analysis. This area can be configured by the user. The LTM is installed normally at around 5 m high, according to provisions of EN 13201-4:2015. Luminance values, according to INRIM laboratory measurements, have an uncertainty of ± 5%.
Image analysis is useful to determine as well if fog is present (condition where the dimming is disabled), if road is wet (uniformity analysis), or if there is snow on its surface.
LTM sensor is fully able to manage a FAI lighting plant

Figure 11, 12 – LTM sensor with computer vision software

V. THE NEW TECHNOLOGICAL FRONTLINE: UE LIFE DIADEME PROJECT

The UNI 11248 leaves the Lighting Designer the possibility to use collected data from a specific road in other neighbouring roads, because it would be too expensive to install an LTM device for each single street. This approach partially introduce some statistical evaluation of the real conditions in the neighbouring roads.
To overcome this problem, Reverberi has been awarded in 2016 by the European Union, the LIFE program, to install an innovative Adaptive Lighting system. Diademe is deploying low cost sensors onto each lighting pole, to gather many data, correlate with few precise sensors, and give a complete map of all relevant parameters to FAI in each lighting point. Therefore dimming will be both more accurate and safer.
The system is being tested in ROME, EUR area, in about 1000 lighting points, and will be installed in 2018.
Reverberi expects to get a 30% energy saving, compared to pre-programmed dimming profiles over LED luminaires, a reduction of scraps of about 30%, and the availability of many information from installed sensors.





Figures 13, 14 Diademe project and testing area in EUR (Rome) (1000 lighting points)

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Comparison of Different Methods of Distribution Factor Calculation

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***Abstract*—The calculation of utilization factors relies on geometric multipliers to arrive at the distribution factors which give the fraction of the source flux arrives directly at each room surface. There are a number of possible assumptions that can be used to derive geometric multipliers each resulting in different values. This paper explores these differences and estimates the potential differences in utilisation values that may be expected. The key finding is the method in CIE 52 may no longer be appropriate.**

***Index Terms*--Utilization factor, distribution factor, geometric multiplier**

INTRODUCTION

The standard method of utilisation factor calculation is being reviewed by CIE TC 3-48 and as part of that work the method used to determine the distribution factors (DFs) has been studied. Distribution factors are used to describe how much light falls onto each of the room's surfaces directly from the luminaires. The first step in calculating the DFs is assessing the direct flux reaching the floor (DFF) formula (1) gives this calculation.

$$DFF = GML1 \times FCL1 + GML2 \times FCL2 + GML3 \times FCL3 + GML4 \times FCL4 \qquad (1)$$

Where:

GML1 to *GML4* are the 4 geometric multipliers calculated according to the formulae in CIE 40 [1]

FCL1 to *FCL4* are the cumulative fluxes for the luminaire for the zones 0 to 41.4° (*FCL1*), 0 to 60.0° (*FCL2*), 0 to 75.5° (*FCL3*) and 0 to 90.0° (*FCL2*).

When the luminaires are mounted to the ceiling the distribution factors may be calculated with the formulae (2) below.

$$\begin{aligned} DF(F) &= \frac{DFF}{1000} \\ DF(W) &= DLOR - DF(F) \\ DF(C) &= ULOR \end{aligned} \qquad (2)$$

Where:

DF(F), DF(W) and DF(C) and the distribution factors to the floor, walls and ceiling respectively

DLOR is the downward light output ratio of the luminaire and ULOR is the upward light output ratio

When suspended luminaires are employed the system becomes slightly more complex with added calculation to determine how much of the upward flux reaches the ceiling and how much flux goes to the upper walls.

Once the DFs are know then the utilisation factors to the floor may be calculated using the formula (3)

$$UF(F) = DF(F) \times TF(F,F) + DF(W) \times TF(W,F) + DF(F) \times TF(C,F) \qquad (3)$$

Where

UF(F) is the utilisation factor on the floor

TF(F,F), *TF(W,F)* and *TF(C,F)* are the transfer factors to the floor from the floor, walls and ceiling respectively.

This process is again slightly more complex if suspended luminaires are used. The basic method for deriving the transfer factors is given in CIE 40[1] however the method has been further developed by Raynham & Bean [2].

Thus utilisation factors can easily be calculated, however, there are a number different approaches to the calculation of the geometric multipliers. This paper will study the differences between the method used in CIE 52 [3] and the CEN method of calculation [4].

UNDERLYING ASSUMPTIONS

Whilst the basic principals of calculating geometric multipliers are set out in CIE 40 [1] the variation between different methods arise because there is less agreement on the number of luminaires and their arrangement within a room. In CIE 52 the number of luminaires used in a room is purely a function of room size with the number being given in Table 1

TABLE I THE LUMINAIRE NUMBERS FROM SECTION10.3.6 OF CIE 52

Room Index (K)	No. in length	No. across
0.6	2	1
0.8	2	2
1	3	2
1.25	3	3
1.5	4	3
2	4	4
2.5	5	4
3	6	4
4	8	5
5	10	6

In the CEN standard it does not spell out exactly how the geometric multipliers are derived, however it does provide different GM values for different luminaire spacing to height ratios (SHRs). Checking the values given in the CEN standard against the basic calculation in CIE 40 it is clear that the GMs for a low SHR luminaire would seem to be based on more luminaires being in the room that for a high SHR luminaire. This is illustrated below

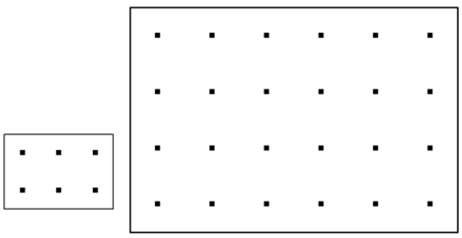

Figure 1

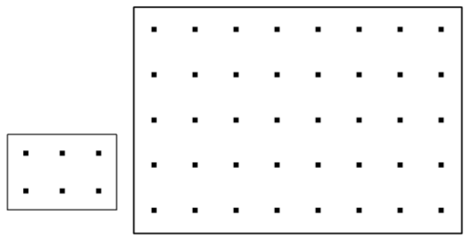

Figure 2

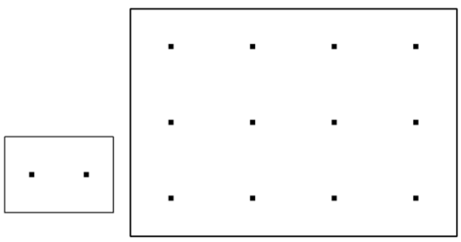

Figure 3

Figure 1-2-3. These figures show the nominal disposition of luminaires in a small room K = 1 and a larger room K = 3. Figure 1 shows the luminaire layout from CIE 52. Figure 2 shows the layout for the CEN standard with a SHR of 1. Figure 3 is the CEN layout for SHR 2.

These changes in layout result in different geometric multipliers.

TABLE II GEOMETRIC MULTIPLIERS FROM CIE 52 AND THE CEN METHOD

	K = 1			K=3		
	CIE 52	CEN		CIE 52	CEN	
		SHR = 1	SHR = 2		SHR = 1	SHR = 2
GML1	0.636	0.636	0.459	0.282	0.258	0.192
GML2	0.121	0.121	0.588	0.118	0.118	0.100
GML3	0.088	0.088	-0.032	0.562	0.563	0.658
GML4	-0.015	-0.015	0.009	0.016	0.016	0.067

Assessment of the impact of Different GMs on the calculated values of UF

To explore the consequences of these different GMs for the UF tables generated it is necessary to do the utilization factor calculations using the GMs from both the CIE 52 and CEN methods. A range of light distributions was needed for the testing so the 10 light distributions of the British Zonal (BZ) system were adopted for this study. These distributions are described in detail in Raynham [5]. The BZ distributions are defined by the mathematical functions given in table 3 and figure 4 gives the polar curves for some of them.

TABLE III THE FUNCTION, NORMALIZATION FACTOR AND SHR FOR EACH OF THE BZ DISTRIBUTIONS

BZ Number	Function	Normalisation Factor	SHR Max
1	$\cos^4 \gamma$	795.61	1.255
2	$\cos^3 \gamma$	636.52	1.405
3	$\cos^2 \gamma$	477.42	1.624
4	$\cos^{1.5} \gamma$	397.86	1.779
5	$\cos \gamma$	318.36	1.989
6	$1+\cos\gamma$	106.11	2.381
7	$2+\cos\gamma$	63.66	2.512
8	1	159.15	2.767
9	$1+\sin\gamma$	89.14	3.184
10	$\sin\gamma$	202.65	1.584

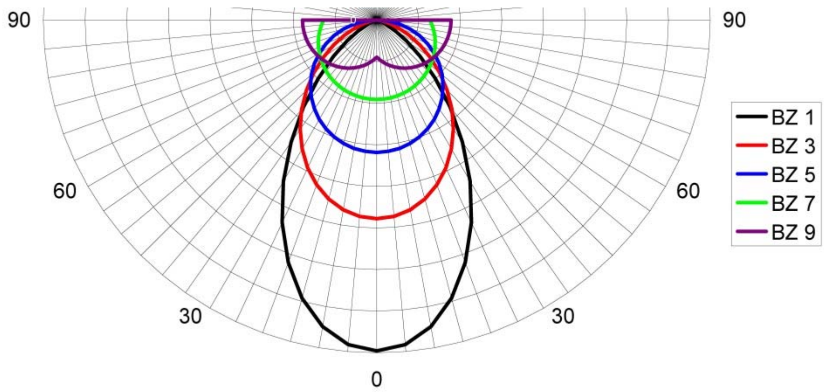

Figure 4 A polar plot of some of the BZ distributions

A set of UF tables was calculated for each BZ distribution by both the CIE 52 and CEN methods.

Results

It was found that in all cases that the CEN method gave higher UF values than the method from CIE 52. Table 4 shows the average and maximum differences between the two methods.

TABLE IV THE AVERAGE AND MAXIMUM DIFFERENCES IN THE UFS CALCULATED BY THE TWO METHODS

	Average Difference	Maximum Difference
BZ1	2.6%	6.4%
BZ2	2.4%	6.0%
BZ3	4.9%	12.1%

	Average Difference	Maximum Difference
BZ4	5.5%	15.6%
BZ5	5.2%	14.7%
BZ6	5.9%	15.6%
BZ7	5.7%	15.1%
BZ8	5.3%	14.1%
BZ9	4.9%	12.9%
BZ10	1.8%	5.2%

As expected the differences are greater where there is less inter-reflected light and in smaller rooms where the role of the walls is more important. Table 5 shows the results for BZ6 which is typical of results for BZ4 to BZ8.

TABLE V THE RESULTS FOR BZ6 SHOWING BOTH CALCULATED UF VALUES AND THE DIFFERENCES BETWEEN THE SETS OF VALUES. THE HIGHLIGHTING SHOWS GREATEST DIFFERENCES.

Values calculated using CIE 52										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		0.693	0.545	0.442	0.669	0.533	0.436	0.627	0.511	0.425
1.25		0.759	0.618	0.516	0.734	0.604	0.508	0.687	0.577	0.493
1.50		0.809	0.676	0.575	0.782	0.660	0.566	0.733	0.630	0.549
2.00		0.881	0.763	0.669	0.853	0.745	0.658	0.800	0.710	0.636
2.50		0.929	0.824	0.737	0.900	0.804	0.723	0.846	0.766	0.698
3.00		0.964	0.869	0.789	0.934	0.848	0.774	0.879	0.808	0.745
4.00		1.009	0.929	0.859	0.979	0.906	0.842	0.923	0.863	0.809
5.00		1.038	0.969	0.907	1.008	0.945	0.888	0.952	0.900	0.853
Values calculated using CEN										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		0.741	0.608	0.514	0.720	0.596	0.508	0.680	0.574	0.497
1.25		0.806	0.680	0.588	0.783	0.667	0.580	0.739	0.641	0.566
1.50		0.854	0.735	0.645	0.828	0.720	0.636	0.782	0.691	0.619
2.00		0.916	0.811	0.727	0.889	0.793	0.715	0.840	0.760	0.693
2.50		0.953	0.856	0.777	0.925	0.837	0.763	0.873	0.800	0.738
3.00		0.983	0.896	0.822	0.955	0.875	0.807	0.902	0.836	0.779
4.00		1.022	0.948	0.883	0.993	0.926	0.866	0.939	0.883	0.833
5.00		1.046	0.981	0.922	1.016	0.957	0.903	0.962	0.912	0.868
Differences in values (%)										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		6.8%	10.8%	15.0%	7.2%	11.1%	15.2%	8.1%	11.8%	15.6%
1.25		6.0%	9.5%	13.1%	6.5%	9.8%	13.3%	7.3%	10.4%	13.7%
1.50		5.4%	8.4%	11.5%	5.7%	8.6%	11.6%	6.5%	9.2%	12.0%
2.00		3.9%	6.1%	8.3%	4.2%	6.3%	8.4%	4.8%	6.7%	8.7%
2.50		2.5%	3.9%	5.3%	2.7%	4.0%	5.4%	3.1%	4.3%	5.6%
3.00		2.0%	3.1%	4.2%	2.2%	3.2%	4.3%	2.5%	3.5%	4.4%
4.00		1.4%	2.1%	2.8%	1.5%	2.1%	2.8%	1.7%	2.3%	3.0%
5.00		0.8%	1.2%	1.7%	0.9%	1.3%	1.7%	1.0%	1.4%	1.8%

DISCUSSION

It is clear from this study that the different calculation methods produce significant differences in the results and for some distributions this is in excess of 5% in average and for particular room and reflectance conditions over 15%. Thus it is necessary to look at the cause of this difference and consider how it relates to actual lighting practice. In CIE 52 the set numbers of luminaires in rooms implies that the luminaires are spaced at a given SHR. Table 6 gives the SHR used in the CIE 52 method. It can be seen that the SHR is quite low, and in most cases below the SHR for the BZ distributions.

TABLE VI THE SHRS IMPLIED BY CIE 52

Room Index (K)	**No. in length**	**No. across**	**SHR Length**	**SHR Width**
0.6	2	1	0.78	0.98
0.8	2	2	1.04	0.65
1	3	2	0.87	0.81
1.25	3	3	1.08	0.68
1.5	4	3	0.98	0.81
2	4	4	1.30	0.81
2.5	5	4	1.30	1.02
3	6	4	1.30	1.22
4	8	5	1.30	1.30
5	10	6	1.30	1.35

The only distributions which come close to these values are BZ1 and BZ2. These two distributions also show only small differences to the between the calculation methods. In figure 7 the full set of differences for BZ 2 is shown

TABLE VII THE DIFFERENCES FOR BZ2 WITH THE HIGHLIGHTING SHOWING THE GREATEST DIFFERENCES

Differences in values (%) For BZ2										
	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
Ri	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.60		2.7%	3.8%	4.8%	2.8%	3.9%	4.8%	3.0%	4.0%	4.9%
0.80		3.1%	4.5%	5.6%	3.3%	4.6%	5.6%	3.5%	4.7%	5.7%
1.00		3.3%	4.7%	5.8%	3.4%	4.8%	5.9%	3.7%	4.9%	6.0%
1.25		2.9%	4.2%	5.2%	3.1%	4.3%	5.3%	3.4%	4.5%	5.4%
1.50		2.4%	3.5%	4.4%	2.6%	3.6%	4.5%	2.9%	3.8%	4.6%
2.00		1.4%	2.0%	2.6%	1.5%	2.1%	2.6%	1.7%	2.2%	2.7%
2.50		0.4%	0.6%	0.7%	0.4%	0.6%	0.7%	0.5%	0.6%	0.8%
3.00		0.2%	0.3%	0.4%	0.2%	0.3%	0.4%	0.2%	0.3%	0.4%
4.00		0.1%	0.2%	0.2%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%
5.00		0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

This table 7 shows that room index 2.5 and above the two calculation methods are in good agreement. In these rooms the SHR used by the CIE 52 method (~1.3) is close the nominal 1.25 SHR of the CEN method. It is only in the smaller rooms where the CIE 52 calculation uses a much lower SHR that there is a significant difference in the results.

CONCLUSION

It is now common place for lighting designs to be assessed using computer software. However, utilizations factors are still useful as they provide a quick and easy way to find which luminaires are likely to be most efficient in a given installation and thus their use simplifies the luminaire selection process. The CEN method of calculating the UF takes into account the SHR of the luminaire providing sets of geometric multipliers to cover a range of SHRs. The CIE 52 method does not do this and implicitly assumes SHR values that would be considered low for most modern luminaires. In practice there are great pressures to reduce the number of luminaires used in any given installation so manufacturers strive to produce luminaires with high SHR values which are then installed close to their maximum SHR.

The method in CIE 52 underestimates the performance of luminaires that have been designed to be used at high spacing ratios and thus may be putting such equipment at a commercial disadvantage. For this reason it may be sensible to withdraw CIE 52 and replace it with method that relies on the SHR of the luminaire being evaluated.

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Documentation of Lighting Design

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***Abstract*— Aim of this paper is to contribute with particular proposals to the problems of documentation of lighting design and to contribute to the standardization in this field. Analytical part of the paper is devoted to the summary of current normative requirements of European set of lighting standards completed by description of an older Slovak standard dealing more in details with preparation of a lighting design documentation. The paper, however, gives focus on new proposals on structuring the lighting design documentation, qualification of competent persons and other relevant information. Suggestions for future continuation of development of an international normative document will be given in the conclusion.**

***Index Terms*-- documentation, lighting design, lighting system, standardization.**

INTRODUCTION

Lighting design including proper selection of luminaires suitable for the each particular application (environment, optical properties etc.), placement of the luminaires and their orientation in space, relevant lighting calculations, evidence of fulfiling the standards, cost analysis, assessment of energy performance and a number of other important parts is a sophisticated process of paramount significance in the stage of building construction design and later in the stage of usage, it determines the quality of lighting as well as operational conditions. Results of the design must be therefore well documented for the future reference and also for operational purposes. And not only results must be documented – all the input data and assumptions must be clearly indicated so the quality of design can be later assessed or even reproduced. Having in mind that results are valid only if the assumptions are satisfied during common operation of lighting systems.

Role of lighting design documentation and its importance is evident. However, up to now there is yet no generally agreed and accepted form of creation of such an important documentation. In result, documents prepared by lighting designers often lack even the basic components like e.g. determination of the mainetenance factor (all the details required like specification of individual components, assumptions, environmental conditions, maintenance plan etc.), reflectance of main surfaces, position and size of task area / immediate surrounding / background area, assumptions for UGR and many others. This is a common practice throughout Europe...

Lack of standard or recommendation in this field is identified in the technical committee CEN/TC 169 Light and Lighting as one of the priorities in its road map for standardization. First efforts in the committee already started-up, the topic is opening a new work item in standardization designated as prCEN/TS 17165 "Lighting System Design Process", i.e. a technical specification under preparation. Aim of this paper is to support the standardization activities and to contribute with knowledge and experience gained during years of designing different types of lighting systems. It is expected that future works will be performed in order to study different aspects of the documentation process, focused on outputs of this process. Lighting design process (i.e. not only the documentation) should be also the subject of standardization, but this is not dealt in this paper.

CURRENT REQUIREMENTS OF EUROPEAN STANDARDS

Current European standards specify only limited number of explicit requirements to documentation of lighting design. They are summarized in Table I. Besides there are some other requirements for lighting design as a process, but these do not concern the documentation.

To have a specific standard on lighting systems design documentation is important to provide a framework for lighting designers. On the other hand, application standards (like e.g. EN 12464-1, EN 13201-3 etc.) should keep the room for specific requirements to documentation of lighting design.

LIGHTING PROJECT IN AN OLDER SLOVAK STANDARD

An older national Slovak standard STN 36 0450:1986 “Artificial Lighting of Interiors” (official English title “Electric Interior Lighting”) provided quite detailed requirements to lighting design documentation. It is a shiny example of how such requirements may look like and it is also an evidence that such requirements are important in practice of lighting systems designing. This standard is not in use anymore, it was (although not fully) superseded by modern European standards in 2011. Hereby we show excerpts of this standard as example for future standardization purposes.

TABLE I. OVERVIEW OF NORMATIVE REQUIREMENTS TO DOCUMENTATION OF LIGHTING DESIGN

Standard(s)	Paragraph	Requirement
EN 12464-1	4.3.3	The size and position of the task area should be stated and documented.
EN 12464-1	4.3.4	The size and position of the immediate surrounding area should be stated and documented.
EN 12464-1	4.3.5	The size and position of the background area should be stated and documented.
EN 12464-1	4.5.2	All assumptions made in the determination of UGR shall be stated in the scheme documentation.
EN 12464-2	4.4.2	All assumptions made in the determination of R_G shall be stated in the scheme documentation.
EN 12464-2	6.6	The maintenance schedule shall be provided and shall be based on the results from the calculations
EN 12464-1 EN 12464-2	4.10 4.9	The designer shall: – state the maintenance factor and list all assumptions made in the derivation of the value; – specify lighting equipment suitable for the application environment; – prepare a comprehensive maintenance schedule to include frequency of lamp replacement, luminaire cleaning intervals and cleaning method
EN 12193	4	Data to be provided (*full chapter*)
EN 13201-5	Annex D	Presentation of energy performance indicators (*full annex*).

The standard STN 36 0450 defined two basic qualifications in lighting engineering:

- **Lighting Designer** – person responsible for lighting part of a project documentation
- **Lighting Operator** – person responsible for the good condition and operation of lighting systems

The standard did not specify more detailed description nor requirements to these qualifications. It is important to note that lighting designer is identified as a person competent in making the lighting design. However, lack of more specification led to the situation when most of lighting designs were made (and still are made) by electrical engineers with very limited background in photometry and limited knowledge of the light and lighting field (including knowledge of valid standards, current technologies etc.) what is necessarily reflected in the quality of lighting desing, not talking about the documentation. It is then often missing in the complex documentation, lighting solution often reduced to one-two sentences within the documentation of electrical installation or in better cases just attached as output copy from a lighting software without a number of important parts.

Requirements to lighting design documentation (in the standard also mentioned as “lighting project”) are stated in the paragraph 2 with general requirements to interior lighting and then in more details in specific paragraph 4. General requirements are as follows:

- **Erection and reconstruction of lighting systems:** Lighting systems shall be erected or reconstructed only in comply with approved project documentation except of local lighting and minor modifications of lighting systems performed in the framework of ordinary maintenance. Lighting designing organizations shall have their own lighting designer.
- **Basic requirements to lighting design:** Lighting design documentation shall contain data determining the scope and operational features of lighting and lighting systems including particular requirements to service and maintenance of lighting systems and their technical equipment. Scope of the project documentation and its extent in accordance with the complexity of lighting task shall be regarded.

Requirements of specific paragraph 4 on lighting design are as follows:

- **General requirements:** Lighting systems shall be designed so that they can be operated and maintained. Requirements to effectiveness of installation and operation of a lighting system shall be regarded. Design of artificial lighting shall be coordinated with the architectural and constructional design of a building, its daylighting and inside equipments. Determination of the manner and basic technical means for maintenance of lighting systems is an indispensable part of the lighting design.
- **Inputs for the design:** Lighting design shall be based on inputs provided for lighting designer, in particular as follows:
  - information on the character and utilization of the rooms or premises
  - constructional drawings
  - placement of the furbishment, technological equipments etc.
  - environmental conditions having impact on the lighting equipment
  - information on surfaces of the rooms, premises or their inside content
  - information on daylight availability or a daylighting project
  - maintenance options and possibilities

  - special requirements on the lighting system

- **Elaboration of the lighting design:** Design of artificial lighting shall be verified by calculations or comparison with similar solutions already verified by measurements. For type solutions conditions of validity shall be checked. Calculated values are deemed as satisfactory if they do not differ from required values by more than ± 5 %.
- **Documentation of lighting design:** Documentation of lighting design shall be in accordance with the stage of the project and the complexity of the lighting task. In the final project stage (project for realization) the required range of documentation shall be at least according to the Table II. Drawings can be completed by additional diagrams if necessary, e.g. details of mounting, orientation of luminaires etc. In simplified documentation placement of luminaires can be substituted by coordinates of the luminaires. It is also necessary to indicate the selected visual task places and assumed directions of sight for assessment of glare. For rooms or premisses where in parts of the space different requirements apply, the zoning shall be provided within the drawings.
- **Contents of the lighting design documentation:** Documentation shall comprise technical information and data on: input materials, light sources, luminaires, maintenance factors, maintenance processes, requirements to surface finishes of the premises, requirements to electrical circuits (separation of lighting circuits, phasing of individual luminaires, lighting controls etc.), auxiliary – safety – emergency lighting (if applicable)

The Table II refers to 4 lighting category classes which are used throughout the standard. For comprehense of Table I, lighting categories A to D are defined by Table II and roughly correspond to human needs described e,g, in the standard EN 12464-1 (paragraph 4.1 on luminous environment).

TABLE II. REQUIREMENTS TO THE CONTENTS OF LIGHTING DESIGN DOCUMENTATION

Documentation	Information / Data	Lighting category			
		A	B	C	D
Required lighting parameters in individual rooms and premises	Illuminance on working plane	+	+	+	+
	Illuminance in selected places of visual task	+	+	–	–
	Mean hemispherical illuminance	–	(+)	–	(+)
	Glare prevention	+	+	+	(+)
	Uniformity of illumination	+	+	+	(+)
	Luminance distribution	+	+	–	(+)
Economical analysis	Economical indicators	+	+	+	+
Drawings	Placement of luminaires Placement of check points at the places of visual task	+	+	–	–

+ required, (+) reccomended, – not required

TABLE III. LIGHTING CATEGORIES

Lighting category	Activity	Priorities of lighting criteria
A	High demands on visual performance	1. Visual performance 2. Visual comfort
B	Average demands on visual performance	
C	Low demands on visual performance	
D	Priority requirements to the perception of space, shape and colours	1. Visual comfort 2. Visual performance

Most of the above mentioned requirements are still actual and in good accordance with the set of current European normative documents. Note that the standard STN 36 0450 is dated back to 1986 when lighting calculations were performed mostly by means of calculators and simplified methods. Requirement to deviation of ± 5 % is disputable; today, minimum requirements should be fulfiled with zero negative tolerance and on the other side motivation not to overlit is given by energy performance requirements (EN 15193) and consequent economical analyses of the designed installation. It can be concluded that the requirements of STN 36 0450 are still applicable and they can be extended.

PROCESS OF LIGHTING DESIGN DOCUMENTATION AND QUALIFICATION OF LIGHTING DESIGNER

Process of lighting design in general and process of lighting design documentation in particular are very important for getting a common standard basis. This is, however, out of the scope of this paper. At least we provide an outline proposal on flowchart of the lighting design process as follows bellow. This chart will need further improvements and detailization of the items.

- Identification of the lighting task
- Lighting audit (if applicable – e.g. for refurbishment of existing lighting systems)

- Framework solution (determines the further steps – e.g. extent of data collection)
- Data collection (gathering all the necessary inputs for lighting design)
- Lighting design solution (essential part of the process, including interim economical outputs)
- Coordination with other sub-systems (feasibility of the design from technical point-of-view)
- Iterative modifications of the design (upon coordinations and approvals)
- Documentation (preparation of a formal documentation)
- Approval (formal approval of the documentation and its acceptance)
- Following processes: realization, commissioning, operation and maintenance

Qualifications in lighting engineering is yet another important topic that needs a common standard basis. First of all it is necessary to avoid incompetent lighting designs. Education of lighting engineers (and other competent persons in the field of light and lighting) is somehow different throughout Europe but it is possible to define minimum requirements to curricula in terms of contents (i.e. subjects and their composition) and hours of study (lectures and trainings). An outated technical report CIE 99:1992 "Lighting Education" dealt with a comparative study of education in lighting worldwide, update of this document would help to define qualifications in lighting. Education of lighting engineers in Slovakia is published in [9].

Brief qualification scheme of competent persons in lighting as proposed is presented in Table IV. The table does not specify curricula of education for the reasons mentioned above. Minimum level of education and minimum years of experience are given in the table instead. It is expected that the qualified persons will have proper professional education in lighting to fulfil the competence stated in the right-most column of the Table IV. Required minimum years of experience are to be discussed and agreed in a broad professional society.

Senior lighting consultant (expert) stands at the top of the qualification chart. This top-level professional should act independently from manufacturers of lighting products and providers of lighting services. Lighting professionals employed at manufacturers, service providers, sellers etc. who provide assistance for products and services can be found under the qualification Lighting assistant. Lighting designer is a person competent for making the lighting design, ideally as an independent subject. Lighting engineer is a practically oriented person who should have broad complex knowledge on all questions relevant to operation and maintenance of lighting systems, although the knowledge need not to be deep. Lighting engineer approximately corresponds to the qualification Lighting operator according to the standard STN 36 0450. Lighting technician is a person to install the lighting system (both mechanical and electrical parts) and/or able to perform common operational and maintenance working tasks.

Lighting designer can be one of two kinds as it is usually recognized in practice:

- **Architectural lighting designer** – normally an architect (seldom electrical engineer) who makes the design where light plays a central role and the illumination is the final product. The focus is on aesthetics of perception and visual comfort.

- **Technical lighting designer** – normally an electrical engineer (or similarly qualified person) who cares in first order on satisfying requirements of technical standards and depending on lighting task the focus can be given to visual performance or visual comfort.

TABLE IV. QUALIFICATION SCHEME OF COMPETENT PERSONS IN LIGHTING

Qualification	Minimum level of education	Years of experience	Competence
Senior lighting consultant (expert)	PhD.	10	To provide professional advice and expertise on the highest level Lighting concepts, Lighting masterplans
Lighting consultant	Master degree	10	Lighting audits (authorized) Energy certification in lighting (authorized)
Lighting designer	Master degree	5	Lighting project (authorized) Lighting design
Lighting assistant	Master degree	3	Assistance on lighting products and services Lighting advisor
Lighting engineer	Bachelor degree or high-school	3	Operation and maintenance of lighting systems (as supervisor) Management of the installation of lighting systems
Lighting technician	high-school or vocational training	–	Mechanical and electrical installation of lighting systems Technical operation and maintenance of lighting systems

Architectural lighting designers are associated in two international organizations: **International Association of Lighting Designers (IALD)** and **Professional Lighting Designers Association (PLDA).** IALD and PLDA are the main authorities regarding lighting design in architecture.

The Table IV is not closed and other qualifications can be added. For example, the table does not specify persons competent in measurement of lighting products (laboratory) and lighting parameters (verification) and others.

Proposal on structuring the lighting design documentation

Framework proposal on basic structure of the lighting design documentation is in Table V. The table is open-ended and can be extended as necessary. The table can be also completed by e.g. specification of which item is compulsory or voluntary, what kind of documentation it refers to etc. Coding in the table is expected to help to find quickly the necessary information when seeking in larger documents. Further development of this table needs some additional research works.

TABLE V. PROPOSED STRUCTURE OF LIGHTING DESIGN DOCUMENTATION

Code	Sub code	Category	Sections
01	00	Identification	**Identification:**
	01		Name of the object
	02		Address of the object
	03		Contractor (name, address, person(s) in charge)
	04		Lighting designer (name, ID number if applicable, signature)
	…		Summary figures
02	00	Methods	**Methods:**
	01		List of instruments for gathering inputs (if applicable)
	02		Design methods applied (brief description)
	03		Calculation methods used
	…		Calculation software used
03	00	Inputs	**Inputs:**
	01		List of all materials and documentation provided or made available to lighting designer
	02		Description of the current lighting system (if applicable)
	03		Description of the premises and/or lighting task (if necessary)
	04		Design values of lighting parameters (normative or agreed with contractor)
	…		Technical data on light sources and luminaires
	…		Technical data on rooms and premises (incl. dimensions, reflectances, environment)
	…		Determination of the maintenance factor incl. all its components and assumptions
04	00	Outputs	**Outputs:**
	01		Description of the lighting solution
	02		Calculated basic (compulsory) lighting parameters (event. deviation from design values)
	03		Calculated additional (voluntary) lighting parameters
	04		Calculated energy performance indicators
	…		Coordinates of the placement and orientation of luminaires
	…		Lightplan with placement of luminaires in individual rooms/premises
	…		Isolux and/or isoluminance diagrams
	…		Instructions for mounting of luminaires
	…		Instructions for electrical wiring of luminaires
	…		Instructions for commissioning and operation of the lighting system
	…		List of luminaires and lighting equipment with or without pricing
	…		Economical calculations
	…		Detailed maintenance plan
05	00	References	**References:**
	01		List of legislative documents used for the lighting design
	02		List of relevant technical standards used for the lighting design
	03		List of technical reports and other normative and semi-normative documents
	…		List of all other bibliography used for the lighting design
06	00	Annex	**Annex:**
	…		Footprints of the building or site

Conclusions

As shown in this paper, the topic of lighting design and all the related problems like qualification of competent persons, documentation of lighting design etc. should be well studied and systematized. Normative requirements should be then specified afterwards. Having a common regular basis for the process of lighting design it makes it easier to handle in practice with documents of satisfactory professional level prepared by qualified persons. This paper is intended to contribute to the problems of lighting design; it is evident that future works in this field will be needed.

References

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[3] *Light and lighting. Lighting of work places. Part 2: Outdoor work places, EN 12464-2:2014*, 2014.
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[6] *Road lighting - Part 3: Calculation of performance, EN 13201-3:2015*, 2015.
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[8] *Lighting Education, CIE 99:1992*, 1992.
[9] D. Gasparovsky, R. Dubnicka, T. Novak and J. Skoda, "Education of lighting technology in Slovakia and Czech Republic,". In Proc. 28th CIE Session 2015, ISBN 978-3-902842-55-8, pp. 1026-1035.

Hauptstrasse von Waldenburg (CH) "Eine nicht alltägliche Lösung"

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GESCHICHTLICHE BETRACHTUNG

Die Ortschaft Waldenburg liegt auf der früher sehr bedeutenden Verbinndungsachse Bern – Basel. Für das Mittelalter sehr klassisch wurde die Ortschaft durch eine Ringmauer geschützt. Zwei bewachte Tore sorgten für einen kontrollierten Zutritt und dienten auch zum Erheben von Wegzöllen.

Bild 1 Historische Ansicht von Norden. *(www.archäologi.bl.ch)*

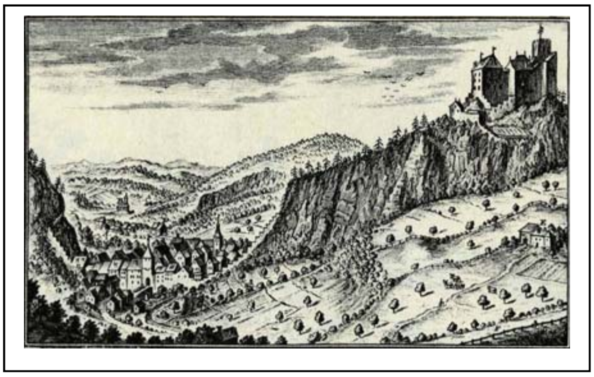

Bild 2 Historische Ansicht von Süden. *(www.swisscasteles.ch)*

Durch die beiden Tore wurde auch die Hauptdurchfahrt definiert. So gab es eine klare Gliederung des Raums innerhalb der Stadtmauern. Die Gassen parallel zur Hauptgasse wiesen eine untergeordnete Funktion auf. Die neue Verkehrsführung, ist darauf bedacht den Verkehr direkt durch Waldenburg zu lenken. Die parallelen Gassen werden nicht oder nur teilweise wahrgenommen.

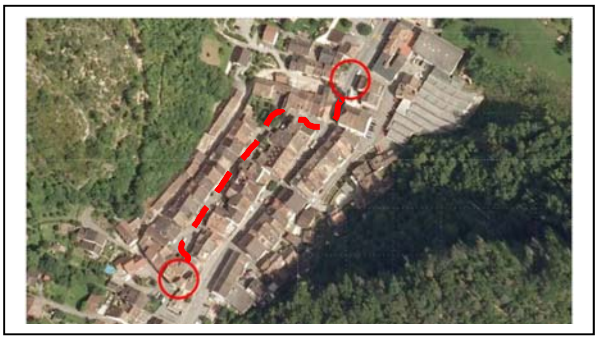

Bild 3 Historische Durchfahrtsachse. *(Quelle: Google-Maps)*

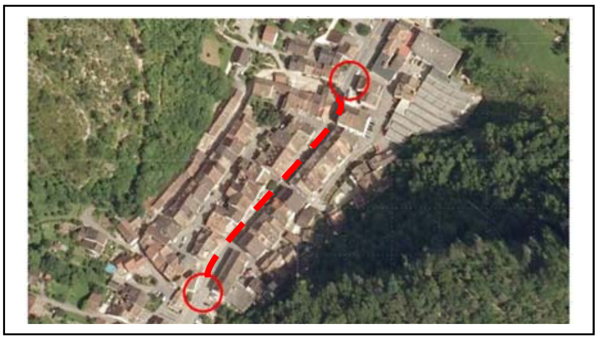

Bild 4 Aktuelle Strassenführung. *(Quelle: Google-Maps)*

Die Sanierung der Ortsdurchfahrt verfolgte das Ziel, die Geschwindigkeit der Fahrzeuge zu bremsen und den Passanten eine höhere, räumliche Aufenthaltsqualität zu bieten. Ergänzend zu den verkehrsberuhigenden Massnahmen beabsichtigte die Bauherrschaft und der gestaltende Architekt eine Sanierung der bestehenden Beleuchtungsanlage. In einer ersten Phase wurde dann ein Beleuchtungskonzept erstellt, welches sich auf die Hauptstrasse konzentrierte. Die gewählte Lösung lehnte sich an der alten Beleuchtung an, welche mit Seilpendelleuchten den sehr engen Strassenraum beleuchtete. Neu sollten LED-Leuchten mit einer zeitabhängigen Steuerung zum Einsatz gelangen. Auf Wunsch des Architekten sollte ergänzend zu der rein funktionalen Lichtlösung eine gestalterische Aufwertung des Raums mittels Licht erfolgen.

Gestaltungskonzept

Um ergänzend zur geplanten Sanierung der bestehenden Strassenbeleuchtung ein Konzept zu erarbeiten, war eine umfangreiche Analyse mit Begehungen bei Tag und Nacht, sowie der historische Kontext von sehr grossem Nutzen. Wir stellten entlang der Durchfahrtsachse eine starke, räumliche Divergenz zwischen dem Tag- und dem Nachtbild fest. So sind die Durchgänge in der Nacht nur schlecht wahrnehmbar und die räumliche Struktur wirkt sehr flach.

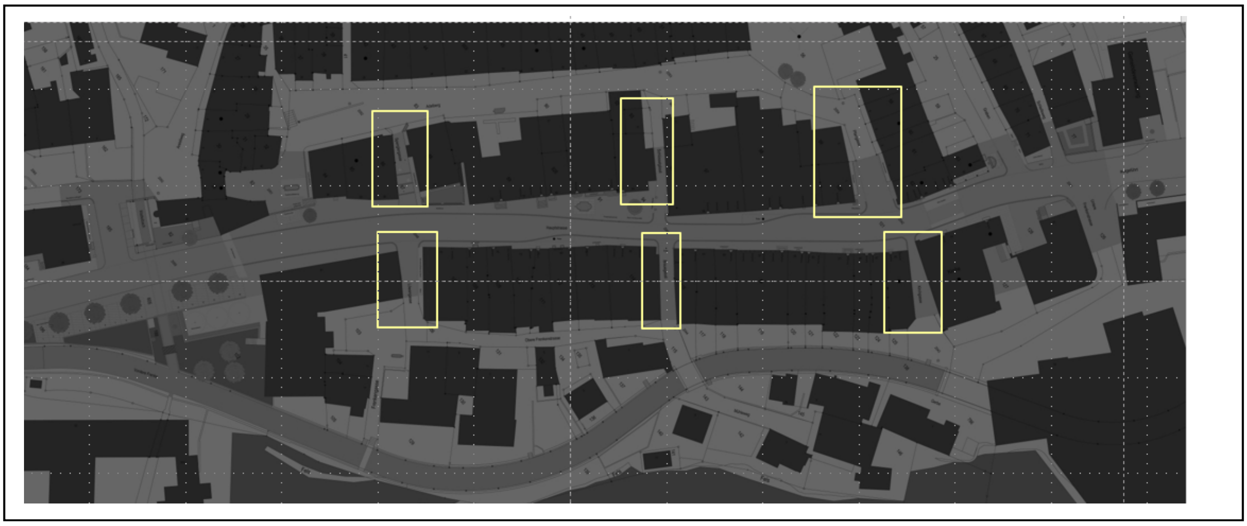

Bild 5 Darstellung der Durchgänge. *(Grafik: art light GmbH)*

Es galt, das technische Konzept mit den Seilpendelleuchten zu stärken. Die Konzeptidee basiert deshalb in erster Linie darauf, die in der Analyse festgestellten Defizite zu korrigieren. Als erste Massnahme sollte mit einer gezielten Anstrahlung der beiden ehemaligen Zugänge dem Betrachter die Geschichte sichtbar gemacht werden. Mit dem Hervorheben der Durchgänge und einzelner Hausecken soll die räumliche Gliederung erlebbar gemacht werden. Um die Qualität der teilweise neu geschaffenen Aufenthaltsbereiche zu fördern, war angedacht dies mit Licht zusätzlich zu steigern.

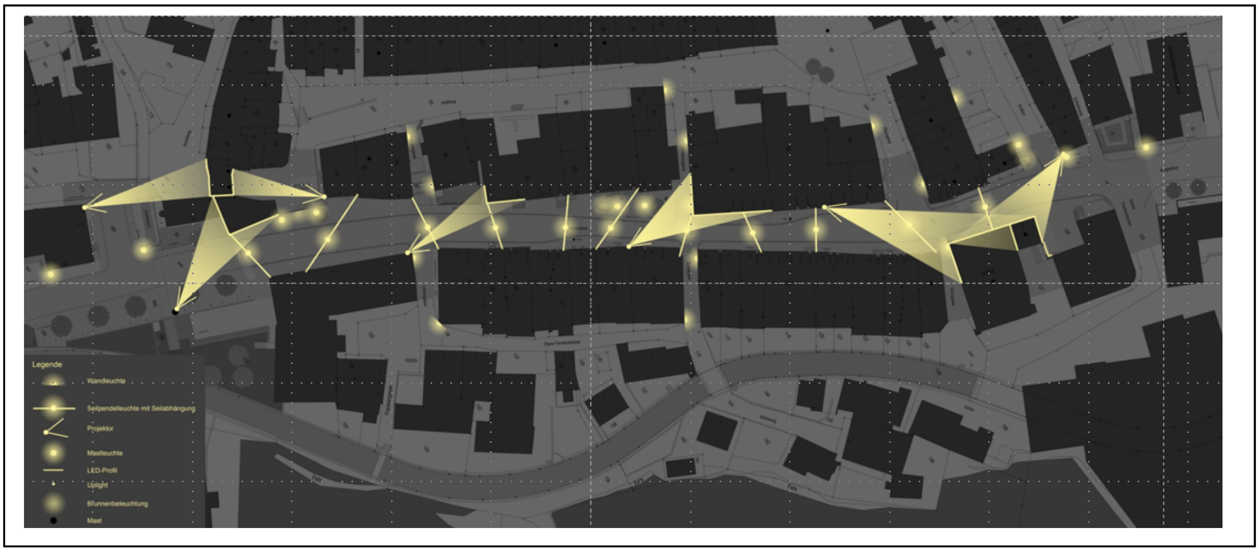

Bild 6 Übersicht Beleuchtungskonzept. *(Grafik: art light GmbH)*

Umsetzung

In der Umsetzung wurden die alten Seilpendelleuchten durch neue LED-Seilpendelleuchten mit einer warmweissen Lichtfarbe (3000K) ersetzt. Damit die geforderte Gleichmässigkeit erreicht werden konnte, mussten teilweise die Seilaufhängungen versetzt und zwei zusätzliche Leuchten installiert werden. Für die Anstrahlung des oberen Tors und der Kirche wurden Gobo-Projektoren, die mit HIT 150W -Lichtquellen bestückt sind, eingesetzt. Als Lichtfarbe wurde ebenfalls 3000K gewählt. Alle Maskierungen wurden so definiert, dass die Lichtimmission so gering wie möglich sind.

Bild 7 Ausschnitt Gobo-Projektion für das obere Tor. *(Grafik: art light GmbH)*

Die Durchgänge werden neu mit zusätzlichen Wandleuchten sichtbar gemacht und sorgen für das Wahrnehmen der räumlichen Tiefe. Die Gliederung innerhalb des Strassenraums erfolgt ebenfalls mit Gobo-Projektoren. Die Projektoren wurden dabei diagonal im Strassenraum angeordnet. Es konnte so eine, für die Fahrzeuglenker (insbesondere der LKW-Fahrer), blendfreie Anstrahlung der Gebäude erreicht werden. Bei den neu geschaffenen Aufenthaltszonen kommen Lichtstehlen mit einer geringen Lichtpunkthöhe von 3.5 Meter zum Einsatz.

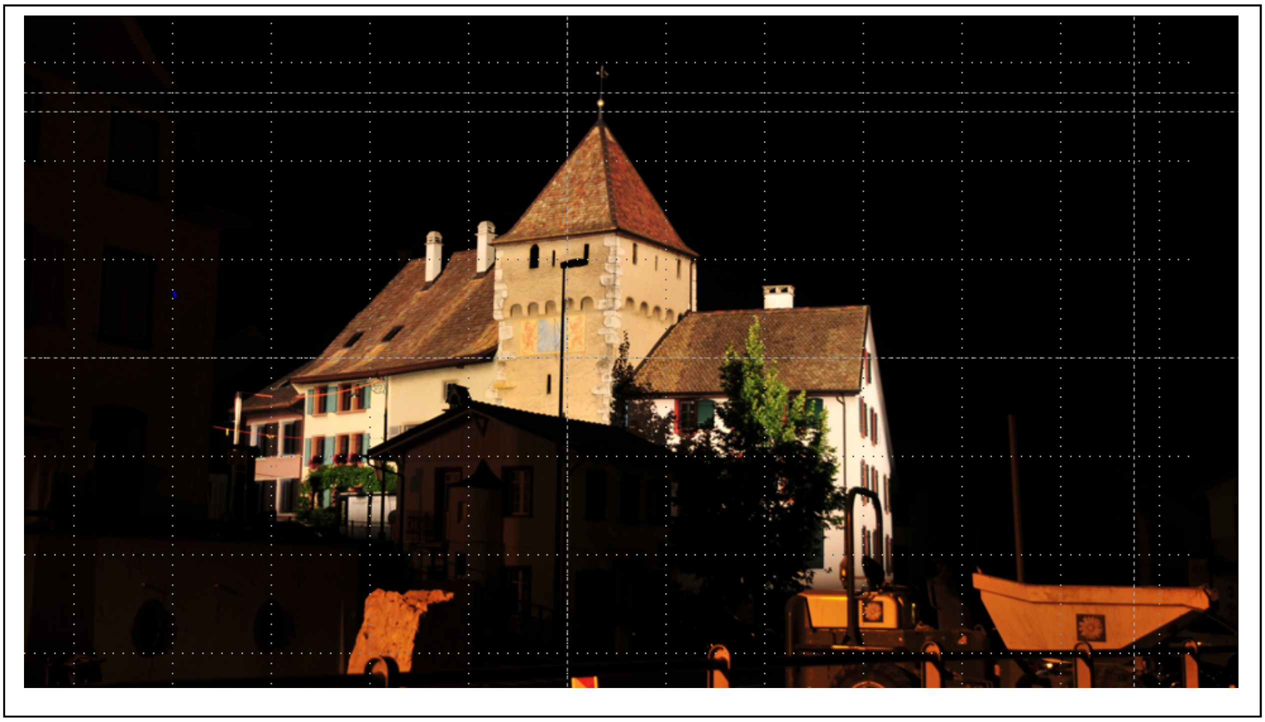

Bild 8 Testprojektion während dem Aufbau. *(Bild: art light GmbH)*

Fazit

Objekte müssen nicht immer theatralisch in Szene gesetzt werden. Oft kann ein viel grösserer Mehrwert geschaffen werden, wenn man sie möglichst natürlich erscheinen lässt. Durch die Definition der Farbtemperatur kann man allerdings beeinflussen, ob ein Platz eher alt und abweisend oder einladend wirken soll. Heute erscheint der historische Ortskern von Waldenburg in seiner ganzen bisher kaum wahrgenommenen Pracht. Der Ort hat nicht nur seine Identität wiedererlangt, sondern auch an Sicherheit und Lebensqualität gewonnen. Dies zeigt sich im Verhalten der Bewohner, welche teilweise wieder begonnen haben ihre Häuser zu renovieren und die Fassaden zu streichen.

Bild 9 Umsetzung Ortsdurchfahrt Waldenburg (CH). *(Bild: EBL)*

Multi-Variable Light Distribution in Road Lighting Increases Safety and Reduces the Energy Demand

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Abstract—**An adaptive light distribution gives a lot of new possibilities to create better safety with less energy. The big question is: how can we design such a development process? The following contribution will help to understand the possibilities and the challenges for the municipalizes, the lighting designer and the industry. The focus of the discussion is on the replacement of luminaires.**

***Index Terms*— Energy demand, Light immission, Multivariable light distribution, Road lighting, Replacement, Traffic safety**

CURRENT LY DESIGN PROCESS – RESPONSIBLE FOR LOW LIGHT QUALITY, LIGHT UNNECESSARY LIGHT IMMISSION AND WAST OF ENERGY

In many cases the product of necessary illuminance for the road class and the lit road area is determined and compared with the luminous flux of luminaires provided by a manufacturer catalog. With only little experience about the matching light distribution a potentially correct luminaire is chosen. Reasons for this simple process are the low limits for luminance homogeneity and the missing photometric inspection after installation.

Because of this bad design process, the consequences are 'over lit' roads with a lot of stray light on the facades, glaring luminaires or roads with non-satisfying luminance homogeneity. Figure 5 and Figure 6 show such an example. The luminaires were replaced. But the light quality – specially the homogeneity - is worst, then before.

Figure 5: Traditional illumination of a road with High Pressure Sodium Lamps

Figure 6: Replacement with LED-Luminaires

Figure 7 and Figure 8 demonstrate the differences on facades. If the reduction of light on the facades is a quality figure, then it is easy to realize this quality, like the luminance pictures illustrate.

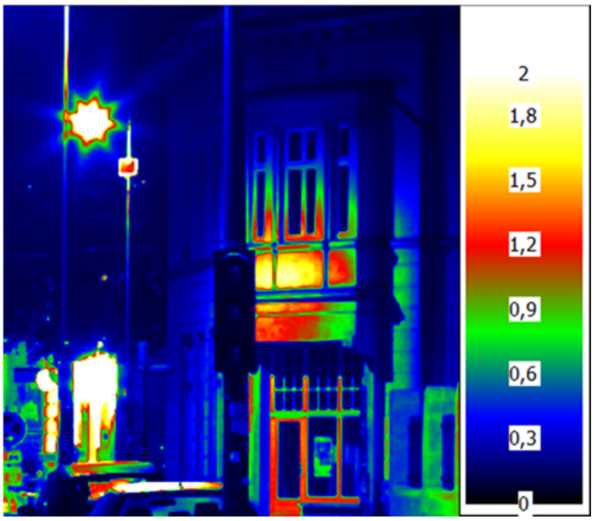

Figure 7: Traditional illumination of a road with High Pressure Sodium Lamps

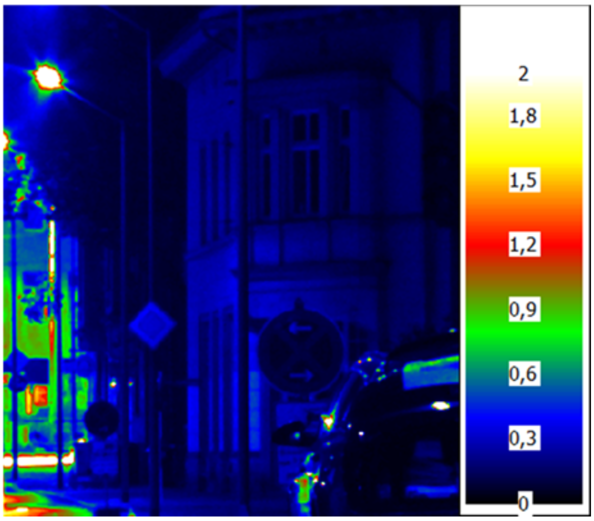

Figure 8: Illumination with adapted optic in a LED luminaire

Today a lot of our cities in Europe are very bright[1]. Schipluiden (Nederland's) is 10.000 times brighter comparable with Kitt Peak in the USA. Berlin is 330 times brighter for cloudy weather comparable the Island Schiermonnikoog in the North Sea. Chrono biologists warn, that the circadian rhythm is destroyed by too much light in the night. The light in our sleeping rooms should be limited to improve the sleeping quality. Recommendations exists from the CIE, see TABLE . The shown values are not scientific proved and probably to high.

TABLE I: MAXIMUM PERMITTED VALUES OF AVERAGE SURFACE LUMINANCE [CIE 150, TABLE 2.6]; E1NATIONAL PARKS OR PROTECTED SITES; E2 INDUSTRIAL OR RURAL AREAS, E3 INDUSTRIAL OR RESIDENTIAL SUBURBS, E4 TOWN CENTERS AND COMMERCIAL AREAS

Light Technical Parameter	**Application Conditions**	**Environmental Zones**			
		E1	**E2**	**E3**	**E4**
Building Facade Luminance (L_b)	Taken as the product of the design average illuminance and reflectance factor divided by π.	0 cd/m²	5 cd/m²	10 cd/m²	25 cd/m²

But it is not only a problem, that we 'lost of the night'. A lot of energy is wasted, which has been produced and transported. For the illumination of roads in Germany is needed 4 Billion Kilowatt-hours per year (equal to 2 Mio tone CO_2), see TABLE .

TABLE II: DEMANDS AND COSTS OF ENERGY

	Berlin	**Germany**
Luminaires in 1000	224	9100
Demand of Energy in Mio kWh	90	4000
Emission CO_2 in 1000 t	45	2000
Operating costs in Mio €/year	24	1000
Costs of Maintenance in Mio €/year	12	500
Potential of saving Mio €/ year	9,1	400

This money should be used for a better design process to reduce accidence, improve sleeping quality and safe the night.

[1] Hölker, et al: Lost of the night. Final report for the BMBF, March 2015

COMPARISION OF DIFFERENT DESIGN PROCESSES

In the follow section, the best standard light from the catalog should be compare with an optimized light distribution for a standard road section.

A. Geometry of road and positions of luminaires

TABLE , Figure 9 and Figure 6 illustrate the used road with the positions of luminaires for the simulations.

TABLE III: KEY DATA OF THE GEOMETRY FOR THE SIMULATED LIGHTING SYSTEM

Pole distance a:	60 m
Road width b:	9 m
Pole high h:	12 m
Overhang u:	1 m
TILT δ:	0 °
Side walk width per side:	3 m

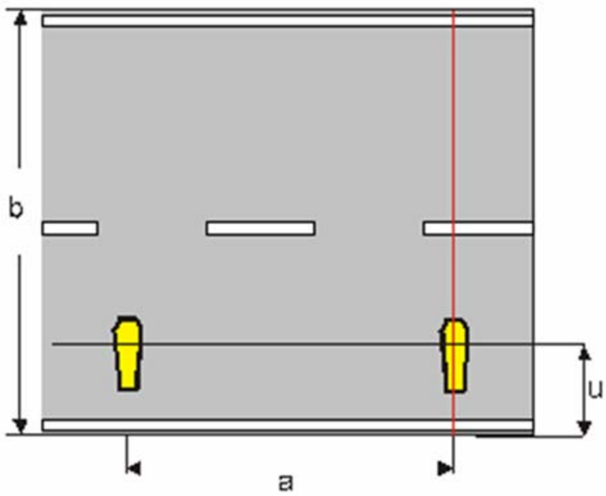

Figure 9: Traditional illumination of a road with High Pressure Sodium Lamps

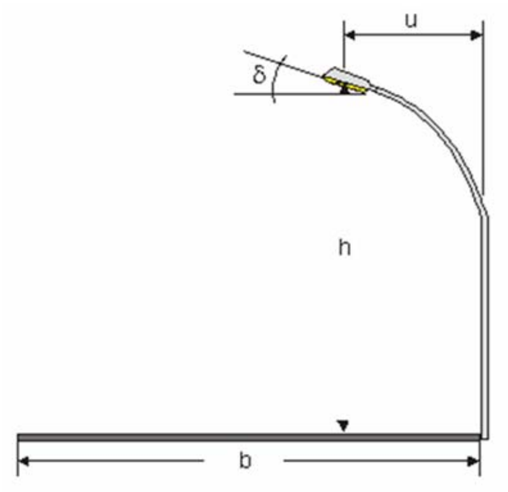

Figure 10: Illumination with adapted optic in a LED luminaire

a. Standard design process for replacement with standard products

The standard EN-DIN 13201describs the quality features for a given street lighting class ME3:

L_{ave} = 1 cd/m^2, U_0 = 0.4, U_l = 0.7, TI = 15, SR_{old} = 0.5, SR_{new} = 0.3.

Calculation of the luminous flux needed:

$$\Phi = E_{h,ave} \cdot A_F \quad (1)$$

Φ: luminous flux
$E_{h,ave}$: average of horizontal illuminance on a reference surface
A_F: evaluated area for the lighting system

Step 1: Identification of corresponded road classes

- CE3 class requirement as the equivalent illuminance class for the ME3 (EN 13201): $E_{,h,ave}$ = 15 lx

Step 2: Assessment field area A_F

- calculation with the values from the TABLE : 9 m · 60 m = 540 m^2
- Surrounding field area: 6 m · 60 m = 360 m^2

Step 3: Calculation of formula (1)

$$\Phi_{old} = E_{h,ave} \cdot A_F = 15\ \text{lx} \cdot 540\ \text{m}^2 + 15\ \text{lx} \cdot 0.5 \cdot 360\ \text{m}^2 = 10800\ \text{lm} \quad (2)$$

$$\Phi_{new} = E_{h,ave} \cdot A_F = 15\ lx \cdot 540\ m^2 + 15\ lx \cdot 0.3 \cdot 360\ m^2 = 9720\ lm \qquad (3)$$

Step 4: Selection of fit luminaire with a specific luminance distribution (for instance Figure **12**).

b. Optimized lighting distribution

Aim: light distribution curve with minimum luminous flux and maximum of homogeneity
Restriction for the simulation: L_{ave} for ME3 with R3 or W4, permissible limits (EN 13201): U_0, U_l, TI,

Figure 11 illustrates the graphical user interface (GUI) of the Matlab program for optimizing of lighting distribution curves.

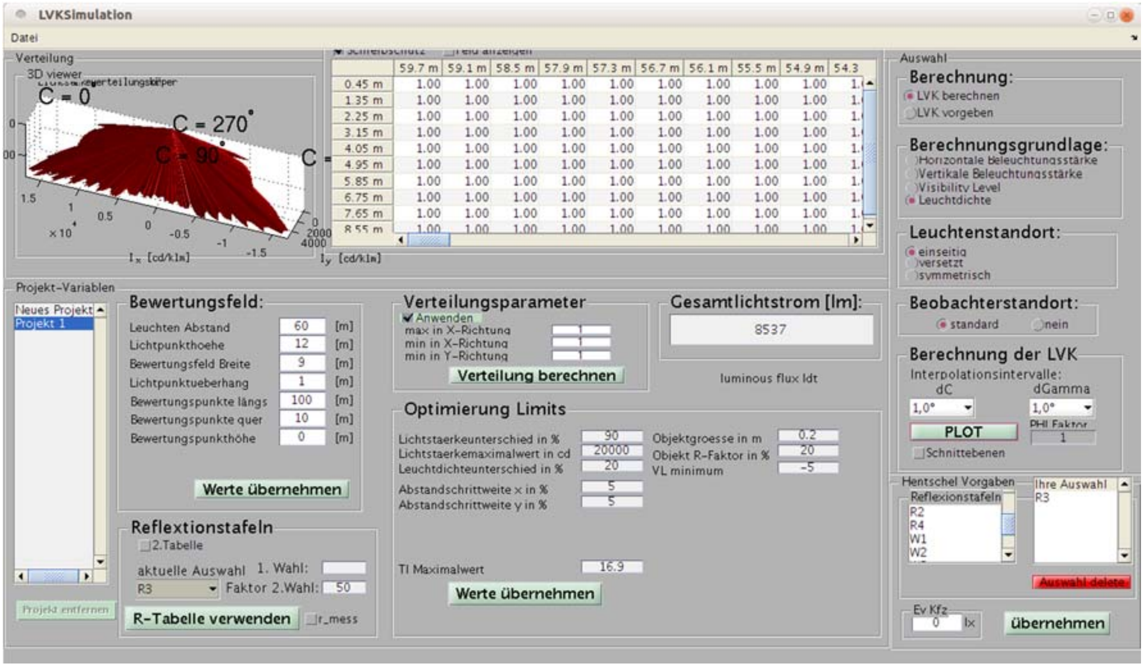

Figure 11: An example for the graphical user interface for optimization of lighting distribution curves

c. Results

The Figure 12 presents the usual used light distribution curve of a very good standard luminaire comparable with the optimal light distribution based on the simulation – see Figure 13. Figure 14 demonstrates an optimal asymmetric light distributions for a better visibility for one-way-lanes.

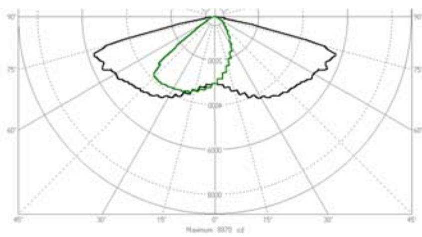

Figure 12: Usual used –light distribution curve

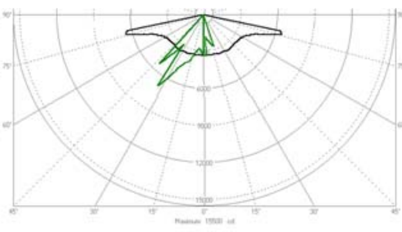

Figure 13: Optimal solution symmetric

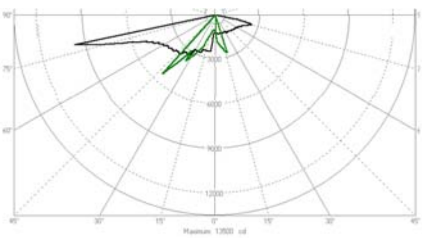

Figure 14: Optimal solution asymmetric

All three light-distribution reveal very clear differences. The results are summarized in TABLE .

TABLE IV: OVERVIEW ABOUT THE RESULTS AND THE SAVINGS USING THE OPTIMIZATION OF LIGHT DISTRIBUTION

	luminance flux needed for CE3	Usual used –light distribution curve	Optimal solution symmetric	Optimal solution asymmetric
Luminance flux (new EN)	9720 lm	13781 lm	8000 lm	6200 lm
Saving			42 %	55 %
Luminance flux (old EN)	10.800 lm	13781 lm	9600 lm	7800 lm
Saving			30 %	43%

The first column presents the calculated values after the simple design process according to equation (1)-(3). The second column gives the necessary values for a real luminaire, what fulfil the standard requirements. The 3rd and 4th columns show the necessary luminance flux from the simulation. The saving potential is based on the usual used light distribution curve.

One interesting point is, that the demand for the optimal solution with 8000 lm is lower than the calculated luminance flux from the simple design process. The reason for this result is based on the flat viewing conditions for the luminance (1°) and the reflection characteristics. It is obviously, the potential for energy saving is very high!

ADAPTED LIGHT DISTRIBUTION FOR DIFFERENT SURFACES

Furthermore, a high potential is based on the correct consideration of road surface. It is general known, that the necessary contrast is depending on the luminance of the road and the object. The luminance of the road is mainly dominated by the distribution of reflection in different angles, see Figure 15. Every surface has its own distribution of luminance factor q. In consequence, every road surface needs its own light distribution, which is optimized by the special reflection characteristic.

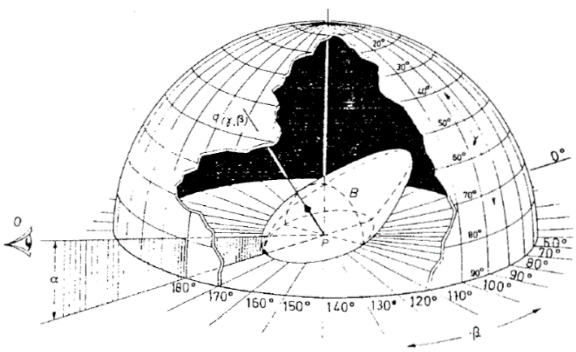

Figure 15: Reflection of a road surface [CIE TR 66]

The following figures show the necessary light distribution for optimal illumination for different surfaces.

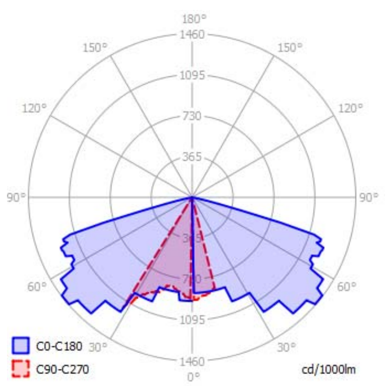

Figure 16: light distribution curve optimized for cobblestone

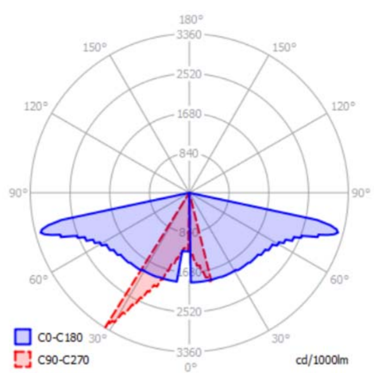

Figure 17: light distribution curve optimized for R3-Table

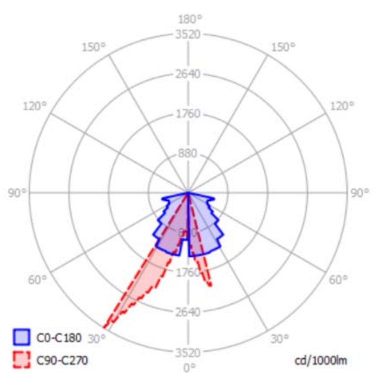

Figure 18: light distribution curve optimized for W2-Table

A standard LVK can supply only a suboptimal result.

ADAPTED LIGHT DISTRIBUTION FOR DIFFERENT WHEATHER CONDITIONS

Figure 19 shows the luminance distribution of a simulation for an optimized light distribution based on a R2-Table. If This light distribution is used for a wet road, then luminance distribution changes to Figure 20.

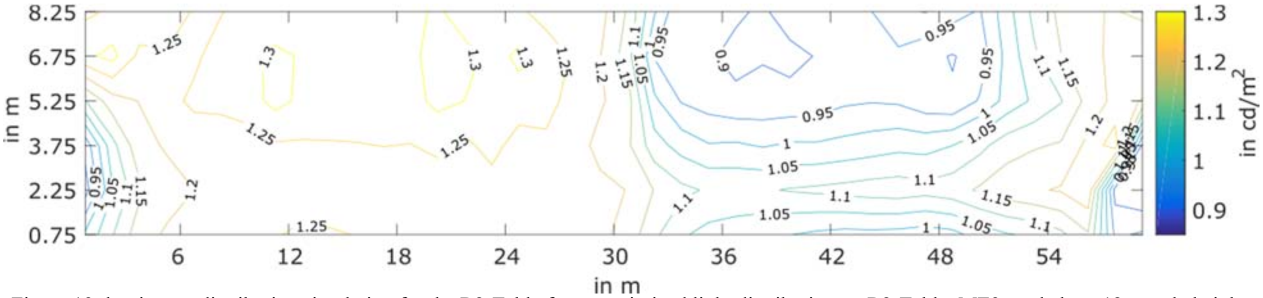

Figure 19: luminance distribution simulation for the R2-Table for an optimized light distribution on R2-Table, ME3 road class, 12 m pole height, 1 m overhang. Solution: L_{min}=0.85 cd/m², L_{max}=1.32 cd/m², L_{ave}=1.14 cd/m², U_0=0.75, TI = 11, Φ = 8000 lm.

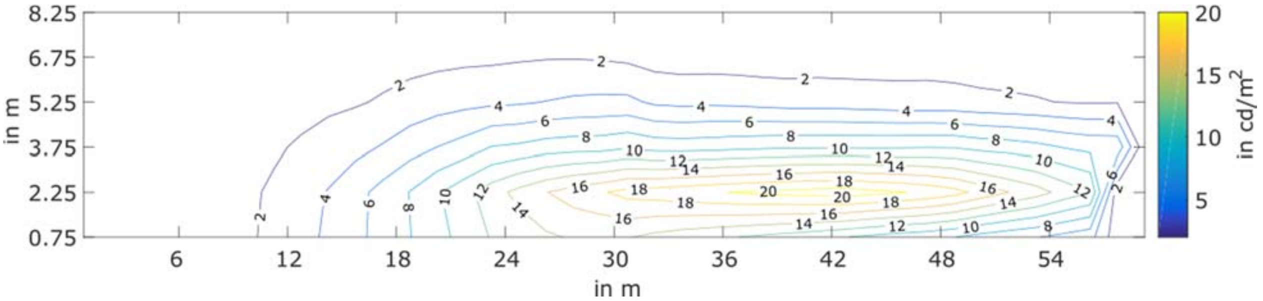

Figure 20: luminance distribution simulation for the W4-Table for an optimized light distribution on R2-Table, ME3 road class, 12 m pole height, 1 m overhang. Solution: L_{min}=0.63 cd/m², L_{max}=21.03 cd/m², L_{ave}=5.03 cd/m², U_0=0.13, TI = 11, Φ = 8000 lm.

The luminance distribution changes complete. The light quality decreases dramatically. The average luminance increases from 1 to 5 cd/m² and the homogeneity decrease from 0.75 to 0.13.

A similar picture is given, when the light distribution is optimized for a wet road (Figure 21). The homogeneity is good enough. The TI value for the evaluation of glare is to high. To reduce this value, it is necessary to reduce the pole high to pole distance ratio from 1:5 to 1:4. When the optimized light distribution is used for a dry road (R2-table), the light quality decrease in a comparable way. Extreme dark zones are not avoidable. The homogeneity decreases from 0.5 to 0.1.

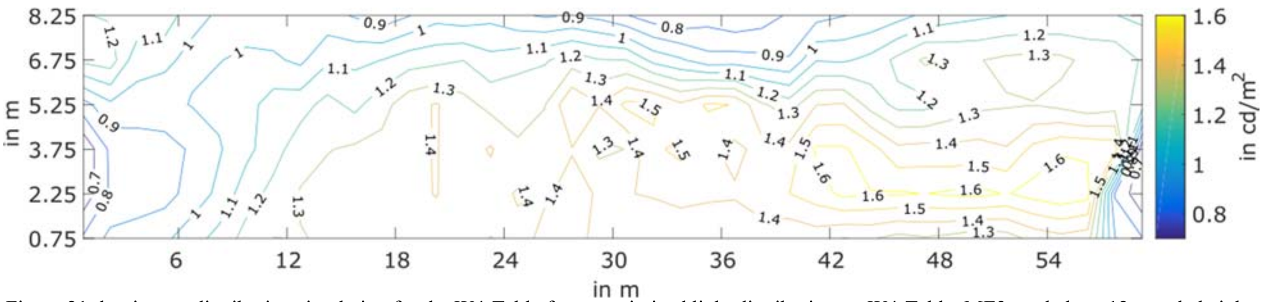

Figure 21: luminance distribution simulation for the W4-Table for an optimized light distribution on W4-Table, ME3 road class, 12 m pole height, 1 m overhang. Solution: L_{min}=0.61 cd/m², L_{max}=1.67 cd/m², L_{ave}=1.21 cd/m², U_0=0.5, TI = 19, Φ = 7450 lm.

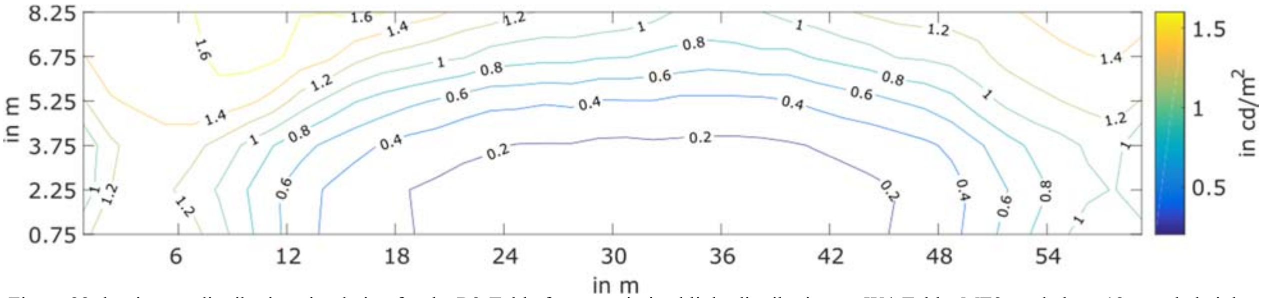

Figure 22: luminance distribution simulation for the R2-Table for an optimized light distribution on W4-Table, ME3 road class, 12 m pole height, 1 m overhang. Solution: L_{min}=0.09 cd/m^2, L_{max}=1.75 cd/m^2, L_{ave}=0.8 cd/m^2, U_0=0.11, TI = 19, Φ = 7450 lm.

In sum, it is not possible to use only one light distribution for the different demands. For a high light quality different light distributions are needed.

Multi-variable light distribution gives us the best and probably the only way to realize these demands. Every large luminaire uses in minimum 2 LED panels. When the panels are equipped with different optics it is easy to realize a multi-variable light distribution.

An innovative design and installation process are needed.

FIRST PROPOSAL FOR A INNOVATIVE DESIGN PROCESS

The design process should consist of 3 steps:

1. The actual existing pole positions are supplied during the invitation to a tender. Additional demands for foot paths and facades are described. A target light distribution is calculated in accordance to homogeneity of illuminance/ luminance or visibility for every pole position (for a minimum of luminous flux and limited glare).
2. A simulation tool tries to find the best fit of the light distribution with available lenses or reflectors for realizing the target distribution. The chosen lenses or reflectors are mounted into the luminaire. The light distribution is measured during the production process.
3. The parallel calculation shows that the luminaire will fulfil the exacting standards of the tender.

SUMMERY AND OUTLOOK

The contribution supplies arguments to improve the design process for road lighting. One assumption is a optimization tool to find the optimal luminance intensity distribution for different criteria (homogeneity of illuminance/luminance or visibility) which is presented here. When the minimum of luminous flux as an optimization target is used, the comparison with current systems will show that 50% of the energy is enough to lit the road with a better light quality. Of course, other areas need light too – but not the whole night!

The presentation will show additionally that we need more lens or reflector types in the future. Basis is the calculation after Bergen[2]. Currently used lenses of manufactures cover 80% coincidence with the target light distribution. But this is not enough for fulfilling high standards.

Finally, alternative configuration processes during the installation will have be discussed. A self-calibration of optimal light distributions is thinkable with integrated video processing. A simpler way could be the adjustment of two different overlapping light distributions using mobile devices (e.g. mobile phone or tablet).

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A New Dimming Control Scheme of LED Based Streetlighting Luminaires Using an Embedded LED Model Implemented on an IoT Platform to Achieve Constant Luminous Flux at Different Ambient Temperatures

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***Abstract*—This paper describes a method with a forward current control scheme that assures constant emitted total luminous flux of streetlighting luminaires, by considering the operating temperature of the luminaire. To set up such a control scheme, the multi-domain model of the LED packages applied in the luminaire must be known along with the thermal model of the entire luminaire. With these two models combined, the relationship between the ambient temperature, the luminaire temperature and the LEDs' emitted total radiant flux/luminous flux can be established. Using this relationship, a look up table based embedded model can be generated that can be implemented in a smart luminaire that can decrease/increase the driving current of the LEDs with which temperature changes can be accounted for while maintaining the total emitted luminous flux of the luminaire at the required level. Such an embedded model has been developed for a given smart, LED based streetlighting luminaire family and has been implemented in a demonstrator system. Preliminary version of the suggested new control has been tested in the field and the recently built demonstrator system has also been precisely tested in a laboratory environment. Our most recent test results obtained for an ambient temperature range of -30 °C and 60 °C are also presented.**

***Index Terms*-- power saving, iso-flux control, smart dimming, temperature compensation, multi-domain LED model**

INTRODUCTION

Temperature dependence of LED operation is often not fully considered during the design of solid state lighting products. If temperature dependence is not carefully considered, solid-state lighting products are typically overdesigned to be robust enough to fulfil the requirements under any possible environmental conditions. Temperature dependent nature of LEDs though, could even be a new benefit if properly considered. Overdesign means designing for the worst case that is the highest possible environmental temperature. Under high temperature LED efficiency/efficacy, thus luminaire efficacy/efficiency is lower than at lower temperatures. This means that e.g. a streetlighting luminaire in terms of its total emitted luminous flux must be designed for the highest foreseen environmental temperature (foreseen hottest summer night). If the LEDs in such a luminaire are driven with the same constant forward current, on colder days (e.g. during the winter) the total emitted luminous flux of the luminaire will be significantly higher than required. With a control scheme resulting in constant emitted total luminous flux, significant electrical power saving can be achieved since at lower temperatures, due to increasing efficiency/efficacy less electrical power, thus, lower forward current levels are sufficient.

This paper describes a method to specify the so called iso-flux control (or constant light output) of LEDs' operating point, in which effect of temperature changes on light output characteristics is compensated by adjustment of the forward current. Parameters for an automated temperature compensation can be identified with the help of multi-domain LED models [1]-[3]. This paper describes our LED multi-domain model based approach applied to the design of the light output control of an existing streetlighting luminaire [4],[5].

DESIGNING LUMINAIRES FOR CONSTANT LIGHT OUTPUT

By monitoring the ambient temperature, a smart adaptive system can fix the light output values through a controlled current source or through pulse-width modulation (PWM) based dimming with variable duty-cycle while maintaining a constant forward current. Such a solution is also known as *constant light output* (CLO) design.

Practical realization of a CLO or *iso-flux* control would require a pre-specified look up table (LUT) of required forward current / duty cycle vs. ambient temperature. Obtaining such LUTs e.g. for PWM-based dimming is not easy; for the calculation the pulsed thermal resistance, the effective heating power and the actual temperature dependence of LEDs' luminous flux need to be known. Our alternate approach was the following.

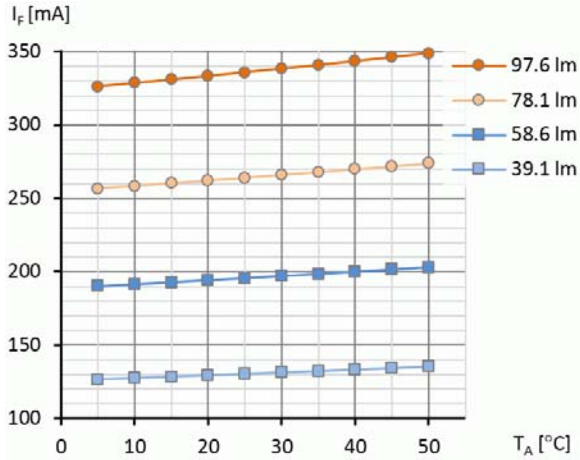


Figure 1 Luminaire Iso-flux characteristics of a test LED – keeping the Φ_V luminous flux constant at 40-60-80-100% of its reference value identified at T_A=50 °C ambient temperature and I_F=350 mA forward current

We had a less complicated, alternate approach based on an analogue control scheme with variable forward current of LEDs, though, it requires detailed knowledge about the so called iso-flux characteristics (set of operating points providing constant radiant/luminous flux values under any environmental conditions) of the applied LEDs. Look up tables containing required forward current vs. ambient temperature pairs to be used for such a control can be obtained by properly set up simulations using a chip level multi-domain model of the LEDs to be controlled [6].

In case of simple 1-LED assemblies (or in cases when there are no considerable cross heating effects and the main heat-flow path is 1D like) merely the isothermal characteristics allow "hot lumen" calculations. Since the junction temperature is fixed, the power dissipation at any measurement point is independent from the thermal resistance of the actual mechanical structure; by substituting the thermal resistance of the required fixture it is possible to calculate the set of ambient temperatures corresponding to the specific points of the isothermal characteristics. (Such isothermal current-voltage-emitted total flux characteristics of LEDs can be measured in an automated way using the T3Ster/TeraLED combined thermal and radiometric/photometric test setup available from Mentor Graphics [7].)

Once the ambient temperature – forward current – radiant/luminous flux triplets are available, by simple regression and extrapolation methods the desired iso-flux *ambient temperature vs. forward current* function (such as shown in Fig. 1) can be derived. On luminaire level, however, multi-domain models of the single LED packages along with the complete thermal model of the luminaire have to be considered, in order to account for the mutual heating effect of the LEDs built into the luminaire.

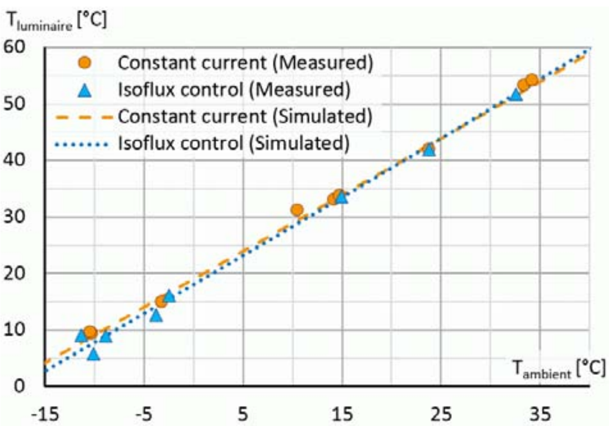


Figure 2 Luminaire temperature vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

We modelled the LEDs used in the PearlLight family of LED based streetlighting luminaires of Hungaro Lux Light Ltd. [8] as well as the largest member of the luminaire family [4]. With luminaire level simulations the total "hot lumens" of the luminaire can be identified for any ambient temperature. The applied modelling techniques and the actual models were verified with thermal measurements [4] and also, with measurements of the light output at different ambient temperatures [9]. The thermal modelling of the luminaire allowed us to identify the relationship between the ambient temperature and the luminaire temperature, see Fig. 2. (This relationship is important for the physical implementation of a temperature dependent light output control scheme since it is simpler to measure the temperature of at the thermal test point of the luminaire in a reliable way than the ambient temperature.) In these experiments the forward current provided by the driver (which was removed from the luminaire itself) was set manually.

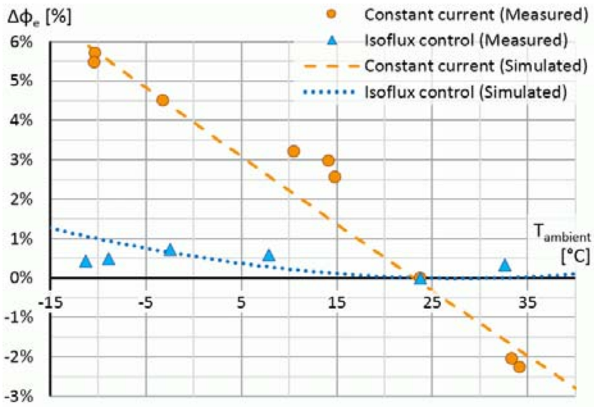


Figure 3. Relative change of luminous flux vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

The forward current values resulting in the same total luminous flux at different ambient temperatures were identified with the help of these models. The luminous flux – ambient temperature relationship established this way was checked by actual field measurements [9]. We had two different forward current setting for the different ambient temperatures. In one set of simulations and measurements the nominal forward current of the original luminaire design was kept constant (constant current driving) while in a second set of simulations and measurements the forward current was adjusted according to the temperature in order to keep the emitted total flux of the luminaire constant (iso-flux control). The results of these first experiments are shown in Fig. 3.

In both control schemes luminaire temperatures are the same – measured and simulated values perfectly match. When the luminous flux is kept constant (blue dots and curves in Fig.3), then, due to the increasing efficacy with decreasing temperature, the forward current can be reduced while the luminous flux is maintained at the specified value. This results in considerable power savings (blue markers and curves in Fig.4).

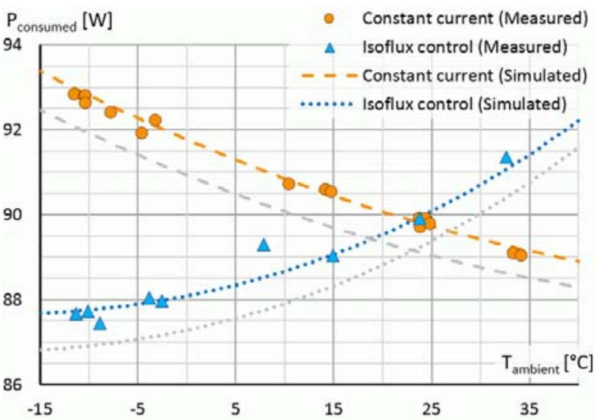


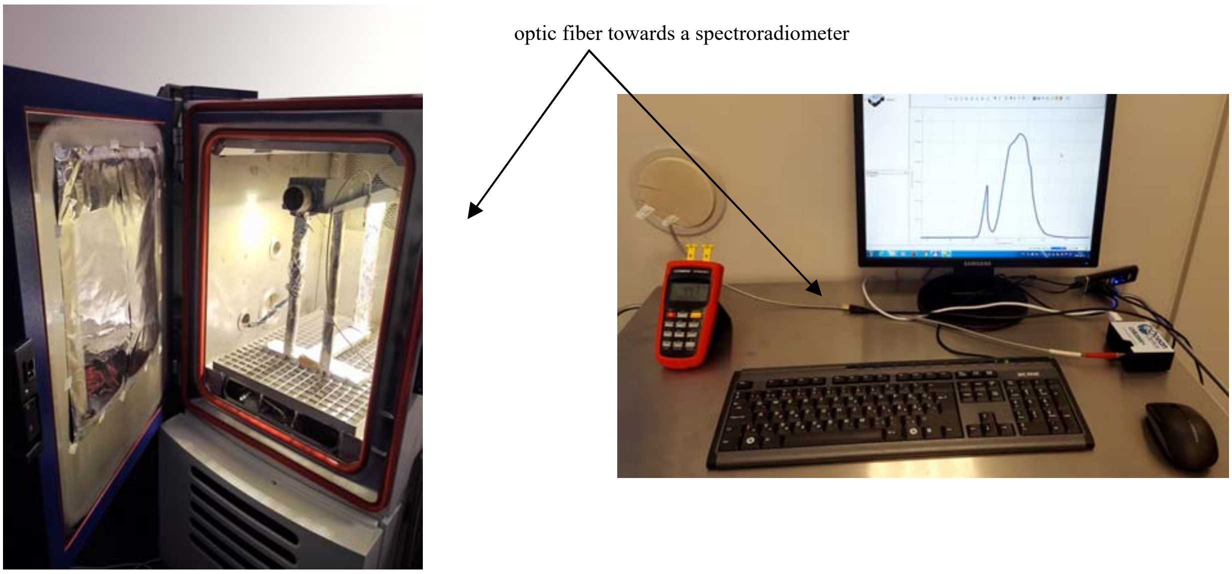
Figure 4. Consumed electrical power vs. ambient temperature for the Hungaro Lux PearlLight 48G luminaire

IMPLEMENTATION IN A DEMO SYSTEM

In the framework of the EU H2020 project EuroCPS H2020 [10] Hungaro Lux Light Ltd. performed an industrial experiment, aiming the implementation of smart streetlighting luminaire with advanced self-diagnostics and communications capabilities, using an advanced IoT (internet of things) platform of a leading manufacturer [11]. As part of this project, the constant light output control (iso-flux control) of the luminaire was also implemented. For the demonstration of the operation of the smart luminaire control the second smallest member of the Hungaro Lux PearlLight family, the PearlLight 24G model was used.

Using the modelling approach described in the previous section we established the luminaire temperature – forward current relationship needed to maintain the emitted total luminous flux of this luminaire model to its nominal value and we turned this into a look-up table (LUT) corresponding to the resolution of the digital reading of the smart luminaire's built-in temperature sensor and the quantization steps of the forward current of the programmable LED driver used. The chosen IoT platform of smart streetlighting luminaire has sufficient processing capacity and is equipped with the right sensor and control interfaces to manage such LUT based control schemes.

With the right look-up table and the complete sensor and communications installed, the smart PearlLight 24G luminaire was placed in a light insulated climate chamber, see Fig. 5. An optic fibre (with the right cos-corrected measuring head) along with the wires of two thermocouples was fed through one of the measuring ports of the climate chamber. The optic fibre was connected to an Ocean Optics 2000+ spectroradiometer – this way we measured the relative change of the spectral radiance in the climate chamber as the ambient temperature was swept between -30 ºC and +60 ºC.



a) b)

Figure 5. Testing the constant light output (iso-flux) control scheme of the demonstrator of the smart PearlLight 24G luminaire of Hungaro Lux: a) the luminaire in the light insulated climate chamber, b) measurement of the spectral radiance and the temperature in the chamber

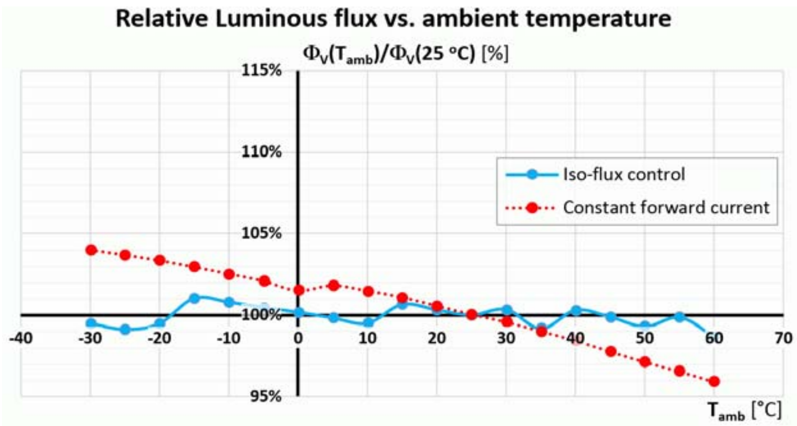


Figure 6. Measured relative change of the luminous flux of the smart luminaire

From the captured spectra the relative change of the luminous flux was calculated. We also measured the actual forward current provided by the LED driver of the luminaire. Like in the preliminary experiments [9], we applied both the constant current control scheme (no change in the forward current) and the constant light output or iso-flux control scheme. The measured relative changes of the total luminous flux of the luminaire for both control schemes are shown in Fig. 6. For calculating the relative change, the total luminous flux value corresponding to 25 ºC ambient temperature was taken as reference. As seen in Fig. 7, the luminous flux of the demonstrator luminaire was kept constant with a relative error less than 1.9% over the investigated ambient temperature range. The diagram in Fig. 7 also shows the actual applied forward current and the ideal forward current. As seen in the diagram, the applied actual forward current changes in a step-wise manner (as it could be programmed in the driver).

CONCLUSIONS AND OUTLOOK

We proposed a new light output control scheme for streetlighting luminaires which is based on the improving LED efficiency/efficacy with decreasing temperature. We proposed a technique based on multi-domain modelling of LED packages and complete luminaires with which the ambient temperature – forward current relationship assuring constant luminous flux output can be established. Turning this relationship into a look up table forms the basis of the implementation of the constant light output control of real luminaires. The applicability of the method was shown by precise laboratory measurements of demonstrator of a new smart streetlighting luminaire. As suggested by Fig. 4, considerable energy saving is achievable with this new, iso-flux light output control scheme. Using archived meteorological data, detailed calculations of the energy saving potential for one of the examples presented here were carried out and published [9].

There are a few open issues. One question is how one should consider the production variance of LEDs' I-V-L characteristics in establishing the right models used for the light output control of the luminaire. This is among the problems currently studied within the Delphi4LED H2020 ECSEL project [12]. Another question is, how the LEDs' iso-flux characteristics do change with aging and how this could be compensated during the life-time of the luminaire. To answer this question requires further research. Some preliminary results in this regard are published in our recent research paper [9].

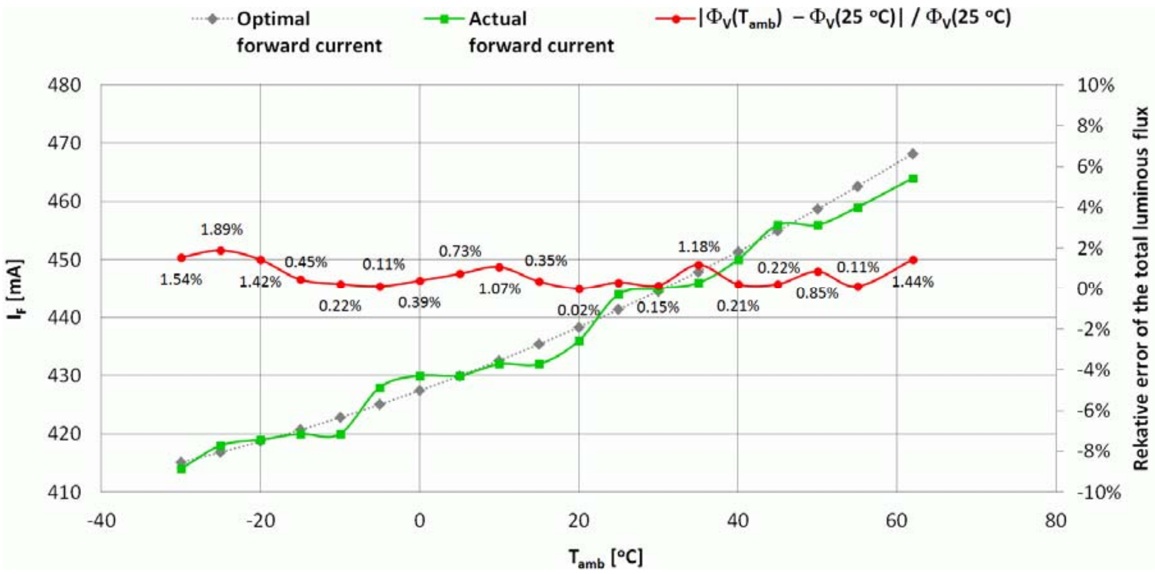


Figure 7. The relative error of the actual luminous flux with respect to the reference value and the applied actual forward current

ACKNOWLEDGEMENT

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A Urban Lighting Renovation Project to Optimize Environmental Performance and Reduce Energy Consumption: Results of a Measurement Campaign

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***Abstract*— In the last few years, the need to reduce costs and to limit energy consumption, together with the availability of financial and carbon reduction incentives led many public authorities to undertake the renovation of public lighting installations. In the North of Italy, a major program of public lighting renovation is being implemented in Torino since 2015. To verify the effectiveness of the interventions, the performance of the new LED lighting systems compared to the previous installations were assessed through measurement campaigns and computer simulations. The paper presents the main features of the project, the methodology adopted for the performance evaluation campaign and the results obtained in terms of both lighting performance (measured luminances and illuminances over representative areas) and energy performance (calculated Power Density and Annual Energy Consumption Indicators as defined in the EN 13201-5:2015).**

***Index Terms*-- urban lighting, energy efficiency, measurement campaign, energy performance indicators.**

INTRODUCTION

Public lighting is a fundamental service for the security of citizens and for the enhancement of urban spaces; however, it also represents one of the most important item of expenditure in the budget of municipal administrations. The operating costs, for energy consumption and luminaires maintenance, can be greatly reduced, for both new and existing installations, through the adoption of new green technologies, which allow the increase of systems energy efficiency and of light sources lifetime. The need of reducing costs, combined with the urge of limiting energy consumption to decrease the emission of CO_2 in the environment, led many public authorities to undertake the renovation of urban lighting plants, in particular by replacing old lighting technologies with new LED luminaires and/or by introducing lighting control systems.

The Italian situation on public lighting has been recently outlined in a national project named “Progetto Lumiere” launched by the Italian research institute ENEA [1]. The scope was to promote the energy efficiency in the field of public lighting and to create a network linking Municipalities, research centers and other stakeholders to share knowledge and facilitate the technology transfer. The studies carried out in the project showed that the lighting sector in Italy (public, industrial and residential), is responsible for a total energy consumption of approximately 50,8 TWh/year, of which 6,1 TWh/year, corresponding to 12%, are used for public lighting. There are about 11 million of light points with a total installed power of 1.595 MW. Furthermore, considering a sample of 809 Municipalities, representing the 10% of Italian municipalities with a population of between 5.000 and 50.000 inhabitants, it was found that there are three types of lamps mainly used in existing plants: high pressure sodium (50% of total installed power) mercury (42%) and metal halide (6% of the total). The average power of the light points is 145 W and it is possible to estimate that the number of light points with luminous efficiency below 70 lm/W is about 2 million [2].

Furthermore, the lighting plants of the 86% of the Municipalities involved in the project are controlled with a traditional switch ON/OFF system (twilight switch - 55%, clock - 28%, astronomical clock - 13%).

In general, these data demonstrate the high potential that interventions of public lighting renovations have in reducing energy consumption: in Italy, on average, savings of about 30%-40% could be easily achieved [1].

THE TORINO A LED PROJECT

A major program of public lighting plants renovation is being implemented in Torino, in the North of Italy. The project, named TORINO A LED, started in 2015 and entails the replacement of 55.000 luminaires: from high pressure sodium or metal halide technologies to LED luminaires. The project involves different types of areas, mainly traffic roads, but also pedestrian streets, squares and parks. The main objective is energy saving, which has been estimated of 20.000.000 kWh/year, that correspond to 3,5 ton/year of CO_2 not released in the environment. Additional energy savings are expected, thanks to the adoption of a control system designed to dim the light in two steps: from 12:00 a.m. to 01:00 a.m. the power is reduced by 20% and, from 01:00 a.m. to 06:00 a.m. the power is reduced by 30%. Besides energy saving and CO_2 reduction, the project aims to guarantee the lighting performances required for safety and visual comfort (as specified by technical standards), to increase the light flux utilisation factor, to avoid obtrusive light and reduce light pollution.

The luminaires replacement is based on the results of a project carried out by IREN Energia. The project was founded on the indications given by two local directives: the Urban Traffic Plan (PUT) and the Municipal Lighting Regulation Plan (PRIC), which respectively provided the classification of the roads and pedestrian areas and the corresponding general lighting criteria. Afterward, each type of area was associated with a lighting category, as required in the standard UNI 11248 [3], and the lighting requirements specified in accordance to the standard EN13201-2 [4]. The dimensioning of the lighting plants was the result of lighting simulations carried out for each type of area or road included in the project. Luminaire characteristics were defined in order to respect, being close as much as possible, the overall lighting requirements (maintained average luminance/illuminance, uniformity, glare control, etc.).

To verify the effectiveness of the renovation project, a measurement campaign to evaluate on field the lighting performance and energy consumption of the new LED lighting systems (ex-post systems) compared to the previous traditional lighting plants (ex-ante systems) was included as part of the project and carried out by the Politecnico di Torino, which operated as a consultant of the IREN Energia lighting group.

The measurement campaign was carried out on a set of urban streets/areas and lighting systems, which were considered representative of the overall stock of lighting plants and urban contexts in Torino.

THE METHOD TO ASSESS THE LIGHTING AND ENERGY PERFORMANCE

Different approaches were adopted to assess the lighting performance and the energy performance of the selected streets sample: a measurement campaign was carried out to verify, in field, the lighting conditions obtained with the ex-ante lighting installations and, later on, with the ex-post LED lighting systems. Besides, the energy performance was calculated from the results obtained through the lighting simulations. In the following sections, the procedure used for the two type of analysis is described in details.

A. Lighting assessment

For each analysed street, the lighting performance of ex-ante and ex-post lighting plants was assessed by means of in-situ photometric measurements. The measurement campaign was based on luminance and illuminance data acquisition, in accordance to what required in the standard EN 13201-3 [5] and EN 13201-4 [6].

Luminance measurements of the road surface were carried out for motorized traffic reads, whilst horizontal and semi-cylindrical illuminance was measured for pedestrian areas and cycleways.

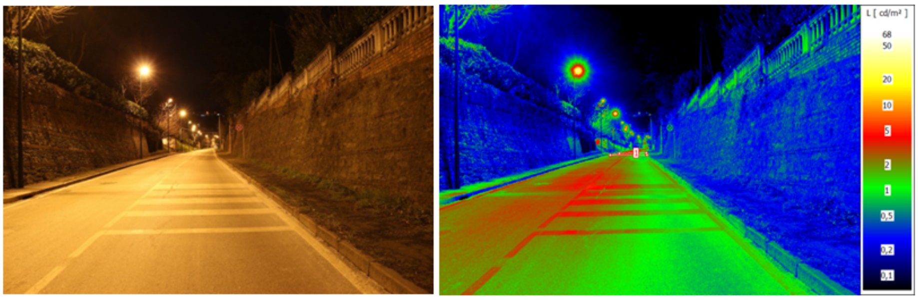
A videophotometer TechnoTeam “LMK Mobile” (based on Canon EOS digital camera) was used to assess the luminance distribution of the framed carriageway as luminance image. The luminance image was acquired considering the observer position in each traffic lane at 60 m from the relevant measuring area of the carriageway.

A method to analyse the luminance images was adopted based on three steps as shown in Fig. 1: step 1) luminance image acquisition of the relevant area of the carriageway (Fig. 1.a); step 2) rectification of the luminance image and definition of the measuring grid (Fig. 1.b); step 3) luminance data analysis (average value, overall and longitudinal uniformity) (Fig. 1.c).

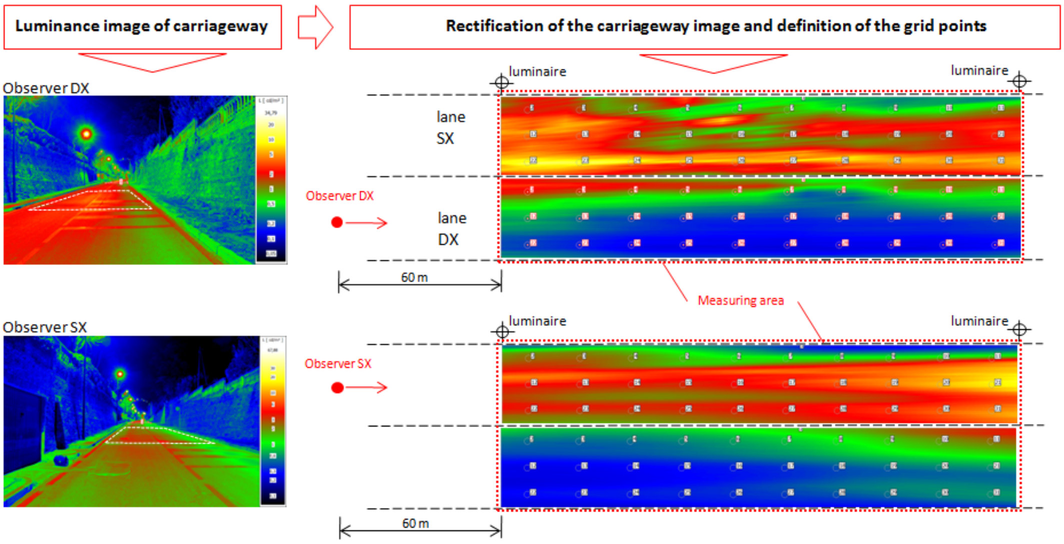
For pedestrian areas and cycleways, horizontal illuminance was measured by means of a Minolta T-1 luxmeter considering grid points at ground level, whilst semi-cylindrical illuminance was measured with a PRC 106 luxmeter equipped with a specific photometric head used at 1.5 m of height to assess facial recognition.

General information on geometrical data, road surface characteristics, environmental conditions, condition of the installation, etc. were also recorded during the measurement campaign as relevant information for the data analysis.

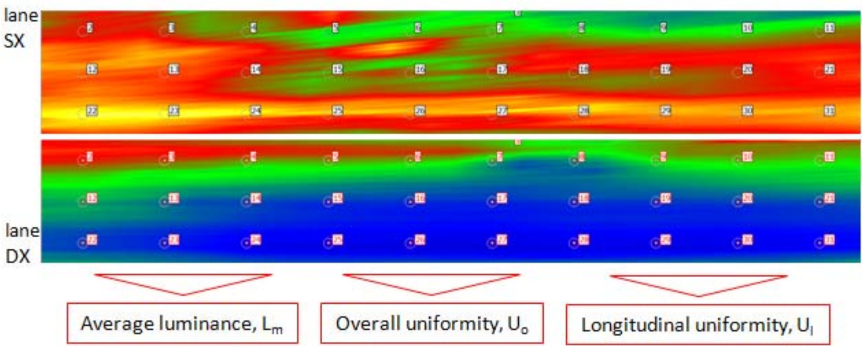
1.a



Visible image of the carriageway. Luminance image of the carriageway.



1.b



1.c

Figure 1. - Example of luminance image analysis for a two lane road with single side luminaire arrangement.

B.Energy assessment

Several factors affect the energy performance and therefore the energy consumption of a lighting system. A major role is played by features of the system components such as the lamps luminous efficiency, the optical efficiency of the luminaires and the ballasts energy losses. The efficacy in exploiting the emitted light flux is another important factor that generally depends on the lighting design choices and finally, the type and features of the lighting control system, designed to manage the on/off switching and/or to dim the light flux, is a further element that affects the public lighting annual energy consumption.

In general, the energy performance of a lighting system can be assessed through parameters that evaluate the energy efficiency of the system or its energy consumption. For public lighting systems, several approaches have been proposed up to now [7] and, finally, two numerical indicators for the assessment of the energy performance have been defined and presented in the standard EN13201-5 [8].

The two numerical indicators are the Power Density Indicator (D_P) and the Annual Energy Consumption Indicator (D_E) and can be calculated with the following formulae:

$$D_P = \frac{P}{\sum_{i=1}^{n} E_{med,i} \cdot A_i} \qquad (1)$$

where D_P – power density indicator (W/lx/m^2); P – system power of the lighting installation used to light the relevant areas (W); $E_{med,i}$ – calculated maintained average horizontal illuminance of the sub-areas (lx); A_i – size of the sub-areas lit by the lighting installation (m^2); n – number of sub-areas to be lit.

$$D_E = \frac{\sum_{j=1}^{m}(P_j \cdot t_j)}{A} \tag{2}$$

where D_E – annual energy consumption indicator for a road lighting installation (kWh/m^2); P_j – operational power associated with the jth period of operation (W); t_j – duration of jth period of operation profile over a year (h); A – size of the lit area lit (m^2); m – number of periods with different operational power P_j

Within this study, the two energy performance indicators were calculated for each analyzed street/area and for both the ex-ante and ex-post installations. The aim was to assess the increase of the energy efficiency and the achievable energy savings. The indicators were calculated considering a part of the lighting installation corresponding to the area used for the lighting design and defined in the standard EN 13201-3 and both the ex-ante and ex-post lighting plants of EN 13201-4.

RESULTS

The results presented in this paper are referred to a sample of 11 reference roads and areas: 9 of them with motorized traffic, and 2 pedestrian areas. This is a subset of the overall sample, as the measurement campaign is still in progress.

A.Lighting performance

The data of the measurement campaign are referred to different sates of the luminaires maintenance: the ex-ante installation were close to the end of their life while the ex-post installation were at the beginning of their life. To allow a comparison of the lighting performance of both types of plants the data measured for the new LED installations were multiplied by the maintenance factor adopted in the dimensioning phase (MF = 0,8).

In Fig. 2 the lighting performance of the ex-ante and ex-post installations are compared. The red lines in the graphs correspond to the performance required according to the standards.

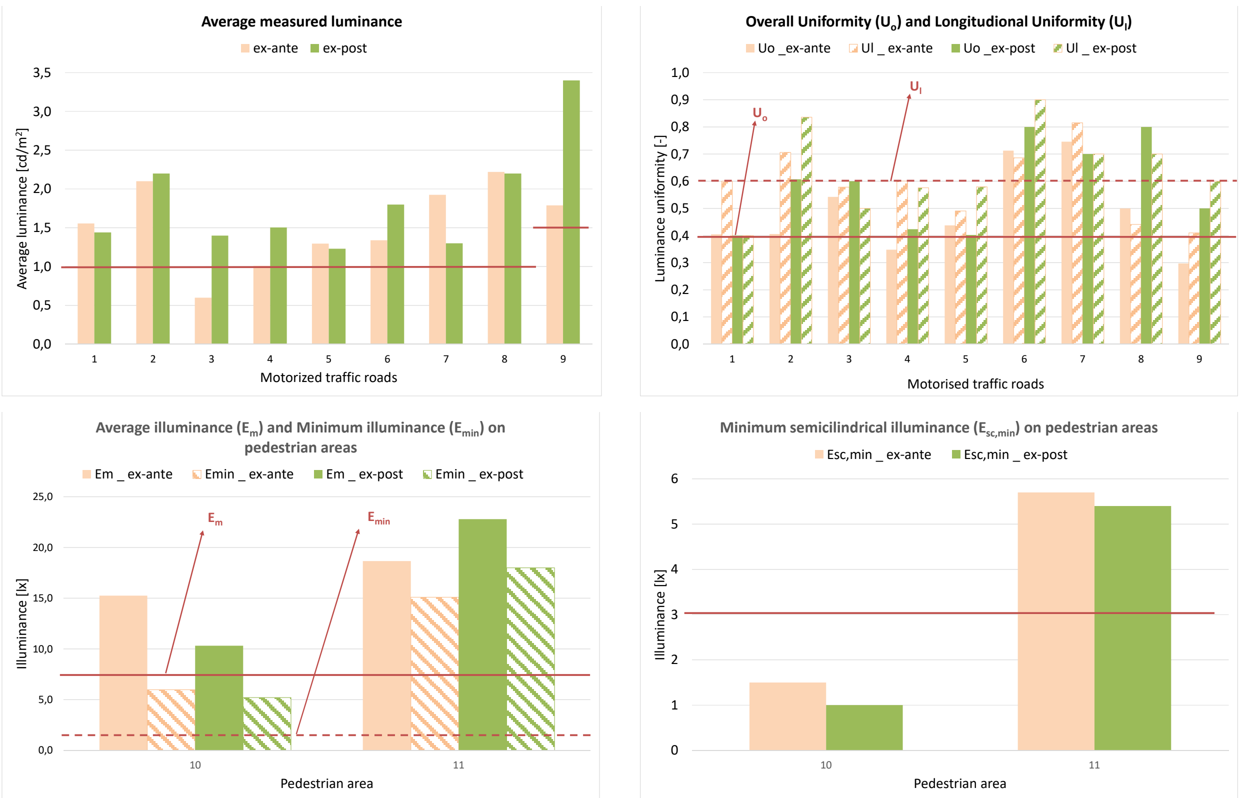


Figure 2. – Lighting performance of the ex-ante and ex-post installations for the motorized traffic roads and the pedestrian areas.

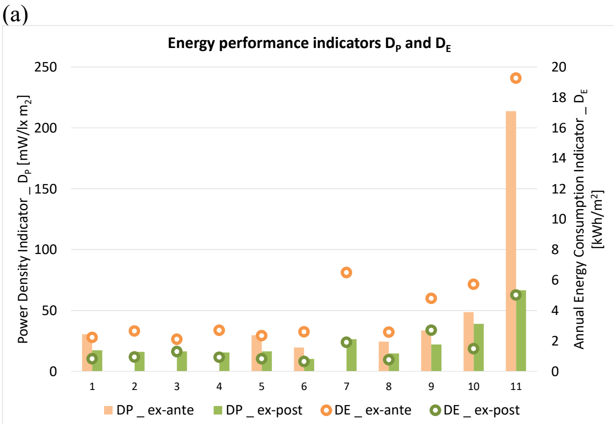
The results of the measuring campaign showed that, for both the ex-ante and ex-post lighting plants of all the selected roads and areas, the minimum required lighting performance is generally achieved. Only the longitudinal uniformity (U_l) and the minimum semi-cylindrical illuminance are, in a few cases, below the required value. The data also demonstrate that, in field, the lighting quantity provided by some installations is significantly greater than the required and simulated value. In the subset of data presented in this paper, the 44% of roads exceeded the required lighting level of the next higher lighting class and the same occurs for 50% of the pedestrian areas. On the other hand, 4 out of 9 motorized roads showed a decrease of the lighting quantity with the transition to LED plants.

B.Energy performance

The results obtained from the calculation of the energy performance indicators are presented in Fig. 3. The D_P of some ex-ante installations were not calculated because the photometric data of the luminaires were not available.

In general the results demonstrate the significant increase of the energy efficiency of the ex-post lighting systems: the average value of the Power Density Indicator (D_P) is 57,2 mW/lx·m^2 for the ex-ante installations and 23,7 mW/lx·m^2 for the LED plants, with a percentage reduction of 42%. The increase in the energy performance is even greater if the Annual Energy Consumption Indicator is considered (D_E): in this case the average values for the ex-ante and ex-post analysed installations are respectively 4,86 kWh/m^2 and 1,58 kWh/m^2, with an average percentage reduction of 64%.

(a)



(b)

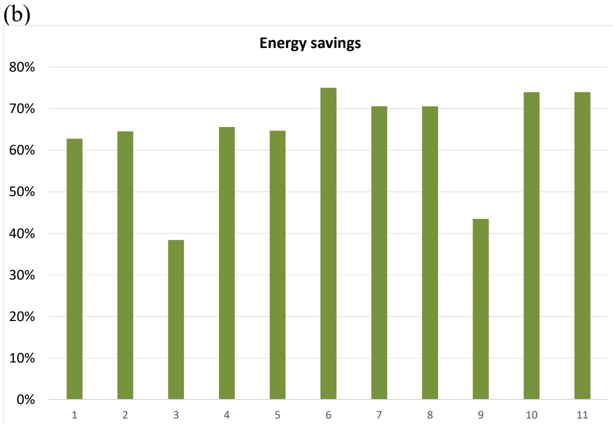


Figure 3. Energy performance indicators for the ex-ante and ex-post installations (a) and energy savings (b)

CONCLUSIONS

The renovation of public lighting systems is among the measures municipal administrations more frequently adopt to reduce their expenditure budget and increase the city's environmental sustainability by reducing CO_2 emissions in the atmosphere. Nevertheless, the renovation of existing installations implies the luminaires substitution on existing poles and bearings and it therefore requires a careful design to ensure that appropriate lighting conditions are achieved in addition to energy savings.

Within this study a specific case study, the TORINO A LED project, was analysed. The study involved the assessment of the lighting and the energy performance of a sample of installations, which were selected to be representative of the overall lighting system typologies in Torino. The analysis was carried out by measuring the lighting performance in field and calculating the energy performance. The results demonstrated that the substitution of traditional high pressure sodium or metal halide lamps with LED luminaires and the implementation of a stepped dimming control system allowed to obtain substantial energy savings (64% on average for the subset of the installations sample considered in this paper). Furthermore, the careful design of the retrofit interventions also ensured the respect of the lighting requirements.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the contributions of Kimo Dogani (Politecnico di Torino) and the IREN support staff for the measurement campaign. A special thanks to the local police for the support in controlling the motorized traffic during the in field measurements.

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Metrology of Road Surface for Smart Lighting

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***Abstract*—The knowledge of the luminance coefficient *q* or of the reduced luminance coefficient *r* of road surface is an unavoidable requirement for designing road lighting installations able to assure adequate road luminance for visual conditions, energy consumption and traffic safety according to standard requirements. Unfortunately *q* available data refers to measurements made during the seventies with no traceability or measurement uncertainty. In the last 40 years the road surfaces pavements evolved as well the road lighting sources and luminaires. EMPIR project SURFACE will provide validated, optimised and reliable geometrical conditions for the measurement of *q* as well as reference data representative of current road pavements and future needs, as support of the European Standardisation process, CIE and European Metrology infrastructure.**

***Index Terms*--EMPIR SURFACE project, EURAMET, Road lighting design, Road luminance coefficient, Smart lighting**

INTRODUCTION

Reference Standard for road lighting (EN 13201 series [1], [2], [3], [4]) considers for motorize traffic the road luminance level the key parameter to obtain adequate vision conditions and traffic safety: the road luminance is directly related to the direction of the incident luminous flux, the direction of view and the reflection characteristics of the road surfaces.

For motorized traffic EN 13201-2 [1] specifies, for the assigned road class, requirements for the average road surface luminance, the overall uniformity of the luminance, the longitudinal uniformity of the luminance, the threshold increment and the edge illumination ratio. The design of every road lighting system is based to ensure compliance with the aforesaid values, and is calculated (i.e. luminous flux installed and luminaires spacing) following [2] and using the reference value of the *luminance coefficient (q)* as tabulated in reference tables for the selected road surface. Unfortunately, reference tables in the standard don’t specify values, but only the geometries (lighting and viewing angles) to which the *q* values should be known. The only published reference data are in a CIE reference document [5] and are older than 40 years and without information on measurement uncertainty.

This means that current road lighting systems have been designed using data of road photometric characteristic not representative of effective road surfaces: in the last 40 years both road surfaces and luminaires evolved as well the awareness of uncertainty and its relationship with industrial tolerances. Some studies show that the current available CIE data [5] can lead to errors on average luminance often over 30% and sometimes over 50% [6]. Solid-state sources (SSL) have sharp luminous intensity distribution; this simplifies the energy consumption optimization but increase the influence of the road surface characteristic in reflection, especially when the luminance uniformities are considered. Moreover SSL brings the opportunity of smart lighting systems, i.e. systems or luminaires able to adapt their luminous flux end/or luminous intensity distribution at any time, according to the brightness and specularity of the road pavement. In these systems to stabilize the road surface luminance, the road pavement is usually framed by a control Image Luminance Measuring Device (ILMD) under different geometrical condition than reference standard geometries. The ILMD calibration is made according to several simplifications on the road surface reflectance behaviour or with on-site procedures [3]. Also the spectral radiant coefficient shall be considered with a specific care in the mesopic concept [7], which has been introduced in some national standards (UNI, BSI) and international guidelines [8].

The knowledge of the road surface luminance coefficient is important in the optimization of the energy performances (EN13201-3 [2] and EN 13201-5 [4]) of the lighting installation, but also in glare evaluation [2] and in the improvement of safety, comfort during night and energy savings trough LED adaptive lighting (infrastructure toward smart cities). The luminance coefficient and/or the reduced luminance coefficient (are the required and unfortunately missed parameters.

Unfortunately EU Standard Organization (CEN) isn’t able to provide the necessary data and research, so a specific pre-normative call was launched under the 2016 calls of the European Metrology Programme for Innovation and Research (EMPIR), that is a metrology focused program of coordinated Research & Development funded by European Commission and participating countries within the European Association of National Metrology Institutes (EURAMET). A Joint Research Project (JRP) SURFACE “Pavement surface characterisation for smart and efficient road lighting”, dealing with road surface photometry, was submitted and subsequently funded for developing metrology research to support road lighting standardisation.

This project is lead by the National Metrological Institute (NMI) of Italy (INRIM) and includes NMI of Estonia, France, Finland, Sweden and Switzerland, plus a National French Research Centre (Cerema) and two industrial companies (Zehntner, measuring instruments and Optis, software simulation), with the support of CEN, CIE and National Standardisation Organisation, road Authorities as well a group of Stakeholder.

SUMMARY OF THE PROJECT

A. Scientific Objectives

The project wants to solve the European standard lacks in road surface photometry:

- providing reference data of current road surfaces, and new reference geometrical condition for reference data useful for needs of smart and LED lighting and for the reduction of the environmental impact (obtrusive light and light pollution) of road lighting installations;
- establishing traceability through an intercomparison open to stakeholder and EU laboratories;
- providing guidelines on metrological specification for instruments, characterisation methods and uncertainty evaluation for road surface photometry, for current and future needs of EU normative;
- making available to EU market a software for uncertainty calculation and Certified Reference Materials for instrument calibration;
- developing two different measuring instrument prototypes.

The results will be used in priority by CEN TC169/WG12 in the next revision of EN 13201 series (mainly part 3) or as an addendum, by CIE – TC4-50 and related technical committees [CIE TC4-51] and by the whole EU lighting engineering community, testing laboratories and road authorities.

B. Structure Of The Project

The project is structured with three technical work packages as shown in Figure 1:

- WP1 devoted to Instruments,
- WP2 devoted to Applications
- WP3 dedicated to Guidelines and database.

Two more work packages take care of *Impact* and *Management.*

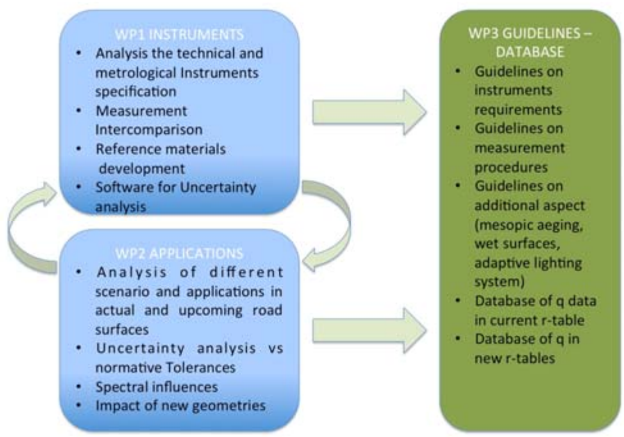

Figure 1 Technical workpackages of JRP SURFACE project

i. WP1

The aim of this work package is to propose technical and metrological specifications for instruments used to measure luminance and (reduced) luminance coefficients of road surfaces in laboratories or on-site, including methodologies for calibration, establishing traceability and evaluating the measurement uncertainty in order to support EN 13201 'Road Lighting', its future revisions and evolution.

The tasks are organized to consider the peculiarities of laboratory measurements, carried out with especially design gonio-photometer on small samples of the road surface, and on site measurements, generally carried out with portable instruments often not able to completely satisfy the standard geometrical constrains.

The measurement traceability and measurement uncertainty of instruments are analysed comparing the different measurement approaches and giving guidelines that will be tested during an intercomparison where real road samples and a set of reference samples are measured by several laboratories.

Generally the measurement of the spectral radiance coefficient is not considered due to the high cost of the requires instrumentations and technical difficulties, but in actual road lighting installations different light sources are used, e.g. high, medium and low correlated colour temperature LED, metal halide lamps, high and low pressure sodium lamps. For this reason it is important to analyse and quantify discrepancies that can rise when the spectral emission of the light source used in the instrument is different from the spectral emission of the lamp used in the road lighting installation.

ii. WP2

The aim of this work package is to analyse the different scenarios and applications related to luminance and (reduced) luminance coefficients of road surfaces in order to propose optimised measurement geometries for the characterisation of photometric quantities for road surface materials to support EN 13201 'Road Lighting', its future revisions and evolution.

It will address the need for improved *r*-tables of data representative of present road surface materials and of geometries, optimised for existing road lighting sources and luminaires, in order to satisfy the requirements of standards on spilled light and light pollution. WP2 will also analyse different road lighting situations to provide the geometrical and spectral factors that need to be addressed to define new angular reference conditions (new geometries) useful for current lighting installation and future implementation of smart lighting and mesopic concepts.

Further to this, the application of EN13201-4 requirements on tolerance analysis will be studied by software simulations and perceptive experiments using virtual driving simulator of OPTIS partner. As well Cerema and ZEHNTNER partners will develop their own instrument initial version.

iii. WP3

The aim of this task is to develop pre-normative guidelines and provide the missing data in *r*-table of current standards and to provide research results and guidelines for the future evolution of European and National standards about road lighting.

Using results of WP1 and WP2 where the single problems are deeply considered and justified, here the goals are to create documents in a normative layout that are a sound contribution to the standards development work of CEN working groups:

- CEN TC169/WG12 for application aspects in the design of road lighting installations and in the tolerance evaluation of the project to reduce and minimize the over-dimensioning of installations,
- CEN TC169/WG7 for the metrological aspects and traceability of instruments.

The same results, joint to worldwide contributions, will be used at CIE Technical committee TC4-50 and could be discussed in ISO TC274 where the “Road reflection properties” is an item in the list of priority topics. The quick dissemination of the results to the SDO is assured by the actions of WP4 and by the strong involvement consortium members in the aforesaid SDO, TC and WG.

The definition of a database (*r*-tables will be an extract of it) will improve the availability of new data considering both traditional and new geometries. It will permit the comparison of measurements and studies considering important aspects like wet/dry conditions, aging and spectral influence. It will also facilitate the adoption of standard *r*-tables that are useful as starting step in the design of road lighting installation or when detailed measurements are not possible or available

iv. WP4

This task (impact) will assure that the results achieved in the technical work packages of the project are effectively communicated to the interested standardization bodies, stakeholders, collaborators and lighting designers communities including instrument manufacturers and software houses.

The consortium will organize training courses, and training material like electronic brochure. Two different symposia on road surface characterisation will be organized under CIE aegis.

IMPACT OF THE PROJECT ON THE EU COMMUNITY

The project will define new optimized measurements geometries of luminance coefficient and up-to-date reference data for calculation. Only the availability of reliable reference data of actual (or oncoming) road materials will allow lighting designers to gather the energy savings and quality parameters forecasted in the standards and the EU commitment to cut energy consumption by 20% by 2020 (Key Performances Target) [9] providing to all users a more efficient and safe road lighting.

It will also strengthen the turnover of old lighting luminaires with new SSL luminaires that combined with adaptive system controls allow to reach energy savings up to 70%. Savings on road lighting have strong impact on country budget because lighting consumption can amount up to 50% of public electrical consumption in Cities.

The project guidelines, the full set of new reference data, the instrument prototypes will stimulate the European market to provide adequate portable measuring instruments for on site characterization: due to the lack of reference data, current EN standards do not consider compulsory on site evaluation of q. The industries will be also to stimulate through the realisation of Certified Reference Materials for calibration of portable device and road lighting verification.

The guidelines on measurement uncertainty and measurement methodologies and especially the planned intercomparison will stress and improve the measuring capabilities of NMI goniometers to materials that are far away from the Reference Materials normally used in metrology (e.g. ceramic tiles or lambertian surfaces) for units maintenance and dissemination.

The CIE scientific community, especially Div 4 community, will receive new fresh contribution to TC4-50 and TC4-51 works. Two different workshops on road surface characterisation are planned: one at the start of the project to endorse the project and stakeholder committee during the next CIE mid term Session meeting in October 2017 and one at the end of the project to disseminate the results under the aegis of CIE.

ACKNOWLEDGEMENT

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SenCity – Evaluating Users' Experiences of Intelligent Lighting for Well-Being in Smart Cities

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***Abstract*—This paper presents the evaluation of users' experiences in three intelligent lighting pilots in Finland. Two of the case studies are related to the use of intelligent lighting in different kinds of traffic areas, having emphasis on aspects of visibility, traffic and movement safety, and sense of security. The last case study presents a more complex view to the experience of intelligent lighting in smart city contexts. The evaluation methods, tailored to each pilot context, include questionnaires, an urban dashboard, in-situ interviews and observations, evaluation probes, and system data analyses. The applicability of the selected and tested methods is discussed reflecting the process and achieved results.**

***Index Terms*—evaluation, intelligent lighting, method, smart lighting, user experience**

INTRODUCTION

Applications of intelligent or smart lighting will be spreading in the near future to various types of urban context. If designed wisely, smart lighting can, besides energy savings, offer added value for urban environments on various levels of experience [1]. However, as the implementations are still rather rare and recent, there is a lack of knowledge on user's experiences to support design processes. Thus, in our research and development, we aim to increase understanding of user's multifaceted experience of intelligent lighting and of the methods for evaluating it.

A. SenCity Project

Sencity – intelligent lighting as a service platform for innovative cities is a national research and development project between Finnish cities, companies and research partners [2]. The project aims at employing lighting infrastructure as a service platform - an IoT (Internet of Things) backbone - for smart lighting solutions and innovative, user-oriented services in urban environments. The project develops intelligent LED lighting pilots in the participating cities, to which the companies involved develop solutions to better respond to the cities' needs. The research partners integrate the project together through the design of pilot contents and realization, user experience evaluation and technical development and testing.

The project pilots smart lighting solutions in six Finnish cities in different kinds of urban environments. The research focus is dual: to study user needs and experiences of smart solutions, and to develop and test technology needed for such solutions. Together, separate pilots in different cities around Finland create a living lab ecosystem for developing and testing innovative solutions. Each pilot has a focus in a different theme or application context. The themes include interactive and communicative lighting and digital services; traffic safety in a residential area; smart lighting and services for kids and young people; and presence-based lighting in bicycle routes and road environments. The pilots are realized in 2016–2018. As the pilots have varying research focuses and contexts, the SenCity project provides an excellent opportunity to test different kind of evaluation methods in real world contexts.

B. Aims and Content

In the paper, three pilot case studies are introduced presenting objectives, contexts, smart lighting applications, and methods that are used in evaluation of users' experiences. The evaluation methods, which are tailored to each pilot context, include questionnaires, in-situ interviews and observations, evaluation probes, and system data analyses. The applicability of the selected and tested methods to each pilot and its specific context, research target, and user group is discussed reflecting the process and achieved results.

Evaluation of Intelligent Lighting in Urban Contexts – Previous Reseach on Users' Experiences

There has not yet been wide research of the experience of intelligent lighting in real-world urban contexts, as the lighting solutions are internationally still in the process of development and piloting. However, some previous research exists and some examples can be mentioned here. The research concerning experiences of adaptive and intelligent urban lighting has covered aspects of safety [3], [4], social experiences [5], [6], [7], meanings and [6], [7], atmosphere and aesthetic experience [5], [6], participation [6], [7], and communication [7]. Most of those aforementioned aspects have also been relevant in experiences of media architecture and described, for example, in [8] and [9]. The evaluation methods that have been used, include, for example, a psychophysical method based on questionnaires [3], and semi-structured interviews and observation [6].

Our previous research has related to understanding of the multifaceted and emplaced experiences of adaptive and intelligent urban lighting, covering all the aforementioned aspects [1], [10]. In our real-world studies in park and streetscape environments, we have applied qualitative methods inspired by ethnographic research. These include the experience gauging walking interview method, which means in situ participant observations coupled with a semi-structured walking interview [1], [10]. Besides this, we have applied semi-structured interviews and questionnaires in electronic and printed form [11].

Experience Evaluation in the SenCity Pilots

In this section, we describe the arrangement and evaluation procedures and methods of three pilot projects, and in the next one, the methods are reflected and discussed. Two of the case studies are related to the use of intelligent lighting in different kinds of traffic areas, having emphasis on aspects of visibility, traffic and movement safety, and sense of security. The last case study presents a more complex view to the issue of intelligent lighting in smart city contexts: How lighting can serve citizens on various levels of experience and what kind of digital services can lighting infrastructure provide for the users? The SenCity project is still on-going and all of the evaluation processes are not yet finished. Thus, the presentation and discussion of methods is based to some extent still on evaluation plans.

A. Case Study 1: Intelligent Road Lighting in a Housing Area, Salo

The first case study concerns an intelligent lighting pilot in a housing area in Salo, where presence sensitive roadway lighting, adapting both to the motor vehicles using the road and to the measured traffic density along it, was tested. Users' experiences of the lighting have been collected with the help of questionnaires from the community of about 1000 households using the road in their daily traffic as well as from other interested inhabitants of the city. The evaluation was accomplished in three parts. These were connected with different phases in the development of the lighting system, the publicity of the project, and how much information was published about it.

In the first phase (23.1.–5.2.2017), the new lighting was controlled in a very basic way (*Daylight level based control*): during the bright period of the day, lights were turned off, and during the dark period, they were on at 100 % control level. The sensor detected the threshold lux level and turned lights on and off automatically. During the second phase (6.2.–26.2.), this basic control continued but a *presence-based dynamic control* was added. The lighting was controlled dynamically so that it was always brightened around a car to the maximum control level of 100 %, and in those parts of the road where there was no traffic, it was dimmed down to 20 % control level. The dimming and brightening was done softly using 3 seconds ramp. The bright area around a car consisted of five streetlights: the one which detected the car with PIR (passive infrared) sensor and two forward and two backward. In the third phase (lighting control from 6.3. onward, questionnaire 19.6.–2.7.), a third control method was introduced along the two former ones, based on the *measurement of traffic density*. Now the lower control level of lighting was adapting to the amount of traffic detected along the route. When the traffic was dense, for example, during the commutation periods in the morning and in the evening, the control level of lighting was dropped to 70 % on those parts of the road were there was no traffic. With the moderate traffic, the level was 40 %, and with the lowest traffic during the night, it was 20 %.

In the first and in the second phase, the questionnaires used were almost identical. Before answering to the questions, the participants were asked to drive the road with test lighting on during the dark period of the day. There was no sidewalk on the side of the collector road, so we were not able to gain feedback from walkers and cyclists. As a background information, we asked about the answerers' use of the road and conditions on it during the driving when they evaluated lighting. Other questions concerned overall impression of lighting; color of lighting; amount of lighting on the road surface and on the environment; evenness of lighting; and glare. The participants were also asked, how well they could see the roadway and other people moving on the road or in the environment. They could also comment what good was in the lighting, and whether there was something that bothered them in it. In addition, they were asked if they had noticed any changes in the lighting during different times of the day or during driving the test route. The people answering to the second questionnaire were asked whether they had noticed any change in lighting after the first questionnaire. Most of the questions were based on rating on a scale of 0 to 5 and with a possibility to comment freely the subject in question.

During the first two phases, the participants were not given any information about the new lighting in the area except that it was realized with LEDs and that the control of lighting was developed during the winter and spring. In the first two phases, we wanted to gain feedback of the genuine experiences on site, unaffected by any previous knowledge. In the third phase, our approach was totally different: the participants were given detailed information of the three different control methods of lighting that had been tested. At this phase, we were more interested in the participants' *attitudes* towards lighting in general and especially towards intelligent lighting and the three tested control methods. The influence of the shared information on users' experiences, attitudes, and values was also interesting to us. At this phase, the participants were not specifically asked to visit and observe the lighting on site. During the third questionnaire, outdoor lights were completely turned off except for a couple of hours in the dead of night, because of the long daylit periods in northern latitudes during the summer months.

For information sharing needs we had designed and developed a test version of an urban dashboard – the City Monitor for Salo [12]. In the dashboard web page, dynamic visualization of the lighting behavior, scalable charts illustrating the average lighting and energy consumption levels, and textual descriptions of each lighting control type were presented (http://sencity.cloudapp.net:8888/). The visualization of adaptive lighting behavior was realized in the form of a dynamic light map, presented on the aerial photograph of the housing area with dynamically altering illustrations of light distribution along the routes. The interface was interactive so that the users could themselves change between different control methods and zoom to different time spans of the chosen date. The PIR sensor data of a single date (8.2.) was used for simulating lighting behavior with the three different control methods, allowing comparison of the energy consumption [12]. The third questionnaire, both in a electronic version and a printed one, contained the same information but in picture and textual mode, without interactive and dynamic simulations.

B. Case Study 2: Presence-Based Lighting on a Light-Traffic Route, Helsinki

The second case study concerns evaluation of presence-based lighting on a light-traffic route in Siltasaari housing area in Helsinki. In this still on-going pilot, the target is to find out what kind of a detailed lighting behavior is suitable for presence-based lighting on routes used by pedestrians and cyclists. The aim is to design and test an optimal lighting behavior which saves substantial amounts of energy without lessening traffic or moving safety or the sense of security of route users during the dark. The piloted intelligent system has the ability of detecting the direction of movement of route users. Thus, the lighting control can be adapted to this information so that the lighting is brightened further ahead a walker or a cyclist than behind.

In the evaluation, two well-designed presence-based lighting behaviors will be tested and compared. The one will be designed to be perceptible by route users and the other to be imperceptible by them, changing the distance how far ahead the route users the lighting is brightened. Lighting will be dimmed to 20 % control level in those parts of the route, where no-one is moving, and brightened to 100 % control level around the route users. The brightening and dimming is done softly. Feedback of the experiences will be collected on site with the help of a questionnaire and a short, structured interview. In addition, questionnaires will be delivered to the apartments near the route, which have a view towards it, in order to find out how presence-based lighting is experienced from the interiors. For example, can dynamic changes in lighting cause disturbance to the inhabitants?

We conducted a preliminary evaluation in order to test our method, during two nights in the beginning of April 2017. We had invited participants from educational institutions for young adults around the test site. Altogether we had ten participants, two of them being primary school and high school aged children, who came with their parents. The evaluation protocol was arranged so that we had three interviewers with questionnaires, standing in the meeting point that was located in the mid-point of the route. First, we had a short introductory discussion with each participant, where we collected the background information. After that, each participant was asked first to walk to the one end of the test route and back. At this point, the first interview and filling of questionnaire was done. Then a participant walked to the other end of the route and came back for the second part of the interview and questionnaire. Each participant was walking and interviewed alone. The lighting control was designed so, that in the other half of the route, the brightened area in front of a walker was longer than in the second half of the route, and respectively, the first type of lighting behavior intended to be imperceptible and the second type intended to be perceptible. The evaluation was conducted from 9 pm to 10 pm, when there was not many other users of the route and it was dark enough outdoors.

The questions after each lighting type concerned the general impression of lighting; amount of lighting; possible sensations of glare; visibility of the surface of the route; visibility of other people; and visibility of surrounding environment. There was also two questions regarding safety: one on the safety of movement and the other on the feeling of safety. Most of the questions were asked based on rating on a scale of 0 to 5 and with a possibility to add comments of the subject in question. The participants were also asked, what was good about the lighting and whether there was something about the lighting that bothered them. Finally, they were asked if the lighting changed in any way as they were moving along the route, and if it did so in their opinion, they were asked to describe it and tell at which point they noticed something.

C. Case Study 3: Intelligent lighting with services in the Harbour Promenade, Lahti

In Lahti, a lake harbor promenade is being developed into an active recreational environment for citizens through introducing there intelligent lighting and new digital services. The 1,5 km long pedestrian route spans from the Sibelius music Hall in the main harbor area towards Sports and Fair Centre in the other end. The area has an interesting history with an important inland harbor, rail traffic, and industry.

The new, intelligent lighting for the area was devised with the help of a user-centric design and development process with city representatives, business partners, researchers, and users of the area. For the process and participatory methods, see [13]. The process is still on-going as the development of the area and its lighting is continuing. In the final design, smart lighting is employed, besides for creating energy-efficient and safe environment with good visibility, for activating and engaging, artistically communicative and informative purposes. Four sub-areas of design area with different kinds of characters were recognized, and supporting lighting and service concepts for them were designed: an active event promenade by the harbor; a historical rail track promenade in between two lakes; a dangerous crossing area of a busy road; and the backyard-type of area with small-scale industry in the vicinity of the sports and fair center. The final solution combines evenly distributed neutral white LED lighting, which is dimmed when no one is moving along the route, with an atmospheric play of dynamically controlled light dots on the path, capable of having colors, for example, for communicative purposes or seasonal themes.

The lighting infrastructure will be a combination of intelligent LED route lighting with PIR sensors, and effect lighting by RGBW LED spotlights and DMX control. Additionally, base stations for a free WiFi connection, web-cameras, loudspeakers, and assembly spaces for extra sensors will be integrated in the smart, wooden lighting poles. Thus, the ensemble will form a development platform for smart city services. The first phase of the project will be finished by the autumn 2017 and the rest during the year 2018. The participation process will continue in the autumn 2017 with a questionnaire about the needs and ideas for using the intelligent lighting system for digital services.

A history augmentation application was piloted and evaluated with users in November 2016, as the idea of presenting information about the history of the area through a service came up in the participation process. The evaluation was conducted with a testing session with a semi-structured interview and observation on site. When the lighting design will be realized and applied in services, for example in a light game application and in communicative purposes, further evaluation of experiences will be conducted. A suitable method could be, besides interviewing and observing on site, the *evaluation probes* method [14], which we have developed in our earlier research. It is inspired by *cultural probes* methodology [15], which was already applied in the user-centric design process of the lighting [13].

Reflection of the Evaluation Methods

In the Table 1, we have summarized a reflection of evaluation processes of the case studies, from the following viewpoints: 1) perspectives of experience aspects that are of specific interest, 2) evaluation methods, 3) successes we encountered, 4) challenges or problems detected, and 5) further ideas for development of methods.

TABLE I. ANALYSIS OF EVALUATION CASE STUDIE

Case Study	Analysis of Evaluation Case Studies				
	Context & Experience Aspects	***Methods***	***Successes***	***Challenges***	***Development Ideas***
1	Roadway Visual impression Lighting quality Visibility Perceptibility of lighting behaviour →Traffic safety Attitudes & values Acceptance	- Electronic and printed questionnaire - Rating scales and open questions - Driving and observing real-world road with two lighting types - Urban dashboard for information sharing	- Good sample: Phase 1: 130 people Phase 2: 106 people Phase 3: 52 people - Motivated participants - Sharing of information was valued by the participants - Combination of rating scales and comments - electronic and printed questionnaires	- Comparability of results weather conditions traffic density - Technology barrier with the urban dashboard and simulations	- Weather conditions more easy to control in the autumn - Observation time fixed to low traffic situation - Development of the dashboard according to the feedback
2	Light traffic route Visual impression Lighting quality Visibility Movement safety Sense of safety Disturbance	- Interview with questionnaire on site - Comparison of two lighting types in different parts of the route - Questionnaires delivered into nearby apartments	- Combination of rating scales and comments - Motivated participants - Good timing in the late evening	- Attracting enough participants for a good sample, in the test evaluation 10 participants - Influence of a different context on the experience - Real-world challenges of the sensor technology: wind and vegetation - Perceptibility of lighting behaviour	- Co-operation with local schools and senior service center, different age groups (teachers, pupils, parents, seniors) - The same test route for all lighting types

3	Harbour Promenade Interaction and participation Communication and information Social experience Atmosphere Movement safety Sense of safety	- Semi-structured interview and observation on site, experience gauging - Evaluation probes - System data analysis - Questionnaire for service users	Participation process and evaluation of history augmentation: Motivated participants Contextual knowledge and ideas	- Complex real-world environment and experiences - Technological challenges of the pilot	- Utilizing urban dashboard in information sharing and evaluation

The case study evaluations, the preliminary and the final ones, have been successful in many ways and provided us with interesting research material. Additionally, the challenges have aided us to develop the methods. In the case 1, *involving a community* with a close contact to the research area helped us to gain an excellent sample of answers from motivated participants. In the case 3 as well, we have already a group of participants who have been involved in user-centric design process. With case 2, we can expect challenges in attracting enough participants for a good sample, especially if we want to interview both walkers and cyclists. Community-oriented approach with co-operation with neighboring schools and the local senior service center will be applied.

Real-world studies are challenging due to the *complexity of environments and experiences*, which makes the research environment and situations not easily controllable. According to our experience, qualitative research methods are usually well suited to them as they are robust. Thus, with case 3, the plan is to apply a *combination of qualitative methods*. Evaluation probes [14] let the participants experience the site and give feedback in their own time without a presence of a researcher. On the other hand, interview and observation on site, in a form of experience gauging walking interview [1], [10], can as a more interactive method reveal other aspects of experience. However, in the cases 1 and 2, we are also targeting to get some quantifiable data and large enough sample for analysis. For that purpose, the *free-form comments supported well the rating scales* and were essential in some parts in *interpretation of results* as the numbers only could easily have been misinterpreted. This was the situation with the case 2, where we realized from the comments that differences in the two parts of the route were influencing more the answers than the differences in lighting. This notion has led us to adjust our research protocol.

Using both *printed and electronic questionnaire* proved to be a good solution as it enabled participants of *different age and technological abilities* to take part. In the case 1, the *sharing of information* about intelligent lighting solutions was appreciated by many participants and they gave positive feedback of the interesting study and the ability to participate in the development of lighting in their city. Even though the shared information was valued, there was also some critical comments of the dashboard details and some feedback that it did not work. The *risk of technology barrier* and *usability issues* should be solved in further development. Nevertheless, this kind of *bidirectional learning process* is essential in participatory design and research and a good way to engage people in studies and in developing their communities.

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An Evaluation Method for Façade Renovation Strategies in Residential Buildings Using Gaze Responsive Visual Comfort Assessments

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***Abstract*— Maintaining daylight quality while ensuring thermal comfort during periods of high solar gain proves to be a challenge in renovated multi-story housing. The objective of this study was to develop guidelines for facade renovation, where overheating problems can only be avoided through façade solutions. As a first step, different shading systems have been investigated and compared in terms of their daylight performance, visual comfort and gaze responsive characteristics. This trio evaluation method is going to be further developed and used for a larger set of selected shading devices.**

***Index Terms*— Daylighting, Gaze Behaviour, Overheating, Residential Buildings, Visual Comfort**

INTRODUCTION

Enhanced daylight quality in indoor environment is dependent on a series of multi-dimensional and dynamic physical and psychological parameters. Each pragmatic combination of these parameters at pre-design phase can lead to a different design outcome. The main challenge is to reach an embracive energy efficient and human-centric decision that allows for maximum use of daylight with energy saving benefits to enrich tenants' health and visual quality while avoiding visual and overheating. Most studies on daylighting and energy savings target commercial buildings with less focus on residential buildings' needs [1]. It is, however, commonly known that in residential buildings direct sunlight penetration is desirable and several countries have regulations to ensure a minimum required amount of direct daylight penetration [2]. Concurrently, advancing energy efficient solutions in renovation phase necessitate adopting high-insulation and air-tightness to avoid heat loss through transmission or infiltration. In addition, residential ventilation systems in many countries are only designed to ensure proper indoor air quality and not to cool indoor air [3] because air conditioning is not an energy efficient option [4]. Venting by opening of windows can be used for cooling purposes in moderate climates, but has limitations related to theft risks and outside noise. In combination with an increase in occupancy hours in residences due to the possibility of remote working, risk of being exposed to high indoor temperatures has increased. This has a negative effect on occupants health, wellbeing and productivity [5] especially among vulnerable groups such as children and elderly [6]. Moreover, elevated temperatures during day-time are followed by consequent high temperatures during night-time day which distorts the sleep quality [7].

To prevent overheating, one solution is to limit the solar heat gains through the façade. Experiences from high performance buildings show that cost-efficient dynamic solar shading can lead to energy savings related to cooling of up to 62% [8]. If the façade strategies are wisely set, an optimized use of daylight can enhance the energy efficiency of the buildings as well [9]. However, the selection of appropriate shading systems for residential buildings proves to be a challenge. This is partially due to limitations on appearance change of certain residential buildings rising from e.g. public preferences and acceptance. Weather conditions mainly in terms of external shading devices can also restrict the use of certain types of devices. Finally, fewer studies with focus on subjective preferences in this type of buildings add on to the complexity of the design decision-making process in such cases.

The objective of the presented study was to evaluate shading systems for façade renovation strategies based on daylight performance and daylight-induced visual risks.

A. Daylight Performance

When renovating residential buildings, one of the objectives should be to ensure maximum use of daylight to ensure tenants' enhanced health, well-being and visual quality, while avoiding visual and thermal discomfort caused by excessive daylight penetration and overheating. Daylight performance can be predicted by use of daylight metrics developed in the past decades. These metrics can mainly be categorized as either static or dynamic. Daylight factor (DF) is a static metric and it is used to measure the amount of diffuse daylight delivered to a point in space under overcast daylit conditions. DF is hence insensitive to climate, orientation, and surrounding of the building [10]. This metric limits exploiting the daylight potentials in buildings while neglecting eventual visual discomfort risks [11]. A number of Climate-Based Daylight Modelling (CBDM) metrics have, however, been proposed in order to overcome this shortcoming. In recent years the metrics such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) have been used for dynamic evaluation of daylight potentials in indoor environments [11].

B. Visual Discomfort

While playing a crucial role in any building's overall performance, discomfort glare is very hard to predict and design for [12] and it is a major concern in developing the right façade typology for its daylight performance. Several studies on discomfort glare in the past decades have led to mathematical models for discomfort glare quantification. These models have a larger focus on artificial lighting conditions and fewer attempt on daylighting with use of artificial lighting base experiments [13] and, more recently, under daylight conditions for Daylight Glare Probability (DGP) [12]. The models are mainly based on empirical methods where human subjective assessments are associated with relevant photometric relations linked with visual visibility and luminance contrast.

Additionally, a few studies have explored objective measures such as certain pupil fluctuation [14] and activities of facial muscles in the vicinity of the eye [15] to identify a source of discomfort. More recent studies have reported physiological responses such as degree of eye opening [16], eye movements and pupil constrictions [17] as indicators for discomfort glare. However, so far, only studies based on subjective assessments by means of questionnaires have been used to quantify discomfort glare.

C. Gaze and Visual Comfort

Gaze direction is where we direct our line of sight by jointly moving our eyes, head and body. With each gaze shift the luminance distribution in the field of view (FOV) changes and the visual system needs to re-adapt. Knowing that visual comfort perception is mainly dependent on the luminance distribution across different parts of the FOV [18], the gaze shifts and the eventual changes in adaptation level can impact the subjective or objective responses to luminous environment. So far, an assumption behind development of existing discomfort glare prediction metrics has been that the gaze direction is fixed towards a task area. In early design phases or in certain building types such as residential buildings, the "task area" is not the main design criteria. However, the visual comfort assessment for these types of buildings still proves to be beneficial.

Several recent studies have addressed the eye physiological response such as an eye opening in relation to glare [16]. Interpretation of the gaze shifts and re-adaptation process have been, however,(arbitrarily) addressed by extending gaze directions to a preferred angular range [19]. The dynamic gaze shifts responses to light and implementation of them in visual comfort assessments was then advanced [20] through a series of experimental studies where gaze observations with eye-tracking techniques coupled with photometric observations with high dynamic range (HDR) imaging techniques were used. The latter study led to development of a new gaze responsive method for discomfort glare evaluations based on prediction of gaze shifts as result of excessive glary patches in the field of view. This is done by means of a predictive model termed Light-driven gaze responsive (GR_L) which calculates the gaze shifts as response to glary patches in the FOV, their size and position in the FOV, and the average luminance the eye is adapted to. The predictive behaviour always sways away from the glary patches.

METHODODLOGY

In the present simulation-based study, six shading systems were evaluated for their daylight performance and afterwards four of them (due to time constraints) were evaluated for gaze responsive comfort. Daylight performance of the six shading systems with manual control were investigated using Diva for Rhino for three floors of the building, two neighbouring density scenarios (with or without) and two vegetation scenarios (with or without). Visual comfort simulations were done based on immersive spatial approach [21] in order to assess the photometric behaviour in a larger visual span. Based on this method several HDR renderings over a range of gaze (view) directions were simulated and evaluated for gaze responsiveness using the GR_L model [21] and visual comfort using the DGP model [12]. The visual span was set to 112.5°, which started from a perpendicular vector to the south-facing window, and ended at 112.5° inside the room where the window disappeared from the FOV. This visual span was divided into six gaze (view) directions and six 180° angular fisheye HDR images. The occupant position in a room (a viewpoint) was assumed to be at 1500 mm from the window and 1000 mm from the wall behind. All visual comfort related simulations were done for four time points during the occupancy hours set for residences (in time periods of 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m.) for one day in a year May 30 using Radiance rendering tool [22] and Evalglare tool [12].

A. Case Study

The case study building is a 4-storey residential building with heritage value located in central Copenhagen. The building represents a larger range of buildings in Denmark built in the period between 1850 and mid-1950s. The floors of the building (except the basement, which is not considered for the daylight conditions assessment) have identical layouts. The relevant specifications of the case study can be seen in Table I. Among the six apartment types, the more common layout with a south facing living room was chosen for the investigation.

TABLE I. STUDY CASE BUILDING SPECIFICATIONS.

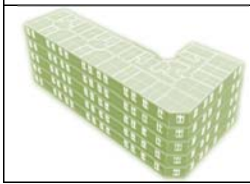
.Building Typology	Year	Exterior Walls	Simulated materials		
			Walls	*Floor*	*Ceiling*
	1850-1950	Masonry bricks (1-1$^{1/2}$ sten, increase with ½ per block from the 2nd floor)	Reflectance 80 % Specularity 0.36%	Reflectance 30 % Specularity 0 %	Reflectance 80 % Specularity 0.44 %

TABLE II. DETAIL SPECIFICATIONS OF SIMULATED SYSTEMS.

Device Position	Shading System	Device	Geometry	Material	Optical properties
	System 1	Double-pane clear glazing	-	-	T_{vis} = 82%
Internal	System 2	Roller blinds	-	Grey	BRDF calculation
External	System 3	Venetian blinds	C-shaped slat	Color 1 – White (Warema 71000)	T_{vis} = 0.00 R = 0.78
External	System 4	MicroShade	-	MS-A	BRDF calculation
Internal	System 5	Roller blinds		White	BRDF calculation
External	System 6	Venetian blinds -45° cut off angle		Color 2 - Grey-Beige (Warema 71005)	T_{vis} = 0.00 R = 0.64

B. Shading Systems

The selected systems from the numerous solar shading devices available on the market can be seen in Table II. System 1 represents the initial façade setting, Systems 2 and 4 include internal roller blinds, which are commonly used in residential buildings due to relatively low cost, easy instalment and operation, which interfere with the architectural form of the building only in a minimal degree. However, the device has limited effect for overheating preventions. In the simulations, the roller blinds geometry was simplified to two surfaces in addition to the glazing: a single surface representing roller blind's fabric with complex optical properties in 95 mm distance from the window pane and a transmission surface to assign the light transmittance properties.

Generic C shape venetian blinds were investigated as System 3 and System 6. There are several technical specifications to consider when selecting venetian blinds such as installation and operational type but it is mainly the slat's material and colour of the venetian blinds that affect its optical properties.

The last simulated device (System 4) was MicroShade. MicroShade is a thin metal sheet with microstructure surface, which is applied on windows with two or three layers of glazing. The device is glued directly to the window pane using glue stripes.

RESULTS

A. Daylight Performance

For all the rooms listed on each floor of the building the daylight simulations in Diva for Rhino were conducted in order to assess the daylight conditions based on two daylight metrics: Daylight Factor (DF) and Daylight Autonomy (DA 150 (lx) set as threshold). Table III shows the DA results for a south facing living room on the first and fifth floors for two different neighbouring densities (with or without) and two vegetation scenarios (with or without). The results of simulations showed that the daylight levels are insufficient, with the DA reaching only 150 (lx) approx. 53.4% of the time in the rooms only on the top floor. As expected, it can be seen that the DA values decrease for lower floors and with presence of a neighbouring building and/or vegetation. Use of shading systems reduces the daylight availability throughout the year. A grey venetian blind has the worse effect compare to all the other systems and we can see that MicroShade has the lowest DA value when either a neighbouring building or vegetation shades the façade.

TABLE III. DA RESULTS FOR FOUR NEIGHBOURING DENSITIES AND THE SIX SHADING SYSTEMS.

DA 150 (lx)	Simulated Conditions						
	Neighbouring density (No vegetation)					Neighbouring density (with vegetation)	
	Without	*Without*	*With*	*Without*	*With*	*Without*	*With*
Shading systems	***Floor 5***	***Floor 3***	***Floor 3***	***Floor 1***	***Floor 1***	***Floor 1***	***Floor 1***
System 1	53.4%	50.0%	22.7%	48.1%	17.5%	47.5%	17.3%
System 2	30.5%	28.8%	9.8%	30.0%	8.2%	29.5%	8.2%
System 3	30.6%	29.2%	9.5%	35.4%	10.0%	35.4%	10.3%
System 4	31.6%	26.1%	3.6%	23.0%	1.6%	1.6%	1.7%
System 5	31.6%	29.6%	10.1%	30.3%	8.5%	30.2%	8.6%
System 6	27.4%	27.8%	8.8%	34.5%	9.6%	34.3%	9.6%

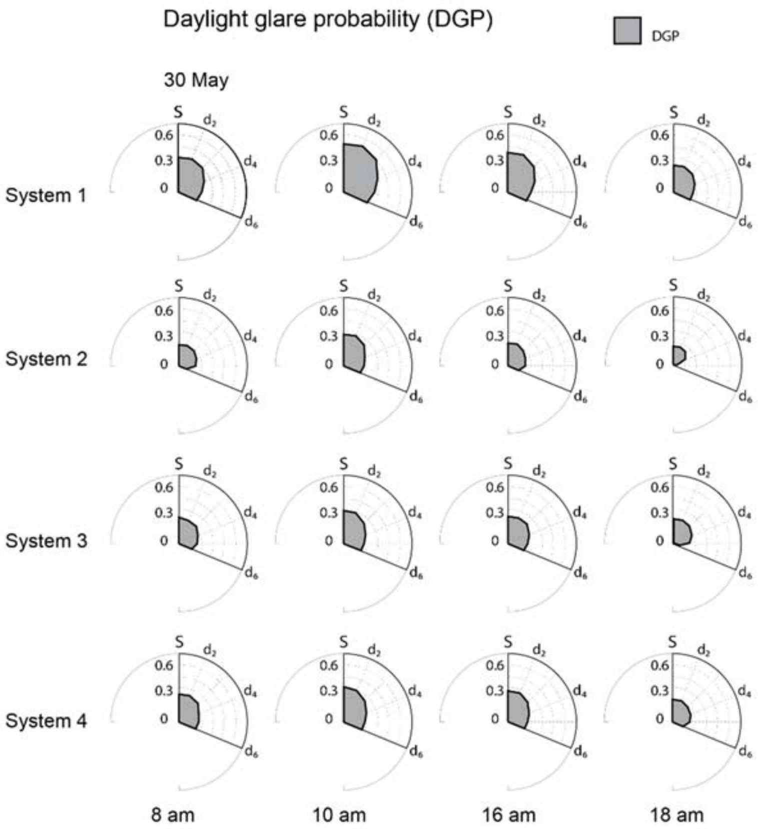


Figure 1. DGP results for Systems 1, 2, 3 and 4 for 4 time points within the occupancy hours 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m.

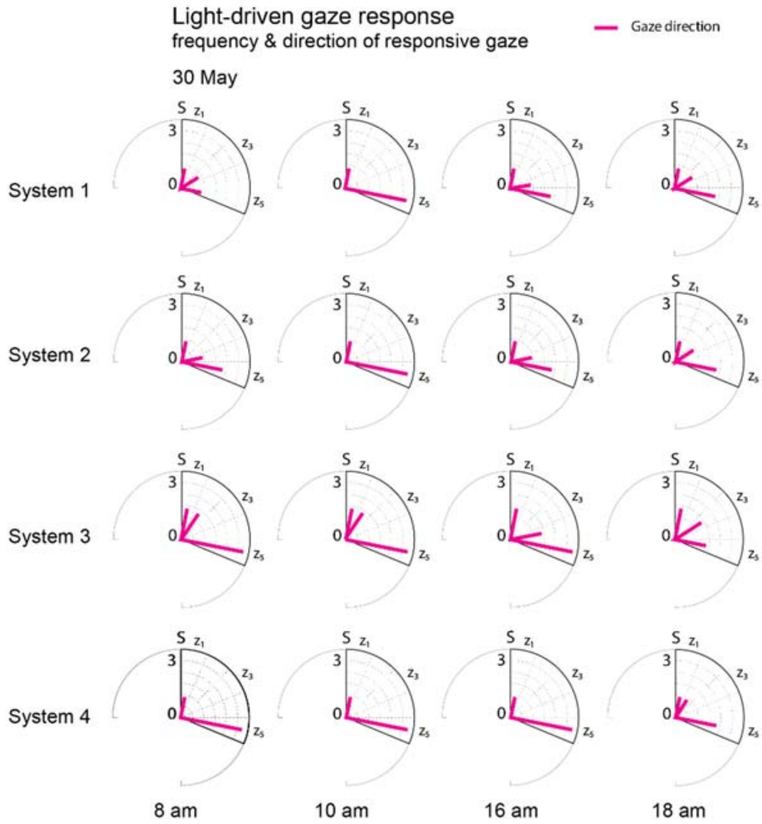


Figure 2. Responsive gaze direction predicted by GR_L for 4 time points within the occupancy hours 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m..

B. Gaze Responsiveness and Discomfort Glare

Radar graphs representing the DGP results for Systems 1, 2, 3 and 4 are shown in Fig.1. The results are reported for the 112.5° visual span where gaze (view) direction d_1 is towards south direction and d_6 at 112.5°inside the room from the window. In the graphs, the panorama extension of the FOV was highlighted. The DGP reduction can be observed by all the shading devices with the same trend over time. This reduction leads to DGP value equal to 0 at gaze (view) direction d_6.

The gaze shift frequency distribution is shown in Fig. 2. The graphs are angular histograms where the number of gaze directions falling in 5 bin zones (z_1-z_5) are shown. The representation of the visual span is the same as the previous graphs. The gaze (view) directions are largely corresponding to the discomfort glare predictions, which means that the highest gaze (view) directions frequencies are on zones where there is maximum discomfort glare reduction by means of the shading devices. This behaviour is consistent with roller blinds (System 2) and MicroShade (System 4) where a slight angle inside the room can assure a minimum exposure to discomfort glare. In case of venetian blinds (System 3), the general reduction of luminance levels in the room due to the 45° cut off angle of the slats, has created an even distribution of the gaze (view) direction frequencies. Moreover, in case of the initial case (System 1), higher glare impacts in all six view directions have shifted the gaze similarly for morning and afternoon. Whereas at 10 a.m. the gaze shift is more prominent due to the brightest glary patches in the FOV.

CONCLUSION

A combined gaze responsive visual comfort and daylight performance evaluations were conducted in order to assess various solar shading systems for residential buildings. The chosen evaluation methods allow assessing the daylight levels availability while assuring avoiding visual discomfort conditions. Daylight performance was assessed using DA. The visual comfort was then assessed for discomfort glare prediction using DGP and gaze responsiveness using GR_L evaluations methods for a selection of four shading systems. These evaluations were done for span of visual field from looking perpendicularly outside the window towards 112.5° inside the room where the window disappears from the FOV. The adopted three evaluation methods define different aspects of design for both façade and the interior space.

This so called “trio evaluation method” will be further developed for a sensitive comparison of the shading devices. Limitations such as neglection of view attraction dependencies for visual comfort assessments are going to be addressed.

ACKNOWLEDGEMENT

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Exploring Interaction with Office Lighting: a Case Study

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***Abstract*— Office lighting is fundamental for vision and for increasing wellness and working performances by considering the physiological and psycho-perceptual, the behavioural and social factors in relation to the working environment and activities. More than only functional, lighting is nowadays required to be flexible and customizable almost individually to deliver lighting quality for all. This article would analyse in detail the vantages and disadvantages of implementing LED lighting systems that provide lighting variability and control at a personal level, by describing, evaluating and critically reflecting on the characteristics of a prototype called Asterism realised at the Laboratorio Luce – Politecnico di Milano for technological assessment which was conducted at the ENEA DTE-SEN-SCC laboratory in Ispra (VA).**

***Index Terms*—Interaction, Lighting Design, Lighting Prototype, Technological Assessment, User Evaluation**

INTRODUCTION

Office lighting is fundamental for vision, for increasing working performances and wellbeing, considering the physiological, psycho-perceptual and personal factors. In addition to this, the social and behavioural factors should be taken into account due to the contemporary working tasks which require individuals to quickly pass from a focused job (individual tasks of concentration or relax) to team activities (creative collaborations and meeting) [1]. Each of these activities can be performed with different postures and requires different luminous atmospheres, which need to be consistent with the context, the purpose and the performed work activities. The use of new technological tools is inducing new ways to gesture and to work both in the micro space of the human body postures as well as in the workspace [2]-[3]: the multimodal use of different technological devices for reading and working (pc, display, keyboard, tablet, smartphone etc.) is determining different visual field and visual tasks [4]. In addition to this, recent studies about office future trends reveal the importance of creating healthy spaces in which workers can be “energized” or “relaxed” or where they can have breakout periods of “daydreaming” to refresh mentally and to be more productive in the long term [5]. According to this premises, more than only functional, nowadays, lighting is required to be flexible and customizable almost individually in order to deliver lighting quality for all. In order to ensure that individuals are able to experience their favourite luminous atmospheres to accompany different working activities and tasks, lighting should be flexible by providing a certain degree of control in terms of illuminance [6], white correlated colour temperature tuning (Cool White-Warm White CCT) or spectral tuning [7], [8], [9], [10] but also lighting distribution [11] for circadian stimulation, for personal satisfaction [12] with positive outcomes in terms of energy efficiency [13]-[14].

RESEARCH SCOPES

The first wave of LEDification [15] has been already applied in the market, providing retrofit of the traditional illumination systems with LEDs at increased efficacy, reduced costs and enhanced reliability through thermal and optical management. Today, the second wave of the application of LEDs technology is driving the design of digitally controlled lighting systems combined with advanced sensors and data elaboration which allow to change the lighting performances by adapting to the need of those which occupy the illuminated spaces. The correct application of the new SSL technologies and smart lighting systems can have an influence in the human psycho-physiological well-being [16]-[17], concurring in improving the overall quality of life (mood, health, satisfaction) of individuals. Office lighting can influence people cognitive performances at work, improving alertness and vitality, providing better sleep quality [18] and enhancing the general mood [19], through circadian rhythm activation/suppression. The quality of life of individuals can be enhanced also if they can control their lighting: when people work in environments that can be changed according to their personal preferences, they evaluate the lighting as of higher quality and the offices as more attractive, showing a more positive mood [20].

METHODOLOGY

The lighting performances allowed by the technological advances need to be supported by complex design decisions that should take into account the appropriateness of the lighting to the context and to the needs of the users [21]. This paper seeks to explore the relationship of users with individually customisable luminous experiences.

The LED lighting prototype, ASTERISM, was realized at the Laboratorio Luce – Politecnico di Milano with the research scopes to test the photometric aspects along with the tuning of white lighting, the efficiency and the lighting control. The case studies methodology [22] has been applied to test the activation or suppression of circadian stimulation, for behavioural control, for testing user interactions, for matching the colours with natural lighting (e.g. daylight during day, warmer dimmer light in evening), for cooling or warming the room to counteract exterior temperatures and for tuning lighting atmosphere according to users' preferences.

This article would analyse in detail the lighting performances provided by the LED prototype by describing, evaluating and critically reflecting on the results of the technological assessment conducted at the ENEA DTE-SEN-SCC laboratory in Ispra (VA).

CASE STUDY: ASTERISM

In this prototype, emphasis was put on the modularity of the lighting fixture for the multifunctional desk, adaptable to different working scenarios, from individual to collective working modalities. It is composed by several functional modules which ensure the maximum flexibility of installation in terms of spatial composition and lighting distribution/variation in relation to working activities. Asterism complies with standard EN 12464-1(2011) regarding omnidirectional glare reduction and consists of a supporting structure with connected lighting modules to create a constellation of luminous elements [23].

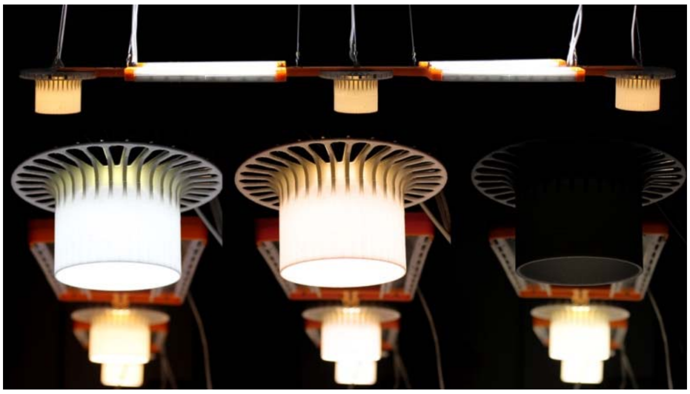

Figure 1. ASTERISM lighting performance: direct –indirect lighting prototype with different CCT and single modules controllability.

The main elements are:

- box for LED driver, Arduino board and XBee Shield mounted on the ceiling;
- three modules for direct illumination (down-light);
- four modules for indirect lighting (light-up);
- management and control system (interface).

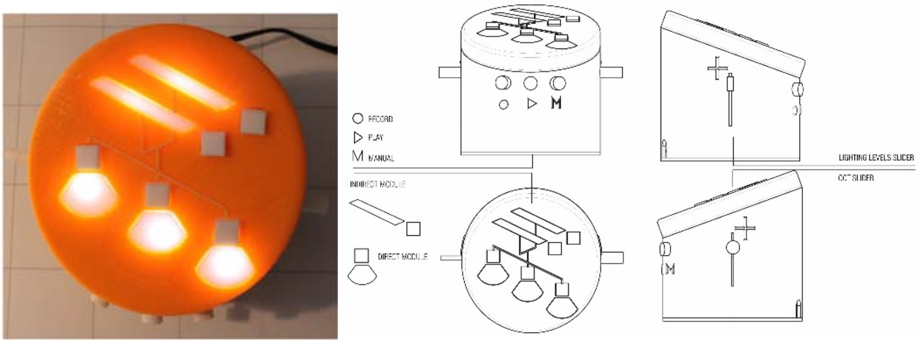

Figure 4. ASTERISM interface and control system

ASTERISM interface allows to control the lighting by selecting different pre-programmed lighting scenes. In addition to this, it allows to turn on and off each lighting module separately. The interface is provided with a visual diagram of switches representing the lighting modules: each switch allows to control manually the CCT (between 3000K and 6500K) and the intensity of each direct and indirect module. As reported in the literature review [24], individuals prefer to save their lighting settings: for this reason the interface was designed to allow to save personal lighting scenes for later recall.

Technological Assessment

A. The Installation

The prototype Asterim has been installed in a room of the ENEA building at Ispra (Italy). The room (4.75m x 5.25m x 2.70m), is provided with daylighting through a wide glass wall facing a big laboratory, the entrance glass door and a window (2m x 0.6 m) located in the upper part of a wall. As the room is located in the North side of the building and there is no direct sunlight. The furniture consists basically of a table (1m x 2m) with chairs, some bookcases, a refrigerator-freezer and a PC workplace. The room is used mainly as control room for the laboratory or meeting room for small groups. Asterism is the main lighting system, allowing monitoring of real usage. People were left free to dim the system according to their personal needs and preferences.

The lighting scenarios used in the tests were the followings:

- Scenario 1 – Workshop supports the multifunctional work during meeting and group activities. Each direct lighting module is turned ON (max intensity) along with the indirect lighting modules. CCT is tuneable.
- Scenario 2 – Focus ensures the creation of an environment suitable for individual work, where the increased focus on the visual task implies higher level of illuminance on the task with direct lighting modules ON. The surroundings are also evenly lit from indirect lighting modules. CCT is tuneable.
- Scenario 3 – Haven configures a private working environment, with only the direct lighting modules on the work surface of the desk, ensuring moderate levels of illumination in the visual task. Indirect lighting is turned off to reduce the perceived space of the room for a subjective solitary concentration. CCT is tuneable.

Figure.. 3 The room where Asterism is installed

B. The Tests

Photometric, radiometric and electrical tests have been performed, mainly to quantify real system performance:

- energy consumption of different elements (lighting modules, control interface) at full power and with different levels of intensity (dimming) and CCTs tuning between 3000K-6500K;
- dimming curve (luminous flux and spectral variation in relation with electric power);
- illuminance and spectral irradiance on the working plane in different dimming conditions: at full power and with different levels of intensity (dimming) and CCTs tuning between 3000K-6500K, for the individual modules and for the whole system;
- vertical illuminance and spectral irradiance at eye level, at full power and with different CCTs tuning between 3000K-6500K;

Energy efficiency of the system has been assessed.

As a general rule, as tests have been performed on field and not in laboratory conditions, care has been taken to minimize disturbance:

- ambient temperature always in the range 20-25°C
- stable conditions before measurements
- double fast measurements, with the system ON and the OFF, to decouple daylight contribution.

After some months of operation, a simple questionnaire has been proposed to assess qualitatively the system performance according to the users satisfaction.

RESULTS

Energy consumption and efficiency are important and are related to performance. Energy consumption is due both to the luminaire and to the control system. Electric power is about 100W at full power, independent from CCT, and global efficiency (auxiliaries and control included) is 62 lm/W, a very good value in this sense. Based on the measured values, consumptions of a typical winter and summer day have been hypothesized, in the "Workshop" scenario. The room is supposed to be occupied from 9am to 6pm, with a break during lunch time. Artificial lighting is in ON-mode and dimmed according to daylight (room occupied). Dimming in CCT, left to the users, does not influence energy consumption. Otherwise, it is in standby mode. As the controls are at the moment "manual", this simulation assumes very "smart" users (and it is indeed true at ENEA Ispra).

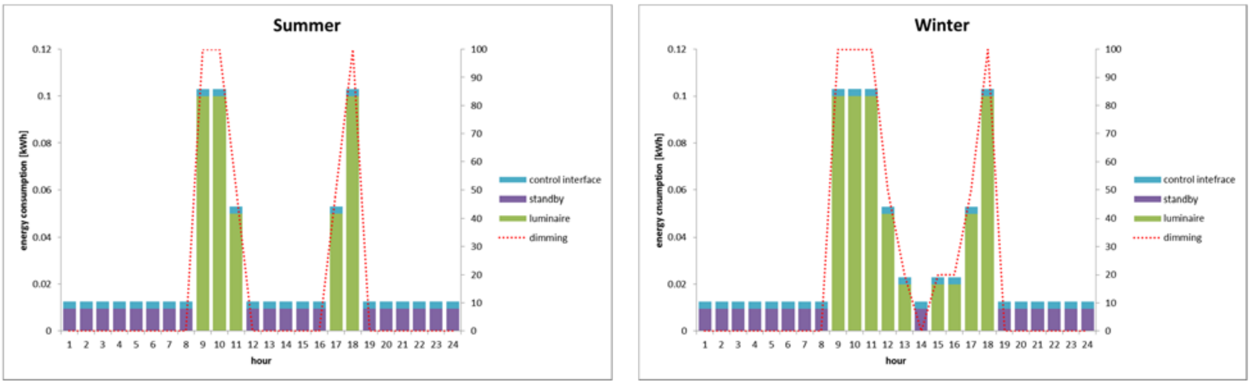

Figure 2. Energy consumption in summer and in winter

Standby mode consumption is not negligible, being 24% in winter and 36% in summer: this can be improved in the future, by adding a device to switch OFF the system, when people are not present. Dimming curve (flux=f(power)) has resulted to be linear and the spectral power distribution (SPD) of the light is independent from the flux-dimming level, ensuring good comfort in dynamic operations. The system is well calibrated, so that illuminance, at a given flux-dimming level, is independent from the white CCT: this is of great benefit for users, who do not have to adjust the amount of light when they move form cold to warm light or opposite. Finally, measurements of irradiance at eye level show that the contribution of the environment (i.e. surfaces of walls, furniture, ceiling) plays an important role: in the figure it is shown the normalized irradiance on the table (horizontal) and at eye level (vertical) with the luminaire totally ON (direct + indirect modules), only indirect ON and only direct ON.

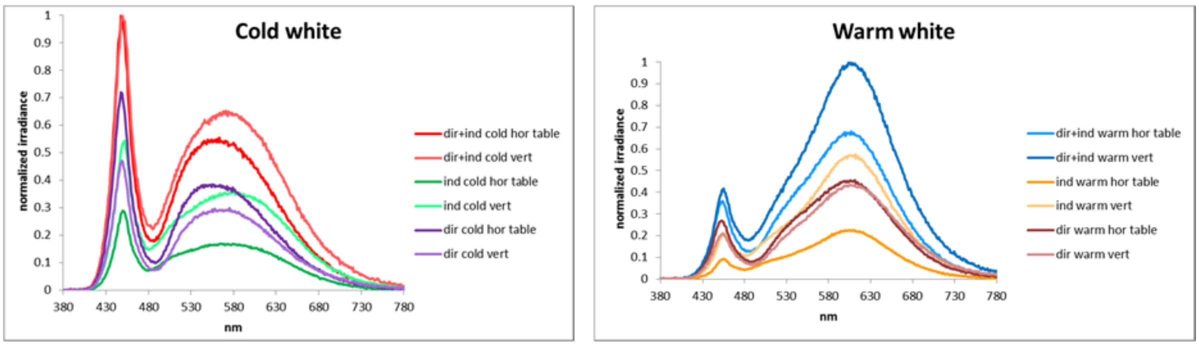

Figure 3. SPD changes measured at eye level and on the table, for indirect and direct lighting distributions

The contribution of the environment, visible from changes in SPD, are more evident for indirect lighting, as expected, and for cold white, as the furniture is light brown with a higher reflectance in "red" than in "blue".

Coming to user satisfaction, the following questionnaire has been proposed (with different timing, to 30 people):

- which type of activity do you perform in the room with Asterism?
- do you think the natural lighting is always sufficient for your tasks?

- do you prefer the old lighting system or Asterism?
- regarding Asterism:
    - do you consider the light sufficient for your tasks?
    - do you prefer direct, indirect or direct + indirect light?
    - do you prefer warm or cold light? Any preference for direct / indirect light?
- is it useful according to you the possibility of dimming? In amount of light? In white hue?
- is it simple to manage / control the Asterism system?

The principal activity in the room has been "meetings", physical or virtual (scenario "Workshop"), while somebody also use the room to work alone (scenario "Focus"). Natural lighting has not been considered as sufficient, mainly in the early morning or late afternoon, so that artificial lighting is needed. 100% of the people prefer Asterism to the old system (traditional fluorescent tubes).

One of the first outcome of the monitoring campaign was that people liked direct + indirect lighting also during individual work, preferring a wider visual angle (scenario "Focus") to a lighting only focused only onto the task area (scenario "Haven").

All the participants with one exception were satisfied with the amount of light with Asterism, taking into account the correct dimming. All the participants with one exception preferred direct + indirect light, in each working situation: the remaining person liked the possibility to choose, according to the mood of the moment (mainly in Focus). Most of the people (90%) preferred warm light, independently of the time of day or other parameters. One person (the same as before) preferred also in this case the personal freedom to choose. Everybody appreciated the possibility to change, both the amount and the CCT of light, but only 2 participants found easy to use the control interface, while the majority found it not user friendly and few people never tried themselves. The conclusion today is very positive. The discomfort with the control interface is perfectly understandable, being a prototype where a minimum training is required: this can be easily solved in future development of the system.

CONCLUSION

The technical characteristics of the installed and operative Asterism are in very good agreement with the design: the dimming is very well balanced, the spectrum is rich and the light distribution gives a pleasant result, beyond standard lighting requisites fulfilment. Energy efficiency is high. People appreciate the Asterism lighting system and appreciate the possibility to "customize". The improvement of the interface of the lighting system needs an iterative user testing and deeper evaluation which should be performed in order to assess the easy to learn first and the easy to use in terms of affordance, feedback and consistency for a more engaging user experience.

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Estimate of the Energy Efficiency Potential in Street Lighting in Serbia

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***Abstract*—This paper summarises the current situation of street lighting in Serbia, i.e. the currently installed technology, typical roads and lighting arrangements. For some municipalities detailed data have been collected while for other municipalities we rely on an inquiry by the Serbian "Standing Conference of Towns and Municipalities" (SCTM). In two cities dynamic light level measurements were conducted. For estimating the saving potential, two scenarios were developed, based on different assumptions in respect to the instalment of LED luminaires and results were extrapolated, based on the available data. One scenario is based on the assumption that only the most inefficient lamp technologies like high pressure mercury (HPM) are exchanged to LED, while the other scenario assumes that all technologies (except already installed LEDs) are replaced. In addition, the current possibilities for the involvement of Energy Service Companies (ESCOs) in the process of improving the energy efficiency of street lighting are presented.**

***Index Terms* –Energy efficiency, Energy Service Companies (ESCO), Public lighting, Serbia, Street lighting**

Introduction

Street Lighting is one of the major consumers of electricity in municipalities, for which expenses have to be covered by municipalities' budgets. Due to financial constrains in many European municipalities street lighting infrastructure has often been neglected for many years resulting in old and inefficient systems. However, increasingly climate protection targets put energy savings on the agenda of central and local governments and the out-dated street lighting systems often offer very high saving potentials – in particular with LED technology becoming more and more affordable. To realise this potential, several countries have launched specific programmes supporting the refurbishment of street lighting. In Serbia the European Bank for Reconstruction and Development (EBRD[3]) is running an EU funded Regional Energy Efficiency Programme (REEP[i]). REEP covers the Western Balkans and has provided - among other things - technical assistance for project identification, preparation etc. for street lighting energy efficiency improvement with a focus on ESCO projects and provides street lighting tailored financing[ii]. The assessment of the energy saving potential for Serbia is based on data collected in the context of REEP[iii] projects[4].

Current Situation Serbia

A. General Information

Serbian municipalities are, by law, in charge of providing public lighting services. However, while public lighting is categorized as a "municipal service" it is also classified as an "energy related activity" under the responsibility of electricity distribution operators. Thus, the ownership of public lighting infrastructure is divided between these two actors. While luminaires and lamps are typically part of municipal property, the electricity distribution companies usually own transformer stations, poles and supply lines. Since 2015 municipalities need to tender annually for the public lighting electricity supply on the market. From available data, an average tariff of EUR 0.064/kWh, including all fees and taxes except VAT can be assumed for 2016. However, electricity tariff is expected to rise in the next years (for households it has already happened). Thus, for the modernization of street lighting, assumed to take place in a timeframe of the next 10 years, a constant average electricity tariff of EUR 0.08/kWh was used for assessing potential financial savings.

B. Data Basis For Estimation

As in many countries, available data on currently installed street lighting is very limited. In assessing the structure of the public lighting system in Serbia, including 5,860,138 inhabitants (without the City of Belgrade) two sources of data were combined. Belgrade City was excluded because the size and the high urban density of Belgrade City would distort the average data for Serbian municipalities. The two data sources are:

- Self-reported data from 30 municipalities in response to a questionnaire sent out by SCTM in 2015
- Data from 17 municipalities collected with questionnaires in the framework of projects carried out by EBRD in the context of REEP

In relation to the above-mentioned number of inhabitants, these two data sources jointly reflect the current PLS in an area with 2,209,049 inhabitants, i.e. a share of some 38 %. The following TABLE I summarises the installed technologies with the average lamp capacities for the available data. The last two columns list the estimated number for Serbia[5] (multiplied by sample factor 2.65).

TABLE I. SUMMARY OF TECHNOLOGIES AND CAPACITIES INSTALLED – DATA SOURCES AND SERBIA (EXCL. BELGRADE CITY)

Available data (38 %)					**Assessment entire Serbia**	
Light source technology	***Number of lamps***	***Share of light source technology***	***Average capacity per technology [W]***	***Total currently installed capacity per technology [kW]***	***Number of lamps***	***Total currently installed capacity per technology [kW]***
HPM	144,128	52 %	142	20,466	382,340	54,292
HPS	122,523	44 %	137	16,786	25,674	2,567
Other	9,678	3 %	100	968	325,028	44,529
LED	775	0.003 %	70	54	2,056	144
All	***277,104***			***38,274***	***735,098***	***101,532***

C. Light Sources

At present, the most commonly installed light sources in street lighting in Serbia are high-pressure Mercury lamps (HPM) with some 50 % and high-pressure Sodium lamps (HPS) with some 45 % while Metal halide lamps (MH) and (Compact) Fluorescent lamps (hereafter CFL/LFL) are only rarely installed. Some municipalities have started with light-emitting diode (hereafter LED) technology, but this is currently still an exception.

Most common capacity for HPM lamps is 125 Watt. Higher capacities, i.e. 250 Watt and 400 Watt are also installed while lower capacities (50 Watt, 80 Watt) haven’t been reported. For HPS lamps 70 Watt, 100 Watt and 250 Watt are frequent.

D. Luminaires

Due to limited investments in the public lighting systems in the last 20 years, luminaires are in general rather old with basic or almost no optical systems to direct the light. Electronic ballasts are practically not installed.

E. Infrastructure

In most municipalities, energy for street lighting is supplied by overhead cables. A street lighting cabinet usually supplies between 40 to 90 LPs. Luminaires are often mounted on poles used in parallel for general energy supply.

Poles height is commonly between 6 meter to 8 meter with some poles in city centres/pedestrian areas are lower and in some main roads 10-meter poles are installed. The most common distance between poles is 30 meter and 40 meter and lighting arrangement is normally one-sided.

[5] Belgrade excluded (applies for the entire paper)

Figure 1. Examples of street lighting arrangements in Serbian municipalities

F. Control

Street lighting in Serbia is often turned on and off according to a switching calendar. In a few municipalities photocells are installed. If a switching calendar is applied, operating hours are reported to be around 4.100 hours.

Light level reduction in night times is very seldom used. Only one of the bigger municipalities reported the application of light level reduction during night hours. I.e. many of the main roads show light levels for rush hours (often 250 Watt or 400 Watt HPS are installed), even if almost no traffic occurs.

G. Light Level

The light quality in main roads in city centres differs a lot from the light quality in side roads of municipalities or in villages. One reason for poor light quality - especially low uniformity - in small villages is that in some cases public lighting has been organised by citizens' own contributions as a modest technical solution to maintaining the system with no lighting design carried out. Several of very basic luminaires with 125 Watt HPM lamps were installed in such a context (see Figure 2)

Figure 2. Basic luminaire with 125 Watt HPM in Serbian villages

In the framework of two REEP projects the illuminance was measured in selected streets in 8 municipalities. In total about 4,000 LP were covered by the measurements. The measurements show a high variety of levels. Generally speaking, light levels in the main roads in the city/town centres are sufficient. In one particular municipality new LED installations provide rather high lighting levels - comparable to M2 - although the streets have rather residential character.

In smaller streets and especially in rural villages, measured minimum illuminance levels are very low which is caused either by high distances between two light poles (in conjunction with poor light distribution) or more often by neglected maintenance (i.e. malfunction of lamps). The lack of maintenance is generally a result of municipal budget restrictions.

SAVING POTENTIAL

Two scenarios for the saving potential in relation to LED technology were developed. One scenario – so-called "conservative scenario" - is based on the assumption that only the most inefficient lamp technologies like high pressure mercury (HPM) are exchanged to LED and HPS technology is not touched, while the other scenario – so-called "progressive scenario" - estimates the potential if all technologies (except already installed LEDs) are replaced. For both scenarios the calculation includes a light level reduction of half of the light points down to 60 % for 6 hours during the night (23:00 to 5:00). The values for the current system are taken from TABLE I above.

For the *conservative scenario* the following saving potentials are derived:

TABLE II. SAVING POTENTIAL – CONSERVATIVE SCENARIO

	Unit	Current system	Conservative scenario	Savings
HPM	[#]	382,340		
Other	[#]	25,674		
HPS	[#]	325,028	325,028	
LED	[#]	2,056	410,070	
Capacity	[kW]	101,471	57,176	
Energy consumption p. a.	[GWh]	420	237	**183**
CO2 Emissions p. a.	[tons]	396,792	223,584	**173,209**
Energy costs p. a.	[M EUR]	33.6	18.9	**14.7**
Maintenance. costs p. a.	[M EUR]	6.7	3.8	**2.9**

For the *progressive scenario* the following saving potentials are derived:

TABLE III. SAVING POTENTIAL – PROGESSIVE SCENARIO

	Unit	Current system	Progressive scenario	Savings
HPM	[#]	382,340		
Other	[#]	25,674		
HPS	[#]	325,028		
LED	[#]	2,056	735,098	
Capacity	[kW]	101,471	28,574	
Energy consumption p. a.	[GWh]	420	118	**302**
CO2 Emissions p. a.	[tons]	396,792	111,736	**285,056**
Energy costs p. a.	[M EUR]	33.6	9.5	**24.1**
Maintenance. costs p. a.	[M EUR]	6.7	1.9	**4.8**

The CO_2 Emission factor for electricity consumption in Serbia is 0.945 kgCO2/kWh (Serbian Ministry of Environment, Mining and Spatial Planning, Belgrade, Serbia, June 2011)

As presented in the two tables above, a high saving potential of 183 Gigawatt hours for the conservative scenario and 302 Gigawatt hours for the progressive scenario is estimated for modernisation of the public lighting systems in Serbia by LED technology. Corresponding financial savings in energy and maintenance costs sum up to 17 million Euros and 29 million Euros respectively.

ESCO APPROACH

A. Rational For An ESCO Approach

The call to modernize and expand public lighting systems is in sharp contrast to the simultaneous pressure on municipal governments to reduce expenditures and improve efficiency. As a result, government institutions have increasingly looked to the potential of using innovative public private partnership (PPPs) such as energy performance contracts (EPCs), to procure infrastructure management services.

Within the EnPC, the private partner is entrusted with the tasks of reconstruction, financing, and maintenance of the public lighting system in the municipality, including the assumption of the risk to achieve financial saving in the course of operation of the reconstructed part of the system. The private partner undertakes to apply such energy saving measures which will ensure financial savings in the system within the guarantee period, in compliance with the public contract and with positive regulations and valid standards in Serbia.

The main goals of award of an EnPC are:

- Capital investment in the utility service of public lighting by mobilizing private capital,
- Improvement of the quality of the public lighting service to citizens in compliance with prescribed standards,
- Implementation of energy saving measures, while realizing savings in the current budgetary expenditures for electricity and maintenance of the public lighting system.

It is important to note that as the EPC is based on "performance" the related procurement process must be "outcomes oriented". The traditional approach to procurement of goods and services - often managed by municipal staff with limited focus on energy efficiency and energy savings - has specific deficiencies in procuring energy efficiency investments for several reasons:

- firstly, the focus of the "subject matter" for procurement is "goods or works", rather than "energy savings",

- secondly, the contractor (i.e. the municipality) traditionally pre-determines the technical solution rather than leaving the identification of the best (economically most favourable) technical approach to the competitive bidding process ("ESCOs compete by concept") and
- thirdly, the traditional procurement process focuses on the initial investment costs rather than on lifecycle costing taking into consideration the initial investment as well as the resulting financial savings through reduced costs for energy consumption and maintenance.

Because of its stable and predictable load as well as the usually high energy saving potential, public lighting has traditionally been in the focus for ESCO approaches.

B. *Legal Framework For Enpc Projects*

The most relevant documents of the Serbian legislation for EnPC projects are the following:

- The Act on Efficient Use of Energy (Official Gazette of RS, No. 25/2013)
- The Rulebook on Model Energy Service Contracts for the Implementation of Energy Efficiency Measures when Users are from Public Sector (Official Gazette of RS, No. 41/2015)
- The Energy Act (Official Gazette of RS, No. 145/2014)

Especially the "Rulebook", a By Law of the Law on Efficient Use of Energy, guides municipalities in developing an EPC projects.

The model agreements stipulated in the Rulebook envisage three main periods of the ESCO agreement:

- Preparatory Period, mainly consisting of planning and design activities related to the relevant project;
- Implementation Period, in which the private partner implements the energy savings measures in cooperation with the public partner;
- Guarantee Period, in which the energy savings potentials of the contracted facility are utilised resulting in financial savings, which are being used (fully or partially) for remunerations to the private partner.

Using this framework, in the meantime 16 public lighting EPC projects are at different stages of being implemented in Serbia.

SUMMARY

The technical saving potential in street lighting in Serbian municipalities is high. Obviously, the potential is the highest when exchanging inefficient lamps like HPM lamps, which still have a share of above 50 % in the public lighting systems in Serbia, to high efficient LED technology.

Although data on currently installed technology is limited, information from several sources could be combined to cover about 38 % of Serbia (in terms of inhabitants and excluding the city of Belgrade). From this data a saving potential can be derived of 183 Gigawatt hours for the conservative scenario (only inefficient technology is exchanged and HPS technology is kept) and 302 Gigawatt hours for the progressive scenario (all light points are exchanged to LED). Corresponding financial savings in energy and maintenance costs sum up to 17 million Euros and 29 million Euros respectively if an average electricity tariff of 0.08 Euro per Kilowatt hour is presumed for the next decade.

Since municipalities in Serbia face budgets restrictions due to heavy debt burden, an ESCO approach could offer a solution. Not only the financial risk could be transferred to the ESCO while ensuring good performance of the system, also specific know-how in energy efficiency measures can be provided by the ESCO. First 16 municipalities are currently in the process of implementing this approach and it is expected that more municipalities will follow.

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[4] [1]The data was mainly collected within the project „ ESCO Pipeline Preparation in Serbia", that was carried out in the framework of the EU funded „Regional Energy Efficiency Programme (REEP) for the Western Balkans" and which is being coordinated by the European Bank for Reconstruction and Development (EBRD).

[1] These estimate reflect the authors' view only and does not represent an official EBRD assessment

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Experimental Investigation of the Correlation between Power Consumption and Luminous Flux of LED Luminaires in Adaptive Road Lighting

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***Abstract*—The introduction of the LED and central management systems (CMS), enabled stakeholders to succeed in having considerable energy savings. The operation of CMS is based on the LED driver dimming properties without considering the LED parameters. The relation between luminous flux and power is examined in this paper, as well as the variation of the power and other critical quality characteristics under dimming such as junction temperature. A noticeable non-linear relation between LED flux and power consumption of the total system was depicted, by a series of laboratory measurements. A variety of power quality parameters was determined such as power factor. With the consideration of the non-linear relation of flux and power and the potential effect of dimming to power networks in mass replacement and dimming schemes, the lighting community stands to gain further energy savings that will be achieved through a correct set of choices in the luminaire components.**

***Index Terms*—LED lighting, dimming, LED temperature, power factor, energy savings**

INTRODUCTION

The introduction of light emitting diodes (LEDs) technology was a breakthrough that helped lighting technology to drastically reduce the energy consumption of lighting installations as well as greenhouse gas (GHG) footprint compared to existing conventional lighting technology sources. In Europe, the percentage of lighting in total electrical energy consumption, has been significant as it accounts for 14% of the total electrical energy consumption [1]. In Europe, an accelerated shift to LED technology would help to achieve EU 20-20-20 energy efficiency targets. In case where solid state lighting (SSL) adoption reached 100%, it would result a 4% lighting share in total EU's electrical energy consumption. Besides their own high energy saving potential, LEDs in combination with central management systems (CMS) and further dynamically adjusted motion and traffic sensors can produce higher energy savings. [2-7]

The revised EN/TR 13201-1: 2014 has set the framework for dimming schemes in the ongoing and rapidly expanding lighting infrastructure refurbishment projects. It provides the methods of selecting alternative lighting classes that consequently allow the dimming of the LED luminaires depending on critical installation parameters such as ambient luminosity, traffic volume etc. The EN 13201-5 introduced the method of calculation of energy performance indicators in road lighting installations. The standard introduces two metrics, the power density indication D_P and the annual energy consumption D_E. [8]

The operation of the remote-control systems and stand-alone drivers has been based solely on drivers' characteristics without considering the LED engine parameters. The widely-used simulation platforms such as RELUX or DIALUX in order to calculate energy performance indicators, they consider a linear relationship between power and luminous flux due to the fact that there is currently very limited information available by luminaire manufacturers regarding the behavior of their luminaires in dimming states. There is a lack of combined information available to the lighting specifiers. Even though the lighting community has set standards and specifications that control initial characteristics of the road LED luminaires, there is currently no wide spread information on the dimming properties and behaviour of road luminaires in adaptive road lighting cases.

An information system that would be available to all lighting stakeholders under a common format would help address this issue and connect the information of the LED sources with those of the LED drivers and/or other components inside the luminaires. The information should be provided in a way that the stakeholder will be able to fully exploit the dimming capabilities of the luminaires resulting in correct D_P, D_E calculations or even higher life expectancy projections in LEDs and other electronic components.

The scope of this paper is to research and model the connection between the LED luminous flux and consumed power of the LED road luminaires that were tested. Furthermore, other various critical luminaire parameters were measured to investigate the total behaviour of the luminaire when it operated under dimming. The dependencies of Correlated Color Temperature (CCT), solder point temperature (Tsp) of the LEDs, case temperature of the driver (Tc) and ambient temperature (Ta) inside the luminaire were considered. The combination of all measured parameters was used to establish the dimming profile of each luminaire.

EXPERIMENT MEASUREMENTS

For the purposes of this study two luminaires were examined. One of the luminaires was modified and tested with two different types of drivers in two different current levels, making the total number of devices under test (DUT) equal to 3. The technical characteristics of the tested luminaires are presented in Table I:

TABLE I. SPECIFICATIONS OF THE LUMINAIRE EQUIPMENT

DUT	*Number of LEDs*	*Driving Current (mA)*	*Driver Rated Power (W)*	*Total Consumer Power (W)*
A	64	500	150	99.16
B	64	700	150	141.94
C	66	700	150	140.20

Each DUT was subjected to dimming following the simple dimming protocol of 1-10V which was available in all three DUTs. The full range of dimming capability of the DUTs was explored utilizing 0.5 V steps for each measurement in the range of 1-10V. For each dimming stage, a set of simultaneous measurements related to various characteristics of the DUT was conducted and specifically output luminous flux, total consumed power, power factor (PF), total harmonic distortion (THD), Tsp LED temperature, Tc Driver Temperature, Ta electrical compartment temperature and CCT measurement.

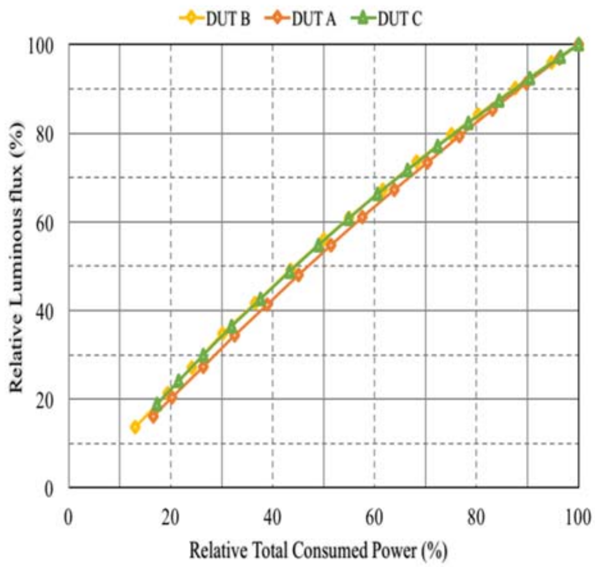

Figure 1. Correlation between relative luminous flux and relative total power of DUT

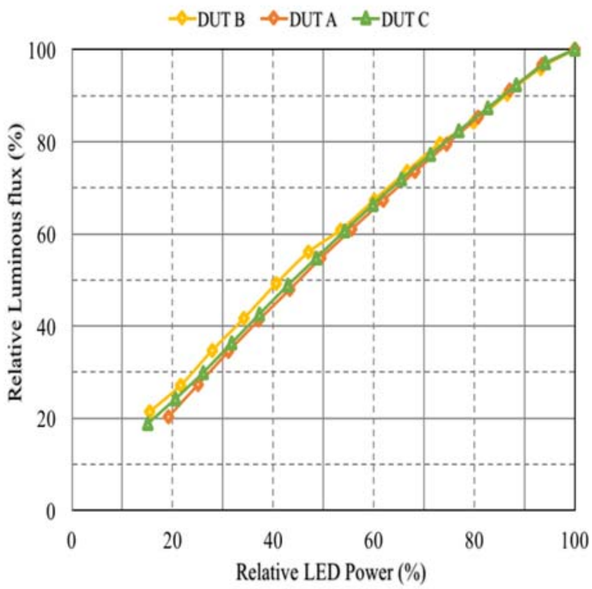

Figure 2. Correlation between luminous flux and relative calculated LED power down to dc current 100mA

A clear nonlinear correlation between the relative luminous flux output and the relative total luminaire power is observed in Fig. 1 in all three cases. The performance of DUT B and C is better than of A, whereas A and B have the same type and number of LEDs. The difference between power and luminous flux could lead to different lighting designs in adaptive road lighting schemes and energy performance indicators calculated in simulation software. For example, a demand for 50% of relative luminous flux is met with 46,9% relative power in A, 44.3% in B and 44.4% in C. The difference between the A, B and C in efficiency, shows that not all the LED module and driver configurations react in the same way under dimming. Consequently, there are more specifications that need to be considered when choosing a LED luminaire intended for dimming, apart from its initial luminous and electrical performance. Furthermore, DUT A having been set at 500mA has already higher efficacy than DUT B and DUT C (set at 700mA), whereas the percentage increase in relative efficacy was lower when all DUTs were dimmed.

To establish the source of the difference between the luminous flux/power curves of each DUT, power indicators were calculated based on LED die characteristics. The LEDs are devices that emit light under constant current. During the experiment, the temperature of the LED module and LED chips' individually was being reduced due to the reduction of the current. Both the current reduction and the temperature reduction influenced luminous performance of the module, while an effort was made the performance to be calculated taking both into account. The results in Fig. 2 indicate that the same demand of 50% relative flux is met with 45.1% of initial LED power in DUT A, 42.9% in DUT B and 44.1% in DUT C.

The power factor levels of each configuration presented in Fig. 3, were not the same and considerable differences were noted. The DUT A had the worst performance in power factor since it had the lowest ratio of initial power and rated driver power, which is common especially when luminaire manufacturers consider wide current range of LED drivers, (e.g 350 mA to 700 mA) to avoid additional costs by using multiple drivers for each configuration of a luminaire family. If the above practice, is not applied with caution, it could lead to lower power factor values. It is important to be highlighted that in nominal conditions all DUT have power factor >0.9 as depicted in Fig.3. Another observation that needs to be further examined is that the wider the driver input voltage is, the worst the performance is in the power quality values i.e. power factor and THD. DUT A and DUT B have drivers that operate between 108-305V and 120-277V respectively, whereas the driver of DUT C has a narrower range of 220-240V. All things considered, a balance of those two important specification aspects needs to be established. For example, a 50% demand for relative flux would lead to a PF of 0.81 in A, 0.93 in B and 0.97 in C.

The distortion of the sinusoidal waveform represented by THD, which is the distortion of the waveform of the current drawn by the driver, can lead to potentially dangerous consequences, such as the overheating of electrical equipment etc. Since the luminaires are non-linear loads, the THD becomes more and more important in wider scale applications especially when dimming is applied. A THD of below 20% is usually acceptable and a THD of 10% is exceptionally good. Low Power Factor although might mean nothing to a residential application, while in a city level application becomes important and rather costly to a power utility and might cause decrease in the total bill rebate of the project owner despite the actual real power reduction induced by dimming and adaptive lighting. In the conducted experiment a demand for 50% relative flux would lead to a THD value of 27.1% in DUT A, 20.6% in DUT B and 11.1% in DUT C as shown in Fig.4. The driver of A which was loaded unevenly in comparison with the other two DUTs, has lower values of PF and higher values of THD. It is evident that when a project is designed with the possibility of adaptive lighting, further attention to specification ought to be delivered in such areas to avoid installation issues.

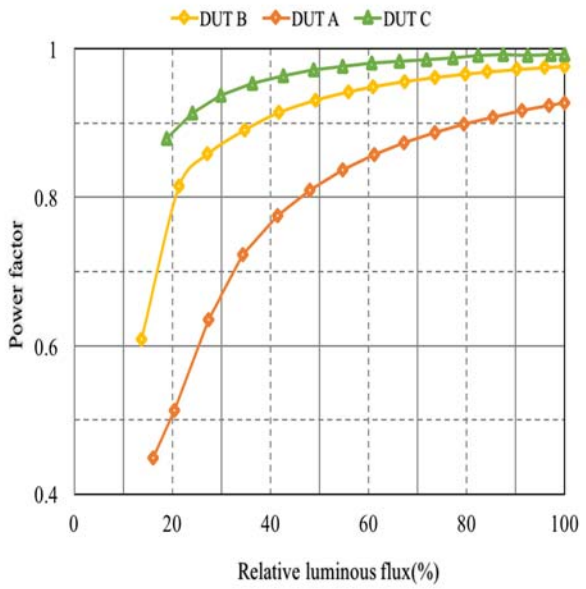

Figure 3. Correlation between relative luminous flux and power factor

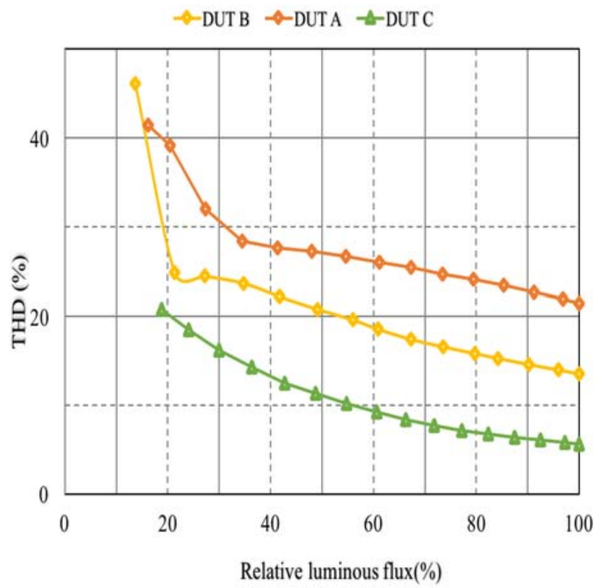

Figure 4. Correlation between relative luminous flux and current THD

The efficiency of the LED driver plays a key role in determining the thermal stresses of the luminaire and ultimately determine its reliability. A highly efficient driver dissipates less heat and allows easier thermal management. The reliability of the driver's components declines as their operating temperature increases. Therefore, a driver operating with higher efficiency can have a significantly improved lifetime and reliability compared to a lower efficiency driver. All 3 DUT have drivers which in nominal luminaire operation deliver more than 90% efficiency. The efficiency of all DUT has been kept relatively high as shown in Fig. 5 where the absolute values of driver losses of DUT B and DUT C are indicatively presented.

As shown in Fig. 6, the reduction of DUT A driver temperature is not proportional to one of DUT B and similarly DUT C, which implies that the LED driver is subject to less thermal stress when operating with lower output current. For 50% relative power, DUT A has 97.8% of its initial driver temperature, whereas DUT B and DUT C share approximately a 94% level. This is explained because driver in DUT A has less thermal load at 500mA current, driving a smaller load at the same time. The initial temperature of driver in each DUT is 47.8 ºC, 58.1 ºC and 60.1 ºC respectively for A, B, C. The reduction of the Tc temperatures of the drivers is positive to their electronic components with the most important of which the electrolytic capacitors, since it reduces catastrophic failure rates thus expanding predicted useful lifetime.

The LED modules are also affected by the temperature. Whilst dimming, the inflow of dc current is decreased proportionally and almost linearly to the dimming signal 1-10V. When driven under different constant currents, the LEDs obtain different forward voltages. During dimming, the reduction of Tsp temperature of the LEDs was measured and considered in the calculations for the power of the modules. The relation of the Tsp temperature and relative flux is presented in Fig. 7 and with the inflow of LED dc current in Fig. 8. DUT A and DUT B have the same temperature behaviour as they consist of the same LEDs and luminaire body.

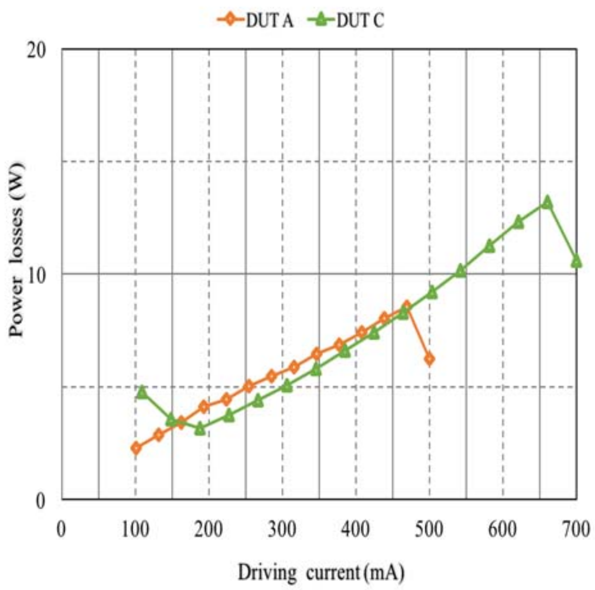

Figure 5. Correlation between calculated driver losses and LED driving current

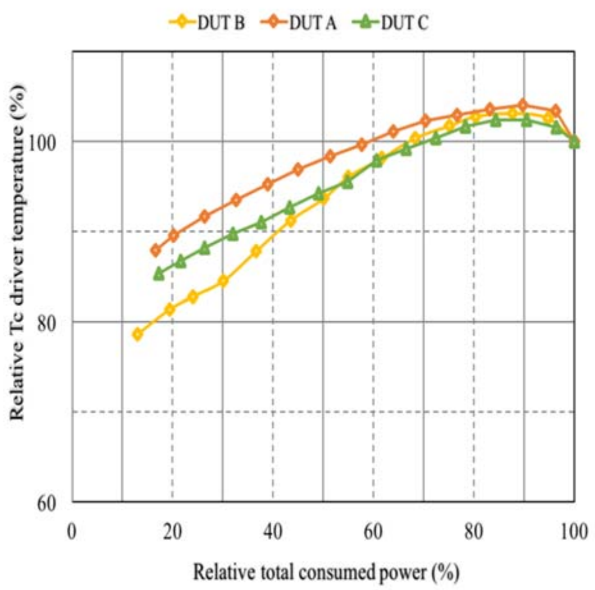

Figure 6. Correlation between Tc Relative Temperature development and relative system power.

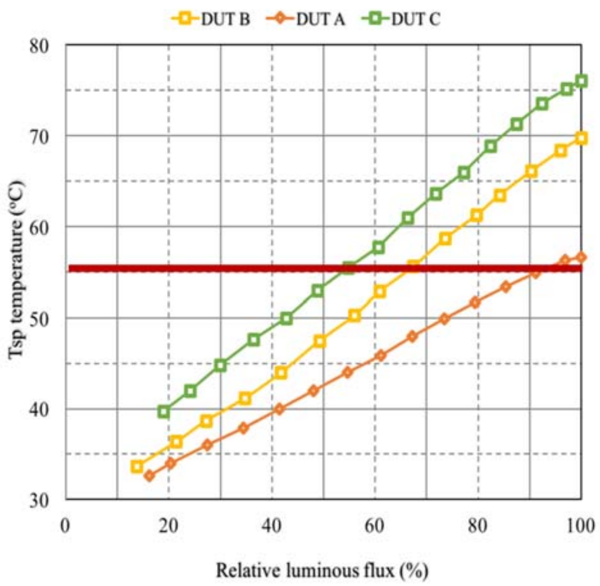

Figure 7. Correlation between LED Tsp temperature and relative flux. Red limit depicts Tsp 55°C evaluation point.

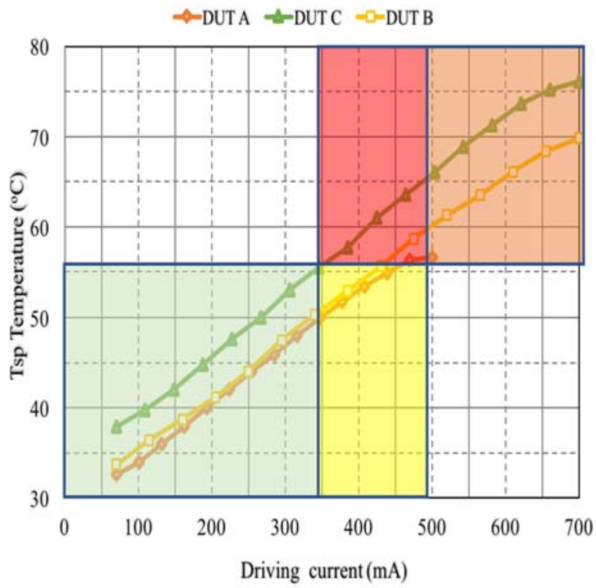

Figure 8. Correlation between Tsp temperature and current. Green area: If ≤ 350mA and Tsp≤ 55°C. Yellow area: 350mA ≤ If ≤ 500mA and Tsp≤ 55°C. Red Area: 350mA ≤ If≤ 500mA and Tsp ≥ 55°C. Orange area: 500mA ≤ If ≤ 700mA and Tsp ≥ 55°C

The temperature of the LED chips and the LED modules is one of the two most critical parameters together with driving current to assess the maintenance of the LEDs flux in a lifetime assessment. The LEDs are tested in groups (datasets) of temperature levels and currents [9], [10]. Each luminaire manufacturer uses the data derived from LM80 reports to make long term projections for its luminaires. As shown in Fig. 8, there are distinct areas of performance throughout the dimming range of each luminaire tested. Those projection performance areas are set, based on the rules and the information provided by the datasets of LM80 reports.

In each of the performance areas a different lifetime projection can be performed [11]. The results concerning the LEDs of DUT A and B are shown in Fig. 9. It is important to be underlined that the green and yellow performance areas were simulated under one LM80 dataset since the performance in green area was rather positive with the maintained luminous flux of the LEDs being equal to 100% of the initial flux after 100000 hours. This performance was considered outside of the scope of this experiment and was not taken into account. The yellow area maintenance indexes were considered for both, instead as next more realistic performance. Ta=25°C is considered in the projections.

The LEDs of a luminaire that is used in an adaptive lighting scheme can benefit from the current and temperature reduction that is inflicted due to the dimming. The positive effect of dimming in the lifetime assessment analysis is mainly connected with the level of dimming what will be done according to adaptive lighting rules. The LED temperature, combined with LED current levels and driver temperature at specific dimming stages, forms an important set of key performance indicators that can enable lighting specifiers to form a total luminaire performance profile.

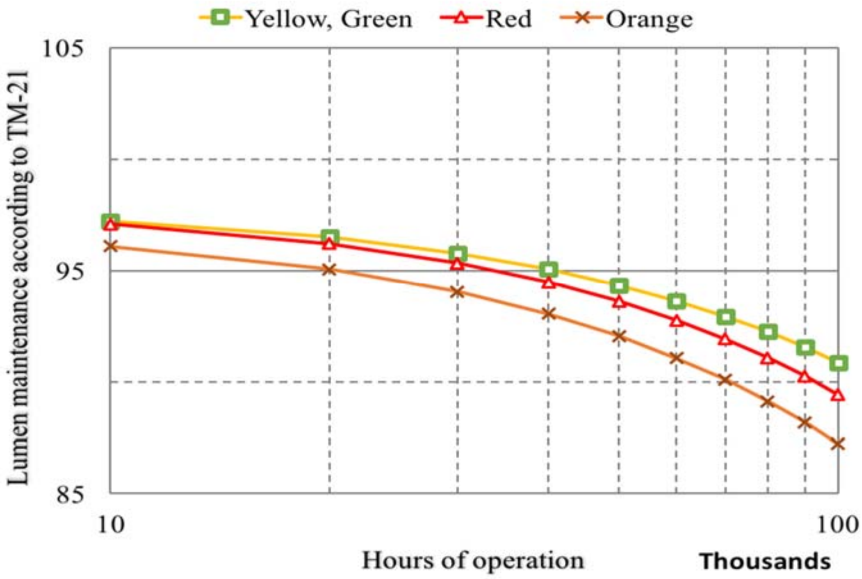

Figure 9. TM-21 long term projection. Variation of performance in Yellow, Green, Red, Orange operational areas of Fig.8

Finally, the CCT was also measured throughout the conduction of the experiment. The results show that the value remained relatively the same in all tested objects. The CCT in A, B, C changed 2.3%, 2.7% and 4.1% respectively towards lower values. It is concluded that the LEDs were not affected during the experiment, in terms of colour consistency.

CONCLUSION - DISCUSSION

The purpose of this paper was to conduct an assessment through laboratory measurements of the correlation between the luminous flux output and the consumed total power under dimming. A clear non-linear correlation was observed in all tested samples, leading to the conclusion that, under proper specifications the relative light efficacy will be higher under dimming. This can lead to further, not anticipated energy savings, making adaptive lighting practises even more appealing. Extreme caution needs to be taken when choosing luminaire specifications. If a LED luminaire is intended for dimming, more characteristics need to be evaluated other than its nominal indexes. Power quality indicators, such as power factor and THD, are critical to massive adaptive lighting employment schemes, as their low performance have an effect to the safety and potential energy savings of the project. Better lumen maintenance can be anticipated when dimming is applied depending always on the magnitude and the duration of the dimming.

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DALEC – Bewertungstool Für Einen Integrativen Planungsansatz

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Abstract*—DALEC (http://www.dalec.net) ermöglicht die Abbildung und das Bewerten der komplexen lichttechnischen und thermischen Wechselwirkungen von Fassaden- und Kunstlichtsystemen. Mittels einer neuen Erweiterung der Webanwendung können in Zukunft auch Räume und Hallen berücksichtigt werden, welche mit Oberlichtern bzw. Sheddächern tagesbelichtet werden. Des Weiteren können mittels einer zusätzlichen LVK-Schnittstelle produktspezifische Leuchten im integralen Berechnungsverfahren verwendet und bewertet werden. Die Funktion eines neuen Variantenvergleiches ermöglicht das übersichtliche Gegenüberstellen unterschiedlicher Ausführungsvarianten hinsichtlich Gesamtprimärenergiebedarf, CO_2-Ausstoß und Energiekosten. Basierend auf der vorgestellten Berechnungsmethodik wird das Potential integraler Planung für 3160 weltweite Standorte aufgezeigt. Hierzu wird mithilfe einer Parameterstudie der Fensterflächenanteil für ein Gebäude mit hohem bauphysikalischen Standard und sehr guter Gebäudetechnik variiert und die Varianten die einen minimalen Energiebedarf bei einem thermischen (Heizung und Kühlung) und integralem Ansatz (Heizung, Kühlung und Kunstlicht) verglichen. Der integrale Ansatz führt zu Fassadenausführungen, die Einsparungen bis zu 40% des Gesamtendenergiebedarfs erzielen.

***Index Terms*— Hallen, Integrale Gebäudesimulation, Kunstlicht, Tageslicht, Web-Tool**

Motiviation

Bereits in der Entwurfsphase wird das thermische Verhalten eines Gebäudes maßgeblich mitbestimmt. Vor allem die Fassadengestaltung in ihrer Funktion als Sonnen- und Blendschutz beeinflusst sehr stark die solare Einstrahlung, den Tageslichteintrag und den resultierenden Kunstlichtbedarf. Dies wirkt sich wiederum auf den Heizwärme- und Kühlbedarf aus. Große Dynamik im Fassadendesign und dadurch sich schnell ändernde Randbedingungen bestimmen den Entwurfsprozess. Aussagen über die Auswirkungen auf den Energiebedarf können aufgrund der Komplexität nur mit simulationsgestützten Hilfsmitteln getroffen werden. Mangels entsprechender Softwarelösungen wird diese komplexe aber notwendige Bewertung in der Praxis meist nicht durchgeführt, sodass energetisch und qualitativ optimale Tages- und Kunstlichtlösungen oft nicht erkannt werden.

Erweiterung

In [1] wurde erstmals von den Autoren eine Berechnungsmethodik im Detail vorgestellt, welche die Abbildung der komplexen Wechselwirkungen für seitlich befensterte Räume mit vereinfachter Eingabe und äußerst schneller Berechnungszeit (<1 Sekunde) für ein gesamtes Jahr in Form einer Webanwendung (http://www.dalec.net) ermöglicht. Im Rahmen des Forschungsprojektes DALEC wurde das Berechnungsverfahren für Räume und Hallen mit Oberlichtern und Sheddächern erweitert. Zusätzlich wurde das Tool um eine LVK-Schnittstelle ergänzt, die es ermöglicht neben typischen Lichtstärkeverteilungskurven auch spezifische LVKs einzufügen und somit gesamtheitlich und integral zu bewerten. Ein neuer Variantenvergleich lässt eine übersichtliche Gegenüberstellung von Gesamtprimärenergiebedarf, CO_2-Ausstoß und Energiekosten von unterschiedlichen Fassaden- und Kunstlichtlösungen zu. Im Folgenden werden diese neuen Erweiterungen im Detail erläutert.

A.Hallenerweiterung

1) Tageslicht

Als Ergänzung zu den befensterten Räumen mit einem bis zu dreiteiligen Fassadensetup wurde die Berechnungsmethodik zur Ermittlung des Tageslichteintrags um Hallen mit Oberlichtern erweitert. Auch hier werden wieder vorberechnete Faktoren in einer Datenbank abgelegt und ermöglichen so eine effiziente und schnelle Berechnungen des stündlichen Tageslichteintrags im Jahresverlauf. Dem User stehen sowohl horizontale Oberlichtöffnungen (Skylights) als auch verschiedene Sheddach Geometrien zur Auswahl. Dabei kann jeweils zwischen transparenter und transluzenter Ausführung gewählt werden. Bei Aktivierung der Sonnenschutzstrategie wird bei Überschreitung einer vom User definierten Grenze für die externe Globalstrahlung das wählbare Sonnenschutzsystem lichttechnisch berücksichtigt und vermindert somit den Tageslichteintrag.

v. Kunstlich*t*

Die Berechnungsmethodik des Kunstlichtmoduls für die Hallenerweiterung basiert auf der Methodik für befensterte Räume. Das Modul errechnet die stündliche Kunstlicht Nutzleistung, die benötigt wird um in einer spezifischen Hallensituation eine definierte Sollbeleuchtungsstärke zu erreichen. Hierbei wird von einem gleichmäßigen Leuchtenraster und einer Messflächenzone für horizontale Beleuchtungsstärke ausgegangen. Die Lichtpunkthöhe wird entsprechend der Hallenhöhe automatisch angepasst, wobei der Nutzer zwischen einer Anbau- oder Pendelleuchte wählen kann. Es stehen analog zum Berechnungsmodul für befensterte Räume 60 LVK Kombinationen zur Konfiguration zur Verfügung. Des Weiteren kann über eine neu entwickelte LVK Schnittstelle eine nutzerspezifische Lichtverteilung importiert werden (siehe Kapitel B). Um die Berechnungszeit kurz zu halten, wurden Vorberechnungen auf Basis normierter LVKs vorgenommen und in einer Datenbank hinterlegt. Es stehen unterschiedliche Steuerungsstrategien (An/Aus während der Nutzungszeit, tageslichtabhängige Schaltung und Dimmung) zur energetischen Bewertung der Lösung bereit. Für eine Komfortbewertung werden zusätzlich aus der konfigurierten Lösung vertikale Beleuchtungsstäken in 1,20 m Höhe und zylindrische Beleuchtungsstärken ermittelt.

vi. Thermische Simulation

Basierend auf der ISO 13790 [2], dessen Methodik auch für seitlich befensterte Räume verwendet wird, kann der Heiz- und Kühlbedarf für die Hallen bestimmt werden. Mittels U-Werte für Hallendach, Sheddächer, Verglasung der Sheddächer, Hallenwände und Hallenboden kann die Dämmeigenschaft der Gebäudehülle definiert werden. Die internen Lasten ergeben sich aus dem resultierenden Kunstlichtbedarf und weiteren internen Wärmequellen (Personen, Maschinen, etc.). Der solare Eintrag wird im Zeitschritt entsprechend des Sonnenstandes und der Neigung der Sheddächer über einen winkelabhängigen g-Wert ermittelt und dem dynamischen Gebäudemodell als solare Last übergeben. Mittels der bereits genannten Sonnenschutzstrategie (siehe Kapitel 1) kann eine Überhitzung der Halle vermieden werden. Entsprechend der Eigenschaften des Sonnenschutzes (z.B. innen- bzw. außenliegender Screen) werden die reduzierten solaren Lasten stündlich ermittelt. Abhängig von den Transmissions- und Lüftungsverlusten sowie den solaren und internen Gewinnen wird die sich einstellende Innenraumtemperatur bzw. der Heiz- und Kühlbedarf für ein frei definierbares Temperaturfenster ermittelt.

B.LVK-Schnittstelle

Um eine differenzierte Betrachtung der Kunstlichtlösung zu ermöglichen, erlaubt die Implementierung einer neuen Schnittstelle im Kunstlichtmodul den Import von nutzerspezifischen Lichtverteilungskurven. Bisher war eine Konfiguration der Lichtverteilung aus fünf generischen LVKs möglich und umfasste 60 konfigurierbare Varianten mit Direkt und Indirekt Komponenten. Die Lichtstärkeverteilungen der generischen LVKs in den spezifischen Räumen waren vorberechnet und in einer Datenbank hinterlegt. Um Berechnungen mit spezifischen LVKs im DALEC Tool zu ermöglichen, wurden Vorberechnungen mit einer normierten isotropen LVK innerhalb eines Stützstellenrasters der Raumvarianten durchgeführt und als strahlwinkelabhängige Lichtstärkeverteilung auf den spezifischen Messflächen hinterlegt. Eine importierte spezifische LVK wird im Onlinetool gerastert auf diese Datenbankwerte „gemapt". Anschließend werden die Werte auf den spezifischen Lichtstrom bezogen. Mit diesem Verfahren ist es möglich Beleuchtungsstärken und erforderliche Leuchten Stückzahlen aus einer spezifischen Lichtverteilungskurve nahezu in Echtzeit zu ermitteln.

C.Variantenvergleich

Die Erweiterung des Variantenvergleiches ermöglicht das Gegenüberstellen von verschiedenen Ausführungsvarianten. Hierzu kann mittels der Angabe von Jahresnutzungsgraden (abhängig vom Heiz- und Kühlsystem, z.B. Wärmepumpe) und Primärenergiefaktoren (abhängig vom eingesetzten Energieträger) auf den monatlichen und jährlichen Endenergie- und Primärenergiebedarf geschlossen werden. Dies lässt die Bestimmung eines primärenergetischen Gesamtenergiebedarfs aus Heizung, Kühlung und Kunstlicht pro Variante zu, welche dann unmittelbar mit den anderen Ausführungsvarianten verglichen werden kann. Die energieeffizienteste Lösung kann somit anschaulich evaluiert werden. Ebenfalls können der CO_2-Ausstoß und die entstehenden Energiekosten pro Variante im Vergleich dargestellt werden.

Parameterstudie – Integraler Ansatz

A. Motivation und Randbedingungen

Im Folgenden wird mittels einer Parameterstudie der optimale Fensterflächenanteil für 3160 weltweit verteilte Standorte bestimmt und dabei der Vorteil von einer integralen Planung mittels DALEC aufgezeigt. Die Parameterstudie basiert auf einem Büroreferenzraum (Tiefe / Breite / Höhe = 5m / 5m / 3m, siehe Abbildung 8), welcher auf der Nordhalbkugel südorientiert und auf der Südhalbkugel nordorientiert ausgerichtet ist.

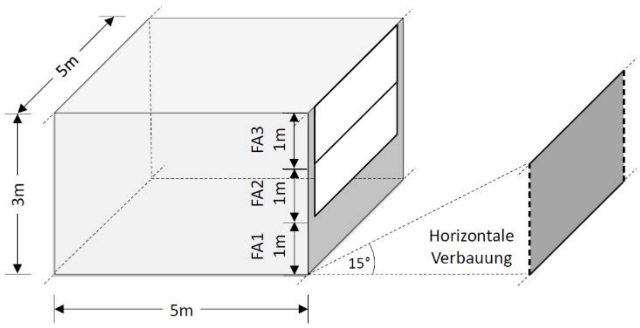

Abbildung 8: Referenzraum und Fassadenunterteilung in drei Abschnitte

Für die untersuchten Standorte sind klimabezogene realisierbare U-Werte notwendig, um ein plausibles standortbezogenes bauphysikalisches Gebäudeverhalten zu implementieren. Schnieders [3] beschreibt Wärmedurchlasskoeffizienten für Außenwand, Verglasung, Dach und Keller für jeden weltweiten Längen- und Breitengrad, um einen Passivhausstandard möglichst kostengünstig zu realisieren. Diese Wärmedurchlasskoeffizienten werden als Basis für die Gebäudehülle für die weltweiten Standorte dieser Parameterstudie herangezogen. Die Bereitstellung der Heizwärme und Kühlkälte wird mittels einer effizienten Wärmepumpe gewährleistet (Jahresarbeitszahl für Heizen = 3 und Kühlen = 3.5). Die Kunstlichtzuschaltung ist mit einer sehr effizienten tageslichtgedimmten LED-Lösung umgesetzt (Anschlussleistung 5.5 W/m²). Die Fassade ist in drei Bereiche FA1, FA2 und FA3 unterteilt. Da der Fassadenbereich FA1 bei transparenter Ausführung nur eine vernachlässige Verbesserung hinsichtlich des Tageslichteintrages ermöglicht, jedoch aus bauphysikalischen Gesichtspunkten deutliche Nachteile mit sich bringt (höhere Transmissionsverluste), wird dieser stets in dieser Analyse opak ausgeführt. Eine detaillierte Beschreibung der Randbedingungen dieser Parameterstudie kann der Publikation [4] entnommen werden. Während [4] bereits eine weltweite Analyse für einen ‚Außenliegenden Raffstore' zeigt, werden in dieser Arbeit unterschiedliche Fensterflächenanteile mit einem Tageslichtumlenkbereich im oberen Drittel der Fassade (FA3) untersucht. Tabelle 1 zeigt hierzu den Fassadenaufbau und die Steuerung bei Blend- bzw. Sonnenschutzfunktion.

TABELLE 1: FASSADENSYSTEMAUFBAU UND STEUERUNG

	Kein Sonnen- oder Blendschutz	**Blendschutz**	**Blend- und Sonnenschutz**
FA3:	Tageslichtumlenksystem 0° Lamellenstellung	Tageslichtumlenksystem 0° Lamellenstellung	Tageslichtumlenksystem Lamellenstellung „retro" (sonnennachgeführt)
FA2:	Kein System (nur Verglasung)	Außenliegender Raffstore Cut-Off (sonnennachgeführt)	Außenliegender Raffstore 45° Lamellenstellung
FA1:	Brüstung (opak)	Brüstung (opak)	Brüstung (opak)

B. Optimierung der Fensterfläche nach ‚Thermischem' und ‚Integralem Ansatz'

Üblicherweise wird im Planungsprozess keine gekoppelte thermische und lichttechnische Simulation durchgeführt. Deshalb wird im ersten Schritt der Fensterflächenanteil im FA2 und FA3 von 10% bis 100% in 10%-Schritten im FA2 und FA3 variiert und die Variante mit minimalem Heiz- und Kühlbedarf bestimmt (‚Thermischer Ansatz'). Im zweiten Schritt wird der Fensterflächenanteil bestimmt, der einen minimalen Gesamtendenergiebedarf aus Heizung, Kühlung und Kunstlichtbedarf erzielt (‚Integraler Ansatz'). Abbildung 9 zeigt den optimierten Fensterflächenanteil für FA2 und FA3 bei ‚Thermischem Ansatz' für südorientiert auf der Nordhalbkugel und nordorientiert auf der Südhalbkugel. Die zum Teil sehr niedrigen Fensterflächenanteile sind aufgrund der nicht nutzbaren solaren Einträge im Winter (Blendschutz) und den erhöhten Transmissionsverlusten durch die Verglasung (v.a. in der Nacht) zu erklären. Abbildung 10 zeigt dies für die weltweitverteilten Standorte für den ‚Integralen Ansatz'. Es zeigt sich, dass beim ‚Integralen Ansatz' aufgrund der Berücksichtigung des Kunstlichtbedarfs deutlich größere Fensterflächen für FA2 und FA3 identifiziert werden.

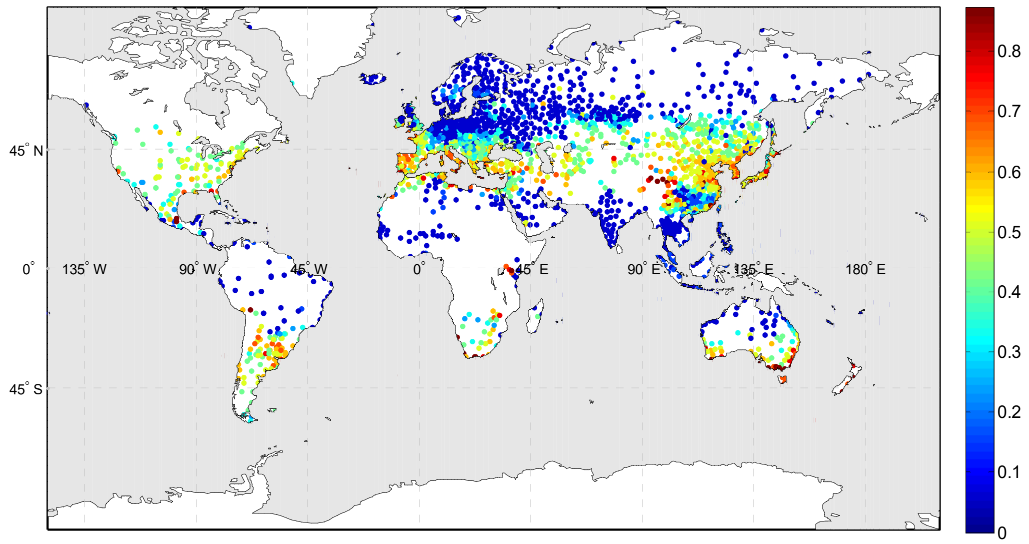

Abbildung 9: Optimierter Fensterflächenanteil für FA2 und FA3 bei ‚Thermischem Ansatz'

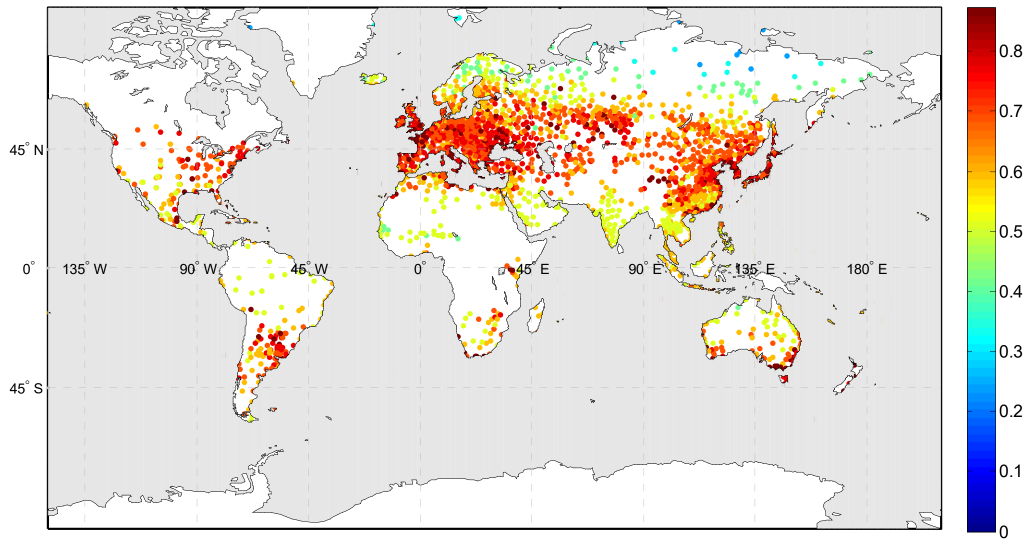

Abbildung 10: Optimierter Fensterflächenanteil für FA2 und FA3 bei ‚Integralem Ansatz'

Zur Bestimmung der Einsparungspotentiale durch integrale Planung wird für die Optimalvarianten aus dem ‚Thermischen' und ‚Integralen Ansatz' der Gesamtendenergiebedarf aus Heizung, Kühlung und Kunstlicht bestimmt. Abbildung **11** zeigt die relative Einsparung aufgrund der gesamtheitlichen Berücksichtigung. Es lässt sich erkennen, dass vor allem in Regionen in der der thermische Ansatz kleine Fensterflächen identifiziert, eine integrale Planung zu deutlichen Einsparungen hinsichtlich des Gesamtendenergiebedarfs (bis zu 40%) führt.

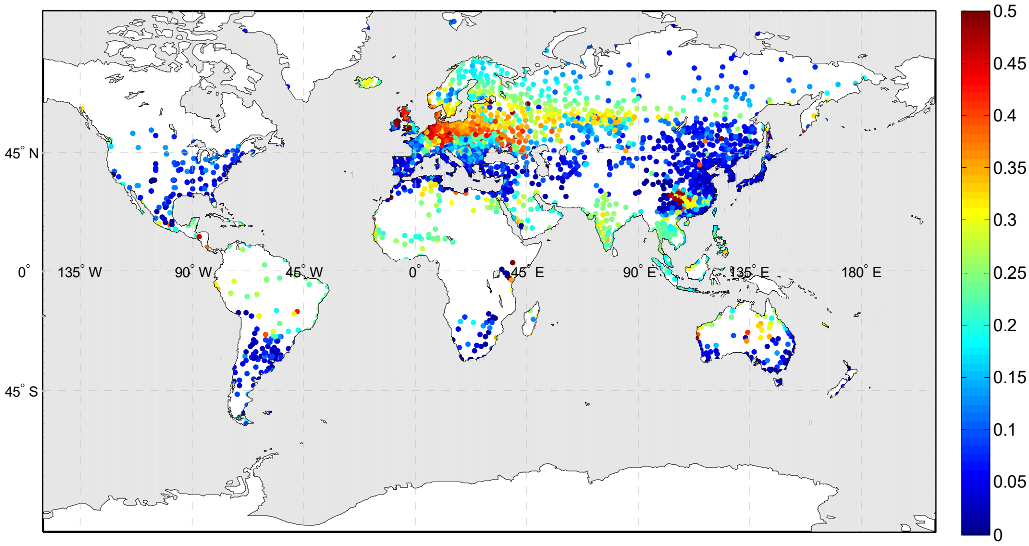

Abbildung 11: Relative eingesparte Endenergie bei optimierter Variante aus ‚Integralem Ansatz' im Vergleich zu optimierter Variante aus ‚Thermischem Ansatz'

ZUSAMMENFASSUNG UND AUSBLICK

In dieser Publikation wurde eine Hallenerweiterung für die bereits bestehende DALEC Methodik vorgestellt. Dies ermöglicht nun das integrale Auswerten und energetische Optimieren von Räumen und Hallen mit Oberlichtern und Sheddächern. Des Weiteren können mittels einer LVK-Schnittstelle produktspezifische Lichtstärkeverteilungskurven berücksichtigt werden. Ein neuer Variantenvergleich ermöglicht das Gegenüberstellen verschiedener Ausführungsvarianten hinsichtlich des End- und Primärenergiebedarfs sowie CO_2-Ausstoß und Energiekosten. Mittels einer weltweiten Parameterstudie des Fensterflächenanteils konnte anhand eines komplexen Fassadensystems (Verschattungs- und Tageslichtumlenksystem) das Potential integraler Planung gezeigt werden. Die Studie konzentriert sich vor allem auf Bürogebäude mit hohem bauphysikalischen Standard und sehr guter Gebäudetechnik (Passivhaushülle, Bereitstellung der Heizwärme und Kühlkälte durch Wärmepumpe, effiziente LED-Kunstlichtlösung). Der gesamtheitliche Ansatz führt zu Fassadenlösungen, die eine Einsparung hinsichtlich der Gesamtendenergie (Heizung, Kühlung und Kunstlicht) von 40% gegenüber rein thermisch optimierten Fassaden (Heizung und Kühlung) erzielen. Diese Ergebnisse bestätigen wiederum den Bedarf an integraler Planung.

DANKSAGUNG

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Energy Efficient Lighting in University Buildings

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***Abstract*— Lighting Engineering Laboratory – LEL - is the main lighting independent consultant around Transylvania (the north-west side of Romania). Over the past few years the Lighting Engineering Laboratory developed and implemented different trial energy efficient lighting solutions for the university buildings. The Building Services Faculty was used as a lighting test area. The starting point was in 2013 - the lighting refurbishment success of the greatest lecture hall by replacing the old 4*18 W fluorescent luminaires by new LED ones and a new DALI lighting control system, get 70% savings in lighting electricity consumption. For 2014 the hallways existing 2*36 W fluorescent luminaires were geared with electronic ballasts and motion sensors. In the same year the faculty outdoor lighting LED system controlled by daylight/time sensors was installed. In 2015 the classic fluorescent recessed 4*18 W fluorescent luminaires were retrofitted using 4*14.4 W LED modules. The overall luminous efficacy of the retrofitted luminaires was around 55 lm/W. In the last year a new emergency lighting system powered from a smart central battery unit was installed. In another class 2*36 W fluorescent lighting system was completely replaced with 37 W LEDs and a modern PLC dimmable control system able to maintain a certain user defined lighting level on the desk working area. The present paper tries to determine the pros and cons of each lighting refurbishment scenario in order to recommend the most appropriate validated solution.**

***Index Terms*- energy efficiency, LED, luminaire refurbishment, sustainable lighting.**

INTRODUCTION

The Technical University of Cluj-Napoca financed for the year 2014-2015 an internal energy efficiency project aiming to determine the present energy consumption for the university buildings. The starting point of this study was this detailed evaluation of the present electricity consumption in university for the last three years.

A detailed measurement of the current consumption of the Faculty of Building Services – UTC-N, with a total area of 4775.98 sq. m was made. The facility electricity and natural gas bills for the year 2012 were analysed Table I.

TABLE I. CURRENT ANNUAL ENERGY CONSUMPTION – UTC-N – FACULTY OF BUILDING SERVICES

UTC-N Faculty of Building Services	Area	ELECTRIC CONSUMPTION – 0.155[euro/kWh]				NATURAL GAS CONSUMPTION – 0.0382[euro/kWh]			
	[sq.m]	[euro/month]	[euro/year]	[kWh/month]	[kWh/year]	[euro/month]	[euro/year]	[kWh/month]	[kWh/year]
	4776	1064	12770	6865	82385	1752	21020	45856	550262

A total energy (electrical and natural gas) consumption of 132.46 [kWh / (sq. m*year)] was identified for the year 2012, based on the utilities bills. A consumption pattern was also identified for the year 2014 electrical consumption. Figure 6 shows the daily electricity consumption in the first eight months of the year 2014. The graph shows the consumption variations after classes/semesters. All the measurements were made in the same day of the week (Thursday) in order to compare theoretically the same class schedule. For the first four months, the electricity consumption is higher (over 20 kWh) from 6.00 AM to noon. For the next three months, the electricity consumption is more constant during the day (over 10 kWh) from 6.00 AM to 2.00 PM. August readings show constantly low electricity consumption (3 kWh) for the holydays, when usually the university building is close.

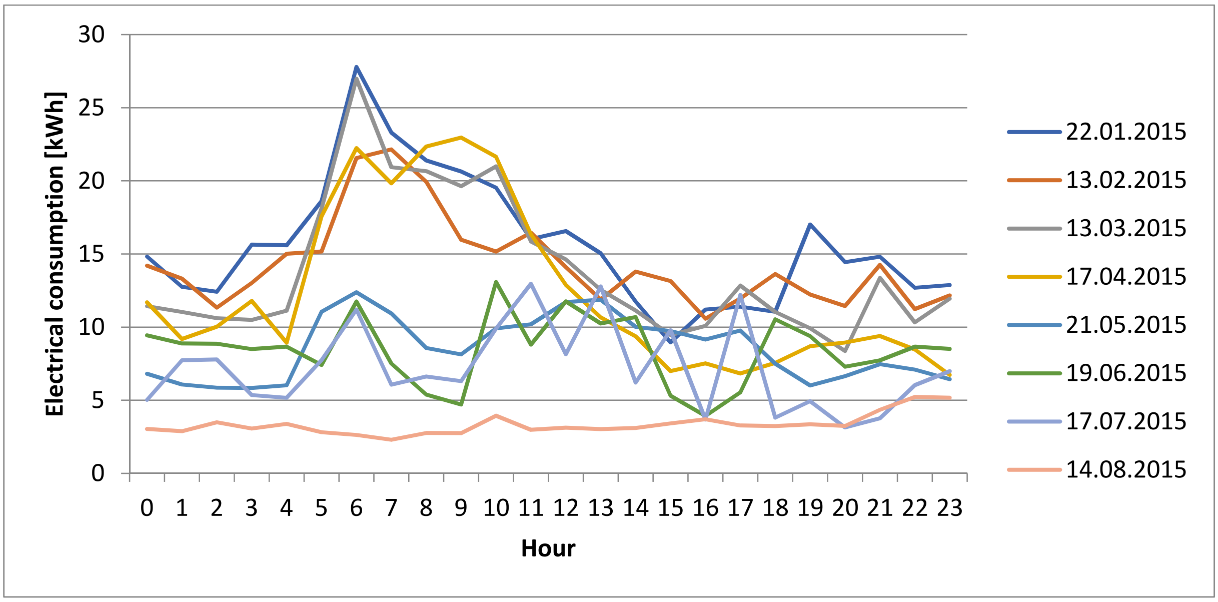

Figure 3. UTC-N Faculty of Building Services daily electricity consumptions

Within the Swiss-Romanian cooperation programme, Cluj-Napoca City Hall, Romania, developed for the year 2014 a new lighting rehabilitation project. The project involved 22 streets and 2 of the city hall buildings. The project was developed by the Lighting Engineering Centre – Technical University of Cluj-Napoca [1].

The public street lighting was using in large majority sodium lamps. Partial the lighting system was upgraded during 1997 - 2007. At this moment, the energy consumed for one year to support the functioning of the lighting system for the 22 streets (1358 luminaires) reaches 1096898 [kWh]. The modernisation of the public street lighting luminaires involved replacing existing luminaires using sodium lamps with modern luminaires based on LED technology which are much more energy efficient. The new luminaires were equipped with wireless communication components and electronic ballasts that allow them to function in different power levels on different time schedules.

For the 2 city hall buildings (19531 sq. m) the current lighting system is based on 1094 luminaires using fluorescent and incandescent light. Upgrading interior lighting system involved replacing the existing luminaires, the fluorescent or incandescent lamps with modern luminaires using LED technology. All lighting equipment was equipped with DALI protocol driver (except those for bathrooms and hallways), allowing their control in the future, using a new tele management system. Additionally, for experimental purposes a new command and control lighting system was implemented, designed with automatic adjustment of light levels, for four offices. Those were equipped with presence sensors and light sensors, which consider the natural light level and the room occupancy level. The future study and oversight of the system will highlight the opportunity of its implementation for all the city hall rooms.

The main objectives of the project were to reduce energy consumption, running costs and carbon dioxide emissions, preserving or even improving the existing visual comfort. By implementing this project there are expected total electricity savings of about 44% for interior lighting, and 54% for the exterior street lighting. The total annual energy reductions are about 762.17 MWh/year with a cost reduction of approximate 75000 euro/year.

This predicts a reduction of annual carbon dioxide emissions by 377 t CO_2 over one year. The CO_2 emissions are calculated taking into consideration the total energy savings and the average value of 494.66 [g CO_2/kWh] for Romania, the year 2012 that was provided by the Romanian Electrical Energy Company – ELECTRICA S.A., Table 2 [2].

TABLE II. THE ESTIMATED PROJECT SAVINGS

	Installed power reduction	**Power consumption savings**	**Carbon dioxide emissions reduction**
	[kW]	**[MWh/year]**	**[tCO_2/year]**
Indoor lighting	43.37	169.70	84
Outdoor lighting	162.32	592.47	293
TOTAL	**205.69**	**762.17**	**377**

Technical University of Cluj-Napoca by the Lighting Engineering Laboratory – LEL – [3] was involved as a consultant for the Cluj-Napoca city council plan to replace existing luminaires with LEDs to reduce CO_2 emissions. The implementation of this project will reduce the lighting electricity consumption with approx. 44% to 54%. The total annual energy reduction is about 762.17 MWh/year with an annual carbon dioxide emissions reduction of 377 tCO_2. The final project proposal was approved and received 1.5-million-euro funding from the Swiss partner.

CASE STUDY

In 2014 the Technical University of Cluj-Napoca started an internal programme to identify electrical lighting consumptions and new refurbishment solutions [4]. LEL is part of this programme and try to find the best energy efficient solutions for replacing the existing lamps and luminaires. In order to reduce the university energy consumption, LEL is presently trying to develop a lighting energy efficient refurbishment strategy. Some experimental ongoing studies are presented to establish the best techno-economical lighting refurbishment solution.

A. University Auditorium

The Faculty of Building Services is the youngest faculty of the nine faculties within the Technical University of Cluj-Napoca. The Faculty's auditorium was built in 2009, after the entire building, has undergone a series of renovations. This auditorium is the largest one in the university, with a capacity of 300 people. The lighting system proposed in the year 2009 was with luminaires equipped with 4xT8 18W fluorescent lamps, with a luminous flux of 4200 lm – Figure2(a). The replacement of the classic system was determined by a series of factors, such us the average illumination level of the blackboard (around the value of 250 lx), lighting distribution, the need of dimming during presentations, electricity consumption, costs etc. The new lighting system uses 30 LED luminaires and 5 LED spots. The 30 LED luminaires are mounted in the recessed ceiling, each having a nominal input of 51 W, with a radiated luminous flux of 3550 lm. The LED spots have a nominal input of 31 W and a luminous flux of 2700 lm – Figure 2(b). The whole lighting system is controlled by a touch screen panel through the DALI interface. It provides various possibilities of creating lighting scenes.

Figure 2.Auditorium lighting system (a) before - fluorescent; (b) after - LED

The new lighting system supports the impression of the space openness, creates condition for concentrated work and enables the students to work out their notes. The DALI interface allows us to create lighting scenes suitable for various types of activities (presentations, full concentrated work). Through the new lighting system, we managed to ensure a good vertical illumination of the auditorium presentation surfaces, a problem that could not been solved by the lighting system equipped with fluorescent lamps. A lighting refurbishment represents a great opportunity for reducing energy and cutting costs. In our case the lighting system equipped with fluorescent lamps fits into efficiency class B, since the value of LENI is 43.40 kWh/sq. m*year. The lighting refurbishment determined an efficiency class A, based on LENI coefficient value of 14.40 kWh/ sq. m *year [2]. This means that the electrical power saving is around 7308 kWh/year with a cost reduction of about 700 euro/year.

B. University Hallways / Study Rooms

As the main lighting source presently used for the university buildings is T8 4*18W fluorescent luminaires, LEL had to find a new refurbishment lighting solution for those luminaires. A new LED refurbishment solution was adopted using 4 LED strips and two LED drivers for replacing the old fluorescent lamps and the conventional electromagnetic ballasts, keeping the same old luminaires shell and reflector. The new electronic LED drivers with variable outputs were used at the lowest levels. The initial electricity consumption of about 89W was reduced by more than 75% to a value of 21W – Figure 3.

Fİgure 3. Luminaire refurbishment solution (a) fluorescent; (b) LED.

The measured illumination levels are presented in Figure 4(a) for the T8 4*18W fluorescent old luminaire and in Figure 4(b) for the same luminaire using new LED 4*14W. The field measurements were made on a 2.4 m wide hallway. The chosen measurement grid was 0.6*0.6 m. The measurements were recorded using a TESTO 545 lighting meter.

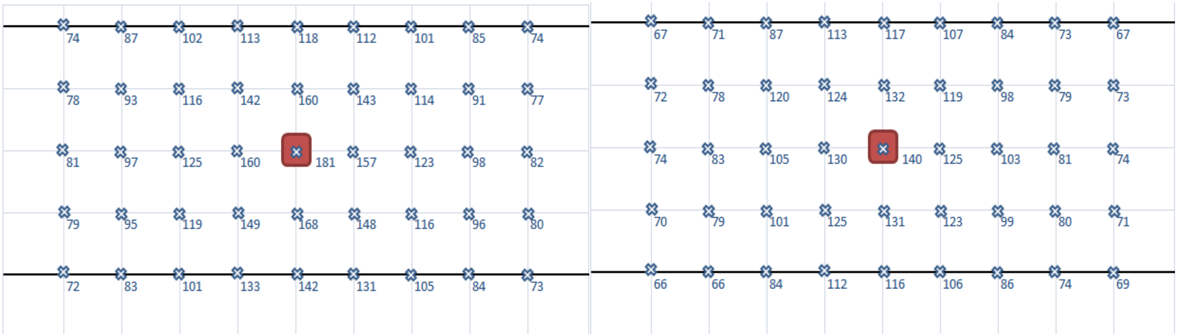

Figure 4. Field measurements (a) - Old luminaire using T8 4*18W, (b) - Refurbished luminaire using LED

According to SR EN 12646-1:2011 – 5.36 Educational Buildings [5], hallways and circulation areas, the requested average illumination level is 100 lx and 0.40 uniformity. Bought lighting systems are close to the required average illumination level – Table III. The LED system has a better uniformity value and uses only 25% electric power.

TABLE III. MEASUREMENT RESULTS

MEASURED RESULTS	T8 4*18W	LED 4*14W
Minimum ilumination level [lx]	72	66
Maximum ilumination level [lx]	181	140
Average ilumination level [lx]	110	95
Uniformity	0.65	0.70

Among other proposed ongoing energy efficient lighting solutions are replacing the existing electromagnetic ballasts of the 2xT8 36W fluorescent luminaires with new electronic DALI protocol drivers (with corridor function) and presence/lighting sensors, which consider the natural light level and the occupancy.

C. Hybrid Tubular Daylight Guidance Systems

A new hybrid Tubular Daylight Guidance Systems –TDGS was developed based on the previous survey studies for a TDGS installed in Cluj-Napoca, [6].

Presently a new Hybrid TDGS is under survey. The new system is using a passive TDGS and a small photovoltaic 40W system powering LED light sources, placed next to the diffuser. A dimming control system is used in order to maintain a certain lighting level on the work area – Figure 5.

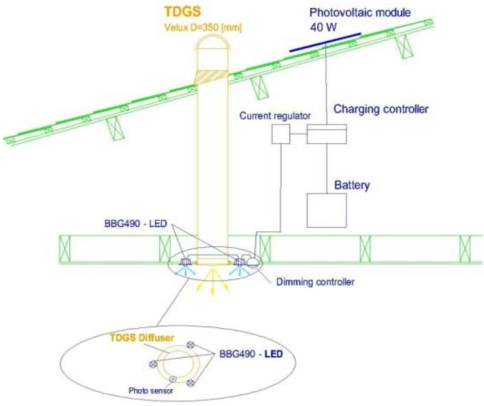

Figure 4.Hybrid Passive Tubular Daylight Guidance System

The designed hybrid system does not need the support of the electric network system, being suitable / adaptable for isolated areas where there is no electricity or for refurbishment solutions where new electrical wiring is not desired.

CONCLUSION

This lighting refurbishment solutions are an ongoing project under survey, where the conclusions will be drawn in the next year. Starting from those case studies, The Technical University of Cluj-Napoca financed the Green Tech Laboratory Project – meant to be an example of how to change the annual energy requirement of the old university buildings (135 [kWh/(sq. m*year)] to a close to zero energy consumption green facility – Figure 6.

The Green Tech Laboratory Project presumes a holistic approach and includes young architects, constructors and building services engineers, starting with vernacular architecture (traditional), passing through traditional materials (straw, wool, hemp) and reaching modern technologies. Without these technologies, the users comfort cannot be achieved, nor a small energy consumption or the transformation into active buildings (Buildings Management Systems - BMS).

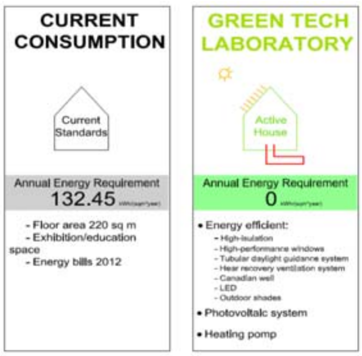

Figure 5.Green Tech Laboratory goal

The present paper is just the beginning of the first Romanian green building model for educational/exhibition proposes. Just the first design steps are presented to discuss and get feedback from the scientific society and previous experiences. The Green Tech Laboratory Project aims to develop a green model for an active house built up using eco, locally available and low-cost construction materials with a very low carbon footprint. The public should see that everyone can afford those eco building technologies (straw, wool, clay etc.) that combined with the latest energy efficient technologies can actually consume close to zero energy and have a minimal impact on the environment.

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Luminance Maps from High Dynamic Range Imaging: Calibrations and Adjustments for Visual Comfort Assessment

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Abstract—**Luminance maps created on the basis of High Dynamic Range Imaging (HDRI) is a technique increasingly used to study the visual environment. But creating HDR images with commercially affordable equipment requires an extensive calibration process to ensure that luminance data and derived spatial information is correct. This paper aims to provide an overview of the necessary steps for the most commonly used HDR calibration process, based on the self-calibration routines in hdrgen/Photosphere. It also addresses commonly made mistakes and aspects requiring special attention. The described steps are: the capture of multiple exposure photographs, the response curve derivation, the HDR image generation, the vignetting and neutral density filter correction, the calibration adjustment by spot luminance measurement and the geometrical reprojection. A detailed description of the geometrical reprojection is included in this paper, since this topic has not yet been described in the literature relating to HDRI, although needed for certain lens types and glare analysis.**

Index Terms— **Calibration; daylighting; High Dynamic Range Imaging; luminance maps; visual comfort assessment**

Introduction

In the field of lighting, HDRI is a technique increasingly used to study the visual environment with affordable equipment. HDRI allows to create luminance maps of the visual field, namely 180° views including luminance value of each pixel of the fisheye view. The technique consists in capturing multiple exposures of a scene and merging them in an HDR image with a higher range of luminance. When calibrated, these HDR images can be used to derive much useful information such as glare sources or vertical illuminance. However, the calibration process is tedious and error-prone since a lot of steps could go wrong. Therefore, this paper aims to present a synthetic overview of the HDRI calibration process, based on the most common tools hdrgen and Photosphere [1], which use self-calibration algorithms. From the capture of multiple exposure photographs to the calibration adjustment by spot luminance measurement, each stage is addressed. A special focus is laid on the geometrical calibration, as this topic has seen little attention in the HDR literature. A thorough description of each manipulation applied to an HDR image is provided, as well as several requirements, options, and common mistakes. References are also made to useful literature.

Calibration of High Dynamic Range images

A. Equipment characteristics assessment

The first step, before starting to create any HDR image, is to get to know the equipment used. Some basic but useful characteristics should be determined for each camera/lens association, as they will be required in later steps.

The no-parallax point, which is the centre of the lens's entrance pupil, can be defined using a tripod with a panoramic rotation unit and a sliding plate on which the camera is set out. Two vertical markers align with the centre of the rotation unit in such a way that when looking into the camera, the rear marker is hidden by the one in front. The camera position has then to be adjusted with the sliding plate so that when it rotates, the rear marker is still hidden by the one in front [2]. In future steps, the camera should be rotated around this no-parallax point to avoid parallax error.

The real viewing angle of a fisheye lens is not always exactly 180°, and the centre of a fisheye view is not exactly at the centre of the image [2]. In order to determine the total viewing angle of a lens and crop the fisheye view images to a square encompassing this total viewing angle, the camera no-parallax point has to be positioned between two reference grids. The no-parallax point should be aligned with the middle vertical lines of both grids, and centred at equal distance from these grids, so that the spacing between two vertical lines of a grid corresponds to one degree at the no-parallax point. When the camera is looking at 0° and 180°, the two middle vertical lines should appear at the borders of the fisheye view image and the distance in pixels between these lines in both pictures should be the same. If additional vertical lines –over the 180° middle lines– appear in both pictures, the total viewing angle is over 180° and can be defined according to the number of additional lines. The image cropping values are defined as the pixel coordinates of the most peripheral lines and the centre of the fisheye view image is in the middle of these coordinates.

The camera luminous range, or the camera maximum luminance capture, should be determined for each specific ISO/shutter speed/aperture combination used [3]. By capturing an image of a very bright light source such as the sun, the maximum luminance capture can be defined as the peak luminance in this image. In any HDR image created using the same equipment and settings, if the peak luminance is near the camera maximum luminance capture and the HDR-computed vertical illuminance is below the measured one, the picture most probably exhibits luminous overflow.

At last, the camera sensor should be checked once in the beginning for stuck or hot pixels [4]. Stuck pixels will always appear over-exposed, even if no light reaches the sensor. Hot pixels, however, are not permanently stuck, but will appear deficient during long exposures when the sensor heats up. To detect stuck and hot pixels, a picture should be taken with the lens cap closed using a long exposure. Every non-black pixel is a defective one and should be replaced, for instance by interpolation using the jpegpixi command, provided that the image quality is preserved.

B. Capture of multiple exposure images

To capture a sequence of multiple exposure photographs, the most common method is the automatic exposure bracketing (AEB). The AEB feature is often included in the camera, but can generally not manage to capture more than five images in a sequence. Software's such as *DSLRRemotePro* or *qDSLRdeshboard*, allows to remotely control the camera and capture over 15 exposure bracketed images in one sequence. In addition to this remote control, the camera should be set on a tripod to avoid alignment problems during HDR generation [5].

A sequence of multiple exposure images has to be taken by varying the exposure time between photographs, since changing the aperture would increase problems associated with vignetting [5] and shutter speed is a more reliable measure than aperture size [6]. A sequence should include as many images as possible, separated by one or more EV-stop. If the sequence is captured under daylighting conditions, the longest exposure time should not exceed a few seconds to ensure stable conditions throughout the sequence. The aperture should be set according to the scene, although it is recommended not to use extreme aperture sizes. On the one hand, small aperture sizes (high numerical apertures) are correlated with greater potential for lens flare [7]. On the other hand, large aperture sizes (small numerical apertures) suffer from a low maximum captured luminance value [3] and a large vignetting effect [8]. A mid-range aperture size, such as f/8 or f/11, can be used as a trade-off. The film speed should be set on ISO 100 and the white balance on daylight [9]. The light metering method is irrelevant and the exposure mode is manual since the aperture and mean exposure time are defined through the remote control software. The focus should be set manually (on the infinite) and locked, to prevent the camera to refocus between each exposure. The image size should be the largest and all other settings should be disabled or set to neutral [5].

Moreover, when the solar disk is in the field of view, it is recommended to insert a neutral density filter between the lens and the sensor to increase the captured range and avoid pixel overflow. For instance, the Kodak WRATTEN 3.0 Neutral Density (ND) filter allows 0.1% of the light to pass through [10]. Although these filters are said to be neutral, they introduce a chromatic shift, especially for the blue channel [11], that could slightly affect the luminous ranges [3]. A solution is proposed later in this paper to counterbalance this chromatic shift.

C. Response function derivation

The camera response function relates pixel values to relative radiance [12] and is specific for each camera, even from the same model [13]. To approximate the camera's response function, several algorithms have been developed, amongst which the one from Debevec and Malik [14] (later modified by Mitsunaga and Nayar [15]) and the one from Robertson [16] are the most widely implemented. The software *Photosphere* and the hdrgen command from *Radiance* can approximate the camera response curves using Mitsunaga and Nayar's method [1] whereas the software *PFStools* offers the option to choose between Robertson's and Mitsunaga and Nayar's algorithms. Both software's and the hdrgen command require as input a sequence of LDR images separated by one EV-stop. These images should represent an interior daylit scene with large and smooth gradients throughout interior and exterior views, and with very bright and dark areas [5], [6], [17]. To limit the vignetting effect on the LDR images used to derive the response function, it is suggested to use a small aperture (such as f/16) to capture the sequence. Three response curves are then derived from this sequence for the red, green and blue channels. A text file is issued, containing the polynomial order of these curves and the coefficients, which are in a reverse order between hdrgen command and *Photosphere*. If several response functions are derived for the same camera, either the smoothest RGB curves are taken or compound curves are produced for the three channels from the average of the coefficients.

D. HDR image generation

vii. Exposures selection

To ensure that over- and under-exposed photographs are captured, it is recommended to take the largest bracketed sequence possible [18]. But in order to facilitate and accelerate the HDR creation process, only LDR images bringing useful information should be used. The –x option in *Photosphere* and hdrgen command to ignore unnecessary exposures should, however, not be applied since it was developed as a time-saver function and lacks accuracy Selection of LDR images has to be made manually in such a way that the darkest exposure has no RGB value greater than 228 and the lightest exposure has no RGB value below 27. These threshold values are preferred over the 20-200 RGB values as they have been empirically recognized to achieve better results. When working on visual discomfort due to glare, it is especially important to make sure that the darkest exposure has no white pixel. This means that the total luminance of the brightest light source in the field of view was captured by the selected sequence.

To select the sequence of useful exposures, a mask should first be applied to the LDR images, so that all pixels outside the fisheye view are set to a neutral colour (such as black) [18]. A script could then automatically count the pixels in the usable region of the image that are below 27 and over 228, and select the right sequence, from the first over-exposed image having no pixel below 27 to the first under-exposed image having no pixel over 228. If over-exposed images all contain black pixels (or inversely), they will all be included in the selected sequence.

viii. LDR images merging

With the derived camera response function and the selected sequence of LDR images, a HDR image can be created using a software such as *Photosphere*, or more directly through a command line like hdrgen or pfshdrcalibrate. Choosing between one of these tools should have no impact on the quality of the HDR image created, since both Debevec and Malik's and Robertson's algorithms have been proved to perform equally well [4]. In *Photosphere* and hdrgen, the default value of automatic exposure alignment and exposure adjustment options is on. But when taking a tripod-stabilized sequence, the automatic alignment option could be turned off to restrict images manipulations. If the captured scene is prone to lens flare, namely scattered light which results in a slightly fogged appearance in HDR images, or ghosts, i.e. moving objects or subjects, options can be selected to remove these artefacts.

E. Chromatic correction (ND filter)

In addition to the reduction of luminances in the image, ND filters have been acknowledged to introduce a chromatic shift, especially in the blue channel [11]. This chromatic shift can be corrected for the visible portion of the ND filter spectrum, by devising a colour transform that maps the RGB components of an image with the filter to the RGB components of an image without it [10], [11], [19], [20]. For this purpose, a Macbeth colour chart has to be photographed under constant daylight conditions with and without the ND filter. By comparing the RGB values of the two pictures, a transformation function can be computed for each channel. These transformation functions account for the chromatic shift and the brightness scaling caused by ND filters. To correct the filtered HDR images, a .cal file containing the three RGB mapping functions should be applied with pcomb command of *Radiance*. Moreover, when using pcomb command, the –o option should be used to ensure conservation of original pixel values and exposure.

F. Vignetting correction

The vignetting effect is the light falloff that can be observed toward the edges of an image, especially when a fisheye lens is used [5]. This light falloff can be as high as a 70% luminance loss at the periphery of the fisheye image for large apertures [8]. The vignetting effect depends on the aperture of the lens, with small apertures yielding less vignetting than large ones [9]. Although it seems like lenses of a same model have a similar vignetting effect [7, 8], it is recommended to derive proper vignetting curves for the lens in use. There are two common ways of deriving the camera vignetting curves. The first one [8] consists in taking, for each studied aperture, one HDR image of uniform targets having the same reflectance and located at known angles in the 180° field of view of the lens under constant and uniform indirect lighting. The vignetting curves can be defined for each aperture on the basis of the ratios of the HDR-derived luminance values of each target on the HDR-derived luminance value of the central target. These curves should be approximated by an even-order polynomial since odd-order polynomials are not possible with actual optical systems. The second method [6], [7], [12], [17], [18], [21] requires only one constant and uniform target, which could be a grey card in a stable and uniform lighting environment, or a stable and uniform light source (such as halogen lamp) in a darkroom. The camera is rotated with respect to the target in intervals (e.g. in 5° steps) until the camera field of view is covered. The HDR-derived luminance value of the target in each HDR image can be compared to the HDR-derived luminance value of the target when it is at the centre of the fisheye view. The vignetting curves can then be derived similarly to the first method, but this second method should provide smoother curves [17].

The vignetting correction of an HDR image can be achieved by applying a digital filter on the fisheye view. More precisely, a .cal file is applied to the HDR image using the pcomb command of *Radiance*, so that each pixel of the HDR fisheye view image is divided according to its radial position, by the right vignetting function.

G. Reprojection

Fisheye lenses project 3D scenes on 2D images with a specific projection method (Fig. 1) amongst equidistant (i.e. equiangular), equisolid-angle (i.e. equal-area), orthographic (i.e. hemispherical), and stereographic (i.e. planispheric) [8]. The two most widely implemented projections in commercially available fisheye lenses nowadays are the equidistant and equisolid-angle methods. Each lens model is related to one theoretical projection but in practice, the implementation of the projection method is not perfect and suffers from small inaccuracies.

When working on visual comfort and glare, geometrical calibration of HDR images is an essential step. The evaluation of vertical illuminance or glare indices, which can be made through the *Radiance* tool Evalglare [22], depends on the solid angle and the position index of each pixel of an HDR fisheye image. But depending on the projection method, the solid angle and the position index vary and should thus be calculated differently. Evalglare is currently able to devise the solid angle and position index from equidistant (-vta) or orthographic (-vth) HDR fisheye images as well as for perspective lenses (-vtv).

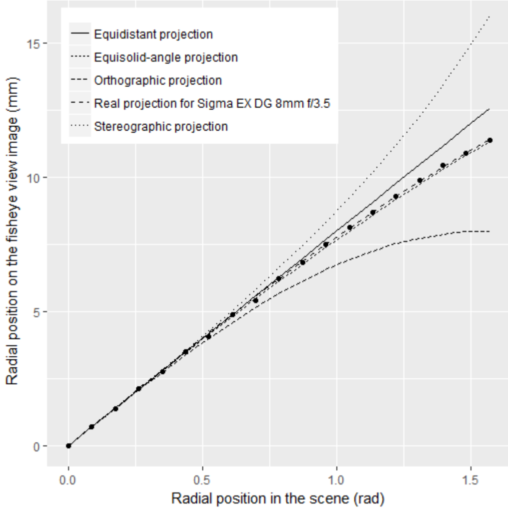

Figure 1. The four theoretical projection methods compared to the projection of a Sigma fisheye lens EX DG 8mm f/3.5

Since on one hand, each lens has its own non-perfect projection function and on the other hand, Evalglare does not support equisolid-angle HDR fisheye images, an image correction is generally necessary. The first step consists in defining the exact projection function of the lens used. One relatively easy way to determine the real projection function of a fisheye lens is to take a picture every 5° of a vertical marker on the horizon line of a fisheye view. The camera should rotate around the no-parallax point until the lens field of view is covered. The radial position of the vertical marker in each picture can then be related to a certain angle of the lens field of view. By computing the Mean Squared Error (MSE) of each theoretical projection function against the measured values, the projection type of the studied lens can be defined as the one producing the smallest MSE. The exact projection function can then be approximated (Fig. 1) from the measured values with a regression model based on the known projection type. Other methods [8], [23] exist to devise the real projection function of a fisheye lens, but require very specific equipment.

Once the real projection function has been defined, two options can be considered. If the projection of the lens is not the equisolid-angle method and if the real projection function does not differ much from the theoretical one, then the theoretical projection function can be used and the HDR image does not need to be geometrically corrected. Otherwise, a distortion function has to be derived to map the pixels of the original fisheye image to the pixels of an equidistant fisheye image. The distortion function transforming an equisolid-angle projection into an equidistant one has already been implemented in Ward's fisheyecorr.cal file. For all other cases, the method consists in approximating the projected relative radial positions (i.e. the radial positions in the fisheye image, on a [0;1] scale, corresponding to each 5° angle, going from 0° to 180°, when using an equidistant projection type) from the original relative radial positions (i.e. the radial positions in the fisheye image, on a [0;1] scale, corresponding to each 5° angle, going from 0° to 180°, when using the lens original projection type) with a second-order polynomial. At last, the reprojection of the HDR image is made through the pcomb command with Ward's fisheyecorr.cal file. Since the fisheyecorr.cal strictly handles the transformation from a theoretical equisolid-angle projection to a theoretical equidistant one, the mapsolid variable of the file should be modified to implement the derived distortion function.

H. Calibration adjustment by spot luminance measurement

The HDR imaging technique allows to collect the relative luminance value of every pixel in the lens field of view. In order to retrieve the real luminance values of the scene, a calibration adjustment has to be done. For this purpose, at least one spot luminance value should be measured on a mid-range grey card in the scene during the LDR sequence capture, using a luminance-meter. The final HDR image is achieved by scaling the relative luminance values of the HDR image with a factor. This factor is the ratio between the measured and HDR-derived luminance values of the grey card [13], and should be around 1.0. It is recommended to collect a spot luminance measure for each HDR image [18]. The software *Photosphere* can be used to calibrate an HDR image by implementing the spot luminance measure.

To check the validity of a 180° fish-eye HDR image, it is necessary to first check the luminous balance. Therefore, the integration of all luminance values over the hemisphere should corresponds to the illuminance value measured by a sensor placed besides the lens [24]. Using the Evalglare tool, the vertical illuminance of the calibrated HDR image can be derived and compared to the illuminance reading of the sensor. If the two values do not match, some areas in the HDR image are over- or under estimated. An HDR-derived vertical illuminance lower than the measured vertical illuminance could indicate pixel overflow in the HDR image.

An additional recommended way of checking the validity of calibrated HDR images is to take more than one spot luminance measure in the scene when capturing the sequence, especially on low- or high-range grey card. The measured values should be similar to the ones derived from the calibrated HDR image [6].

I. Evalglare-ready images

Frequently, luminance maps created on the basis of HDR images are processed by the Evalglare tool to devise some useful information, such as glare indices or vertical illuminance. But in order to be correctly implemented in Evalglare, a few more steps and verification are required.

1) Cropping

HDR images have to be cropped to a square, encompassing the circular fisheye view. By using the predetermined cropping values (as explained before), an HDR image can be cropped with the pcompos command of *Radiance*.

2) Resizing

Evalglare's performance drops when processing large HDR images. Thus, the final HDR images should not exceed 1500x1500 pixels (minimum size: 1000x1000). The resizing of HDR images can be done by using pfilt.

3) View type and exposure modification

Although a calibrated HDR image should have been reprojected to an Evalglare-supported image, the view type information has most probably not been modified in the header of the image [25]. The header of an HDR image is the location where all settings and parameters of the image are stored [13]. Evalglare, which reads the information of the header, will therefore wrongly evaluate the projection type of the image and produce incorrect results. The view type information should be modified in the header using the getinfo command of *Radiance*, not only for the projection type, which generally is equidistant (-vta), but also for the extent of the fisheye view, which should correspond to the total viewing angle of the lens. E.g. for a 180° lens, both directions should be set to: -vv 180 –vh 180.

Moreover, several *Radiance* commands modify the header information, especially the view and exposure information which is essential to Evalglare [25]. Evalglare expects a valid view type and exposure value, which correspond to the real lens type and real exposure of the image. The pcompos and pcomb commands mark the view information line in the header as "invalid" by adding a tab. The view type modification should therefore be done at the end of the process, so that it is still valid when running Evalglare. These two commands also mark the exposure information as "invalid", so that it is not possible to retrieve absolute luminance values from the modified HDR image. This can be avoided applying pcomb command with the -o option as the very first command from those two (pcomb -o before pcompos), since this option "includes" the exposure into the pixel values. In that case, the remaining "invalid" exposure line has to be deleted. It is also advised to use the pfilt command only with the -1 option to avoid additional exposure lines entry. In any case it is recommended to check the header before and after using a command.

CONCLUSION

In this paper, the various stages required to create and calibrate an HDR image are described. These stages comprise the equipment characteristics assessment, the capture of multiple exposure images, the response function derivation, the HDR image generation, the ND-filter chromatic correction, the vignetting correction, the reprojection, and the calibration adjustment by spot luminance measurement. The authors believe that conducting the calibration process step by step allows to have a better understanding of the transformations applied to HDR images.

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"FluxGage" A Photometric Test System for LED Luminaires Based on Solar Panels

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***Abstract*— A novel photometric test system for LED luminaires is presented. The new photometric system called „FluxGage“ uses solar panels to detect and measure light. By placing a diffuser and a black pinhole array over solar panels we achieve a detection surface which is also an absorber. This enables the system to be the same size as the DUT (Device Under Test), as opposed to an integrating sphere which is at least 3 times larger than the DUT. Simulations and experimental results show that this system can measure total flux with an uncertainty of 4.3%. The demonstrated system is used in 2π-geometry. The system measures total flux, color parameters (CCT, CRI, chromaticity, etc.) and flicker.**

Index Terms*— *LED measurement, light absorption, solar panels, total luminous flux

INTRODUCTION

The integration sphere is the standard instrument for measuring luminous flux and color of light sources [1], [2]. The fundamental makings of the integrating sphere are its spherical geometry and the white diffusive coating on its interior. Integrating spheres must be at least 3 times larger than the DUT. Additionally, the effect of the DUT‘s absorption on the measurement (self-absorption) must be calibrated. With LED luminaire sizes ranging from few centimeters to meter or more, the required integrating sphere diameter reaches 2-3 meters.

The FluxGage system is based on an opposite approach – a detection surface which is also an absorber, ideally absorbing every photon emitted by the DUT. With this approach, multiple reflections inside the measurement cavity and between the measurement cavity and the DUT are avoided. Consequently, spherical geometry is not required, the measurement device can be the size of the DUT, and the measurement does not depend on the DUT.

The detection surface should have the following properties:

- It detects light, i.e. it transforms light into a measurable electrical signal.
- Light detection does not depend on angle of illumination.
- Very little reflection.

These properties are realized in the structure presented in Fig. 1:

- A solar panel is used as the detection surface.
- A diffuser is used to reduce the angle dependence of the solar panel responsivity.
- A dense array of pinholes is placed over the diffuser using black matte paint, thus making most of the surface black. The light incident on the panels is therefore spatially sampled by this dense array.

The FluxGage system, based on this concept, provides a small and cost effective solution to LED luminaire testing.

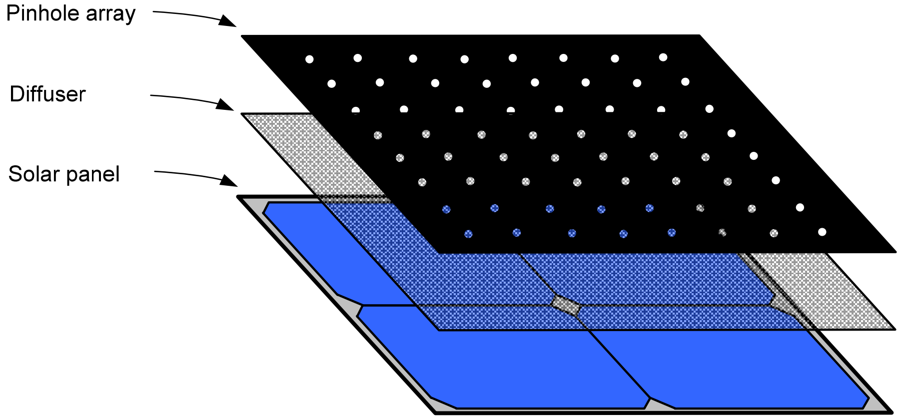

Figure 1. Absorber Structure

In the next sections we will discuss:

- System description
- How total luminous flux and color properties (CCT, CRI, Duv) are measured.
- Error budget analysis based on simulations.
- Experimental results of a full system based on this technology.

SYSTEM DESCRIPTION

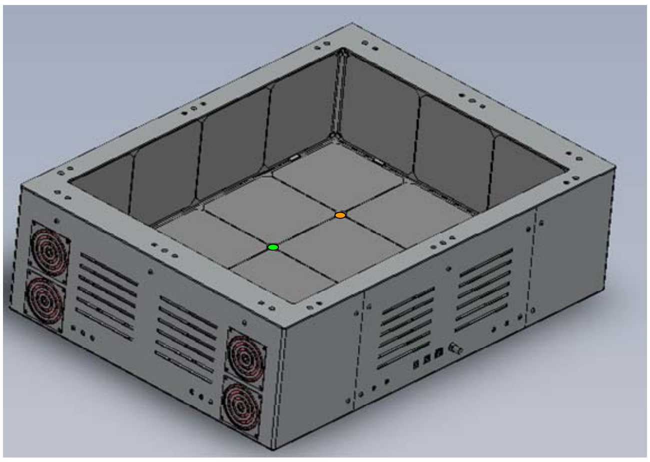

Figure 2. FluxGage System

An image of the FluxGage system is presented in Fig. 2. The solar panel absorbers on the inside walls make the measurement cavity. The small green circle indicates the position of a fibre optic sensor which delivers light to a spectrometer inside the system. The small orange circle indicates the position of a photodiode which is used to measure flicker. An integrated temperature sensor monitors the temperature inside the system and controls the fans seen on the side.

The FluxGage system is used in 2π-geometry with the LED luminaire positioned over the opening and facing the solar panels. The system measures total flux, color parameters (CCT, CRI, chromaticity, etc.) and flicker.

TOTAL FLUX MEASUREMENT ANALYTIC MODEL

In this section we present the mathematical derivation of the total flux measurement. We assume the solar panel responsivity is spatially uniform and is not sensitive to illumination angle. We further assume a spectrometer is used to sample the spectrum of the DUT and that the spectral content of the DUT is uniform in all directions. A more realistic analysis is brought in the next section.

The total current, I, produced by solar panels is given by

$$I = \int R(\lambda)\Phi_e(\lambda) \tag{1}$$

Where R(λ) is the responsivity of the solar panels (including the pinholes) in [A/W·nm], and $\Phi_e(\lambda)$ is the spectral flux of the DUT in [W/nm]. The spectrometer is measuring the normalized spectrum S(λ) given by

$$S(\lambda) = \frac{\Phi_e(\lambda)}{\Phi_e} \tag{2}$$

Where Φ_e is the total flux of the DUT in [W]. The normalization is achieved by scaling S(λ) such that $\int S(\lambda)d\lambda = 1$. Having measured S(λ) with the spectrometer, color quality parameters such as CCT, CRI, and chromaticity can be calculated directly.

Substituting (2) and (1) and rearranging yields

$$\Phi_e = \frac{I}{\int R(\lambda)S(\lambda)d\lambda} \tag{3}$$

Substituting again into (2) yields

$$\Phi_e(\lambda) = I\frac{S(\lambda)}{\int R(\lambda)S(\lambda)d\lambda} \tag{4}$$

Having obtained $\Phi_e(\lambda)$, the total luminous flux in lumens can be calculated using

$$\Phi_v = \int \Phi_e(\lambda)V(\lambda)d\lambda = I\frac{\int S(\lambda)V(\lambda)d\lambda}{\int R(\lambda)S(\lambda)d\lambda} \tag{5}$$

Where V(λ) is the photopic function.

ERROR BUDGET ANALYSIS

In this section we examine several systematic uncertainty contributors in a real FluxGage system, and ways to mitigate them. These factors are:

- Uniformity of solar panel responsivity
- The dependence of the solar panels responsivity on illumination angle
- Localized spectrum measurement
- Secondary reflections from the DUT

A. Uniformity of solar panel responsivity

We tested 5 solar panels, each with 6 monocrystalline silicon solar cells (156x156mm) which were custom produced for this project. The panels were illuminated with white, red, green and blue LEDs. We measured the photocurrent produced by every cell. The uniformity of the photocurrent was better than ±0.3%. This indicates that solar cells technology is very mature and reliable and a high degree of uniformity in the solar panels can be achieved.

B. Angular dependence of the solar panels responsivity on illumination angle

Fig. 3 shows the responsivity as function of illumination angle, K(θ), of the solar panels to white LED light with and without the diffuser. Ideally K(θ) should equal 1, indicating the panels responsivity does not change with illumination angle.

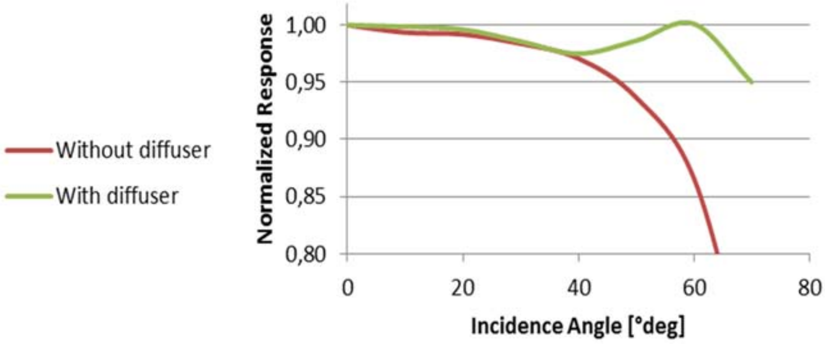

Figure 3. Illumination angle dependency of solar panels with and without diffuser

We developed a MATLAB simulation in order to analyse the effect of K(θ) on measurement accuracy. The concept of the simulation is shown in Fig. 4.

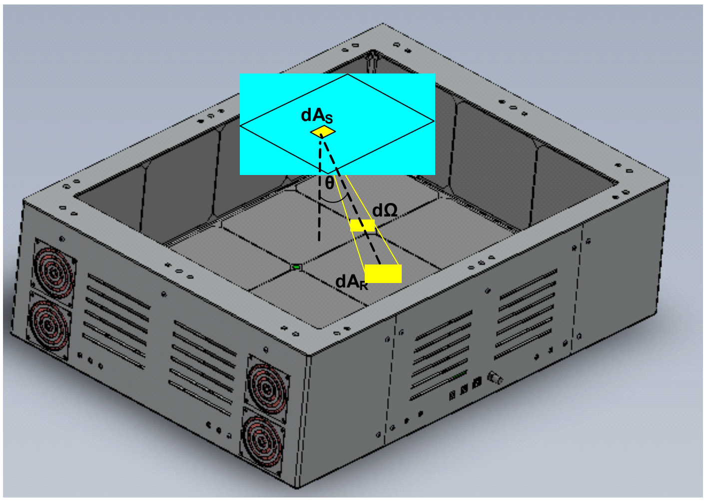

Figure 4. Illumination angle dependency of solar panels with and without diffuser

In the MATLAB model, the LED luminaire is positioned over the FluxGage opening. The luminaire surface is divided into area elements dA_S, and the FluxGage detection surfaces are divided into area elements dA_R. For every dA_S and dA_R we calculate the flux element $d\Phi_v$ incident on dA_R based on the subtended solid angle dΩ and the luminance, L.

The total incident luminous flux is given by $\Phi_v = \iint_{A_S A_R} d\Phi_V$, and the total detected luminous flux is given by $\Phi'_v = \iint_{A_S A_R} K(\theta) d\Phi_V$.

The change in the ratio between Φ_v and Φ'_v for different luminaire sizes and illumination beam angles is the uncertainty contribution of K(θ). As the luminaire size and beam angle increase, more rays hit the panels at slant angles and the effect of K(θ) is more noticeable.

Fig. 5 shows a false colour representation of the detected irradiance on the bottom and side walls of the FluxGage for a luminaire which is 40cm long, 30cm wide and has a beam angle of 120° FWHM (Full Width Half Maximum).

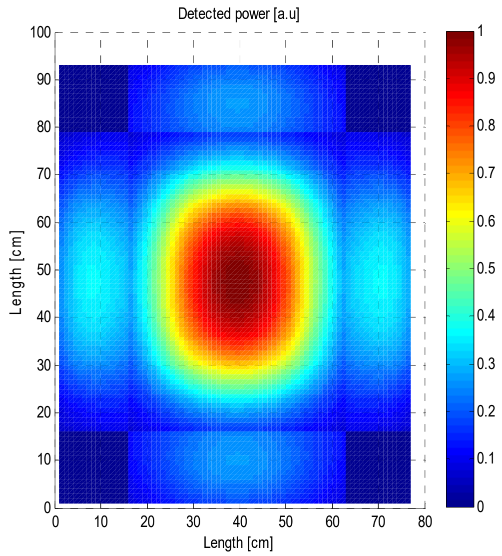

Figure 5.Simulation of the detected power as function of position on the bottom and side walls.

The simulation results show that the error due to the sensitivity to illumination angle K(θ) is between -1.2% (for a small and narrow beam DUT) and -6.3% (for a large and wide beam DUT). If the system is calibrated using a calibration standard with a beam angle of 80° FWHM, the error will be shifted to ±2.6%. Furthermore, since this is a systematic and predictable error, a correction factor can be applied based on the size and beam angle of the luminaire being measured.

C. Localized spectrum measurement

In an integrating sphere system, the measured spectrum represents an average of the light emitted by the light source. In the FluxGage system, the spectrum is sampled at a single position as seen in Figure 2. If the spectral flux of the source is the same in all directions, the measured spectrum and the average spectrum are the same, however, this is not a realistic case.

The uniformity of the spectrum affects both the colour measurement accuracy and the total flux measurement accuracy. This uncertainty is evaluated using equations (1)-(5). We modelled several LEDs with spectral flux $\Phi_e(\lambda)$ and used different spectra for S(λ), representing the fact that the spectrometer is measuring a different spectrum than the average spectrum of the light source.

In an extreme case where the measured spectra S(λ) has a CCT of 2500K and $\Phi_e(\lambda)$ has an average CCT of 2600K, the error in the CCT is obviously 100K , and the error in the flux measurement is 8%. Experiments with some real luminaires give an uncertainty of about ±15K in the CCT and ±2% in the total luminous flux. By using a split fibre sensor, the spectrum can be sampled at several positions on the FluxGage surface thus reducing the incurred uncertainty.

D. Secondary reflection from the DUT

In an integrating sphere system, self-absorption of the DUT has a large effect on the measurement. This is because the DUT changes the average reflectivity of the sphere which, in turn, greatly affects the sphere’s throughput [3]. Calculating this effect is not practical due to the infinite number of reflections that occur inside the sphere, and it must be calibrated for every DUT.

In the FluxGage system, the reflectivity of the black pinhole array seen in Fig. 1 is about 4%. This means that up to 4% of the DUT’s flux is reflected back towards the DUT. A large and reflective DUT may reflect this light back into the FluxGage, while a small or non-reflective DUT will reflect very little. Consequently, the effect of the DUT ranges between 0% and 4%. We should only consider a single reflection, as the next one will be attenuated to a negligible level (4% of 4% = 0.16%).

Several correction methods can be applied:

- Adding a fixed 2% to the initial calibration to shift the error from 0%-4% to ±2%.
- Apply a phenomenological correction based on the size and tone of the luminaire surface.
- Add a light source for automatic secondary reflection correction.

d. Summary of error budget analysis

The uncertainties discussed in the previous sub sections are summarized in the following table. Since there are systematic errors, that are summed arithmetically and not geometrically (rms). The resulting uncertainty is 7.8%. By applying various correction factors as described earlier we estimate an uncertainty of 4.3% can be reached which is comparable with good integrating sphere systems.

Uncertainty contributor	Uncertainty	Uncertainty with correction factors
Initial total flux calibration	1%	1%
Non uniformity of solar panel responsivity	0.3%	0.3%
Angular response of the solar panel	2.5%	1%
Localized spectrum measuring	2%	1%
Secondary reflection from the DUT	2%	1%
Total	**7.8%**	**4.3%**

Figure 6. Table showing the total uncertainty of the FluxGage.

V. EXPERIMENTAL RESULTS

A FluxGage system was built and tested. The unit size is 770mmX560X230mm. The size of the measurement opening is 640mmX480mm. The unit was calibrated using a tungsten halogen standard (Labsphere FFS-400). Several LED sources (BridgeLux VARO 29 COB) were measured using a reference system which included a 1 meter integrating sphere from Labsphere and a spectrometer (Ocean Optics Torus). The integrating sphere was calibrated with the same tungsten halogen source.

We compared the results of the integrating sphere and the FluxGage. For total flux values between 1,000 lumens and 30,000 lumens and for CCT values between 2700K and 5700K, the difference was up to 1% in the CCT and 1.5% in the total luminous flux.

We then moved a LED source across the opening and 'mapped' the measured luminous flux. Using this information, various luminaires were synthesized by superposition of the measured data. The results of the synthesized luminaires were in very good agreement with the simulation presented in section IV/B. This shows that the system is very predictable and that correction factors based on the size and illumination angle of the DUT can be applied.

VI. CONCLUSIONS

We presented the FluxGage, a LED luminaire tester. This system provides a small and cost effective solution for testing LED luminaires in 2π-geometry. The black measurement surface and the lack of multiple reflections make the system much more predictable and allow using information about the DUT such as size, beam angle and surface reflectivity, to calculate correction factors.

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Influence of Measuring Equipment Parameters on Recorded Luminance Values in Context of Glare Measurements

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Abstract – **This paper presents a list of the problems related to the luminance distribution measurements with the use of imaging luminance measuring devices. The potential measurement errors are especially connected with the luminance distribution measurements used as a component required to calculate glare. The results of the luminance measurements for light sources and luminaires of heterogeneous luminance distribution depending on the measuring distance variable are presented. The research results are enriched with a luminance analysis depending on depth of field of the measuring set. The research is extremely essential in terms of using the imaging luminance measuring devices to measure the road lighting parameters – permitted by the new standard, EN 13201 as well as the more frequent application of imaging luminance measuring equipment to measure glare.**

Index Terms— Glare, LED, light measurements, luminaires, luminance distribution

INTRODUCTION

A dynamic development of the lighting technology in the second decade of the 21st century, especially in the field of light emitting diodes, forces us to adapt modern measurement methods to the current requirements of the lighting market. The number of high luminance light sources is growing, causing an increase in number of potential problems. One of them is the problem of discomfort glare and ways to measure it. Both calculation and measurement methods connected with this parameter have a series of disadvantages and advantages. Among the serious disadvantages, there can be dominant digital "models" of light sources and luminaires, which do not include, actually, any direct information on luminance distribution. To make the measurement results correspond to the calculation results, computer simulations and visual impression of the people assessing the lighting, the measuring devices should correctly record the analysed parameters. Therefore, it should be considered what a term "accurate measurement" means as far as the presented case is concerned. The accurate parameters recording means the situation under which the measurement result is possibly close to what the human eye records. The modern measurement systems, among which there are undoubtedly ILMDs - Imaging Luminance Measuring Devices, are potentially ideal to record all parameters used to calculate glare. However, the basic parameters of the equipment recording luminance should be considered.

The early research done by the author [1]-[3] proves that especially as far as the small light sources are concerned, such as chips of surface oscillating around 1mm2 and multi-source luminaire systems, the measurement distance has a huge impact on the recorded values (Fig. 4). Specifying, it is not directly the measurement distance alone, but it is an angular field of view of single pixel of the recording sensor, which is connected with a sensor size, dimensions of single photo-cell, focal length and technology that is used to make this structure (B/W, colour). The results of analyses carried out prove that if the measurements apply to the luminance value, in the context of measurements or calculations connected with the parameters directly referred to the human eye [1], the suggested field of view of single photo-sensor should correspond to a known average angular resolution typical of the human eye. In the recent years it has been decided to undertake the issue of verification of many recording equipment parameters that may turn out to be a weakness of this modern technology. It is a necessary step in order to prepare the grounds required to propose a measuring method allowing us to obtain the objective results of photometry of the parameters directly referred to the specification of human eye. You have to realise that currently there is no technically advanced alternative to the luminance measurement technology using ILMD. Therefore, it is impossible to explicitly discredit its accuracy in the area of glare measurements without proposing a method of solving or reducing the identified problems. That is why there were some attempts made to indicate the method of selecting and verifying the measuring equipment in order to obtain the measurement results that would represent the real impressions of the glare felt by the people. Additionally, a problem of the influence of depth of field of digital recording equipment with respect to the measured luminance values was dealt with. [3].

RESEARCH GAP

Simplicity of taking the imaging luminance measurements with the use of ILMD is both, advantage and disadvantage of this type of measuring equipment. Of course, the accuracy of the received measurement results cannot be ignored, however, you have to realise that under certain circumstances the measurement results may be far away from impressions perceived by the human eye. The problems may take a dual nature. The first one is a situation widely described by the author [1]-[3], in which a type and angular resolution of single photo-sensors, causes making some measurement mistakes. This case applies to the measurements of the objects whose luminance shows a very high heterogeneity (Fig. 2) [4].

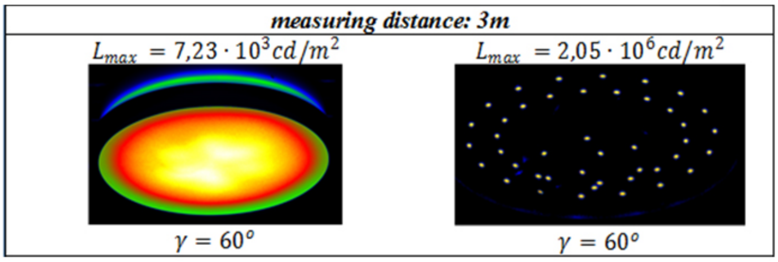

Figure 1. Example luminaires optionally with homogenous and heterogeneous luminance distribution

The situation intensifies when the ILMDs equipped with a Bayer filter mosaic are used to take the measurements [3]. As far as a single photo-sensor is concerned, it measures the average luminance for the entire light source and its closest surrounding. When misadjusting the resolution of the measuring device to the resolution of the human eye each time, the significant measurement errors may be made. As for the case of small high luminance light source and considerably darker surrounding (Fig. 1), when the resolution of the image is too high, the luminance value may be overvalued compared to the one perceived by the man, and as for the too low resolution – undervalued. That is why the luminance factor for the glaring light sources in the glare calculation formula will be distorted, which may cause some considerable calculation inaccuracies. The next component of the measuring equipment specification, potentially adversely affecting the obtained measurement results, is a parameter of depth of the field received from a set of the matrix and lens used. It should be tested if the objects of the same luminance, located in the sharp range of depth of the field have the same luminance as those that are beyond. It is a very frequent case happening while measuring the luminance for large or significantly long objects. There are a lot of examples in everyday life: luminance measurements of luminaires for the road lighting, measurements of luminaires for the emergency lighting, measurements of the corridors or big rooms illuminated with a large number of the luminaires. The distances of the luminaires being in the field of view of the measuring device, the closet to the lens, may not exceed a few meters, and the distances of the farthest luminaires – even a few dozen meters. In the meantime, while making the simulation calculations based on the photometric data of the IES or similar files, the same value of average luminance for the luminaires is always substituted. It is connected with the fact that the luminance indicated for the simulation purposes is calculated on the basis of the luminous intensity value in a given direction and apparent surface area, part of the luminaire illuminating in a given direction (C, γ), recorded in the IES, LDT or similar files. Therefore, what should be done to have the simulation calculation results, after substituting the data of photometric files, identical to the verification measurement results from the ILMD, and what is the most important thing, coincident with the feelings of the people evaluating the glare under given conditions? The capabilities of measuring equipment should be used carefully, making the measuring conditions as close as possible to the parameters of the human eye [1],[5]. All the presented analyses only refer to the measuring equipment that has corrections adjusting the quantum efficiency curve of the sensor to the spectral sensitivity curve of the human eye. All the attempts to use traditional DSLR cameras as a measuring device to measure luminance distributions additionally need, at least, carrying out the adjustment of, for example, matrix spectral sensitivity curve. The issue of digital luminance measurements is commonly investigated in terms of extending the High Dynamic Range (HDR) [6]-[8], however, in general, there is no detailed research treating the above described measuring problems.

LUMINANCCE DISTRIBUTION MEASUREMENTS OF SMALL LIGHT SOURCES

Leaving aside the nuances differing the calculation formula for UGR and UGR for small light sources [9],[10], the analysis of correctness of the luminance measurements for different measuring device configurations was carried out. The differences were deliberately omitted, since the calculation software based on photometric data files to calculate luminaire luminance does not take into account a change in luminance characteristics of different structure of the luminance distribution given by the luminaire. Such a state will be until the typical simulation software to calculate luminance uses only a luminous intensity value and surface that is responsible for generating this luminous intensity. Due to the fact of omitting the luminance distribution, the average value may be identical for two extreme cases of lighting fixtures presented in Fig. 1. If the luminous intensity of both luminaires is identical in a given direction (C, γ) and surface area of the luminaire is the same, the average luminance value used for calculations will be the same.

Therefore, you should consider which lighting fixture will seem to be “brighter”, whether perhaps the luminance impression will be the same. Such studies of a group of the surveyed of more than 100 people, are currently being carried out by the author of this paper. This publication focuses, however, on the technical issues to a higher extent. The current analyses explicitly present this existing problem. In 2016 the research, in which the luminance distribution of LED chip of the surface area close to 1 mm^2 was measured, was done. The measurements were taken for the selected measuring distances as well as different positions of light source (Fig. 2 and 3), covering the shift of the light source along x and y axes.

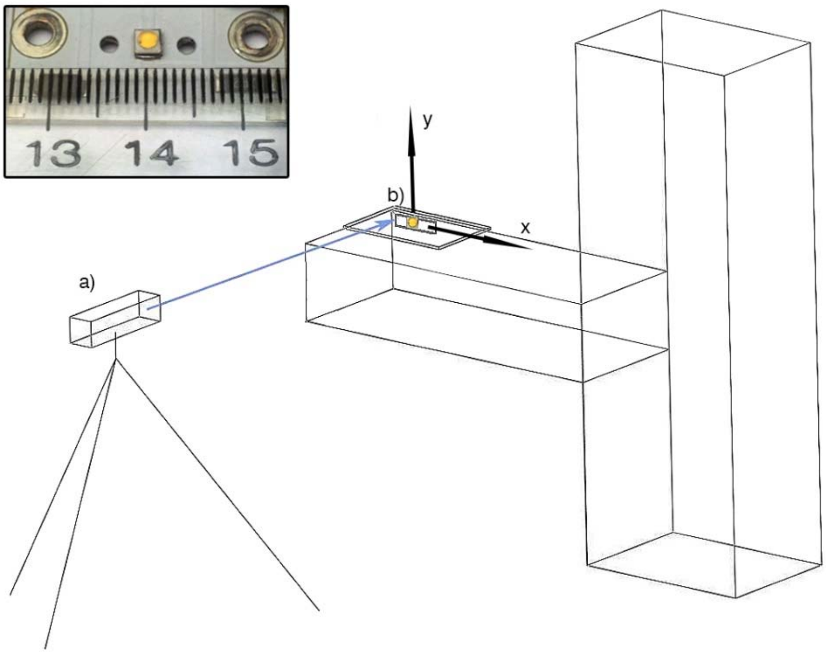

Figure 2. Measuring stand a) ILMD; b) H,V Goniometer and the used LED chip dimensions

The recorded luminance distributions and diagrams explicitly show that depending on the position of light source and ILMD, the results change significantly (Fig. 3). The second part of research has been done this year and covered the diagrams of dependences of the focus image /depth of the field and the measured luminance.

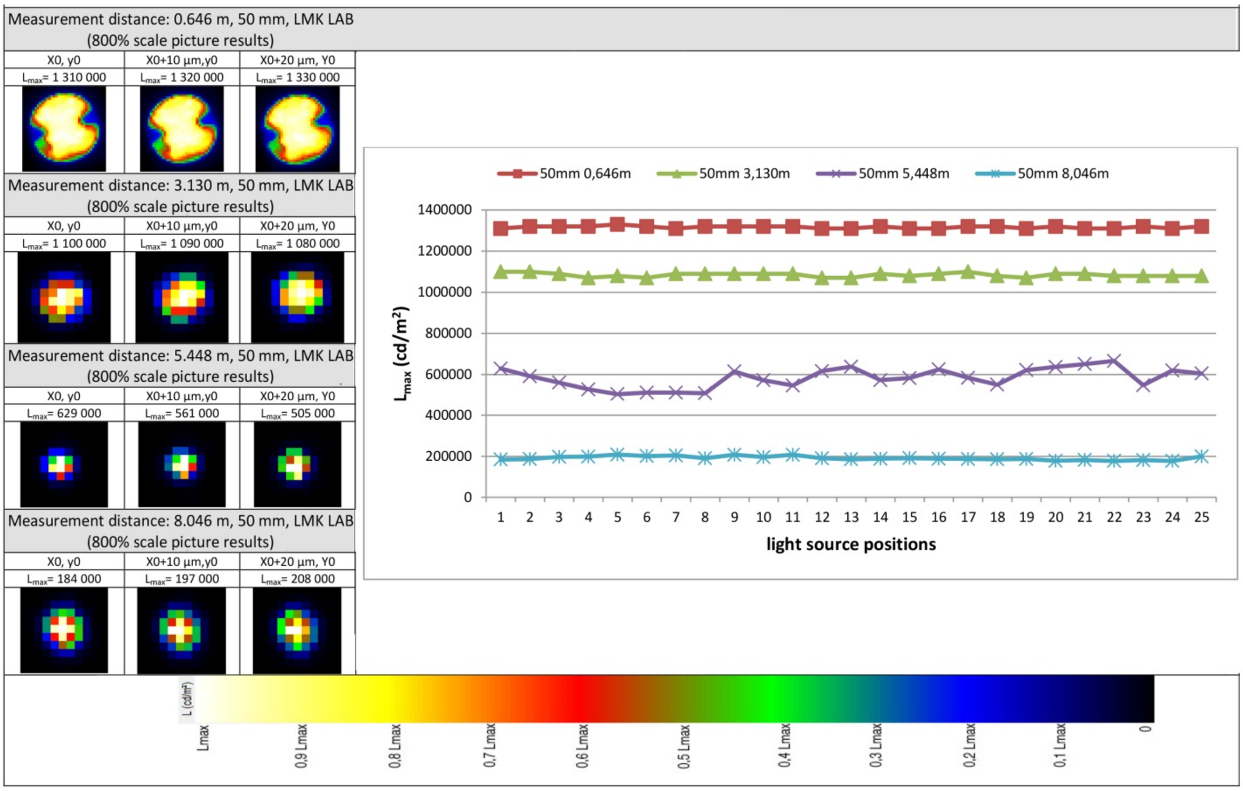

Figure 3. Results of luminance distribution measurements for the next positions of light source, at given measuring distances

LUMINANCE DISTRIBUTION MEASUREMENTS TAKING INTO ACCOUNT DEPTH OF FIELD PARAMETER

For the purpose of this paper, a series of measurements was taken, using the OLED RGB display of very high luminance uniformity exceeding 95% and test panels specially designed (Fig. 4). All images were prepared with a native resolution of the display. The measuring stand was constructed with the use of 6-meter photometric bench. At one of its edges, the ILMD (Fig. 4b) was installed; the focus was set up at the component of the image of interest, at a given distance. Afterwards the luminance measurements were taken without changing the point of focus of the device during the measurements, after changing the position of the measured component relative to the imaging luminance measuring device (Fig. 4).

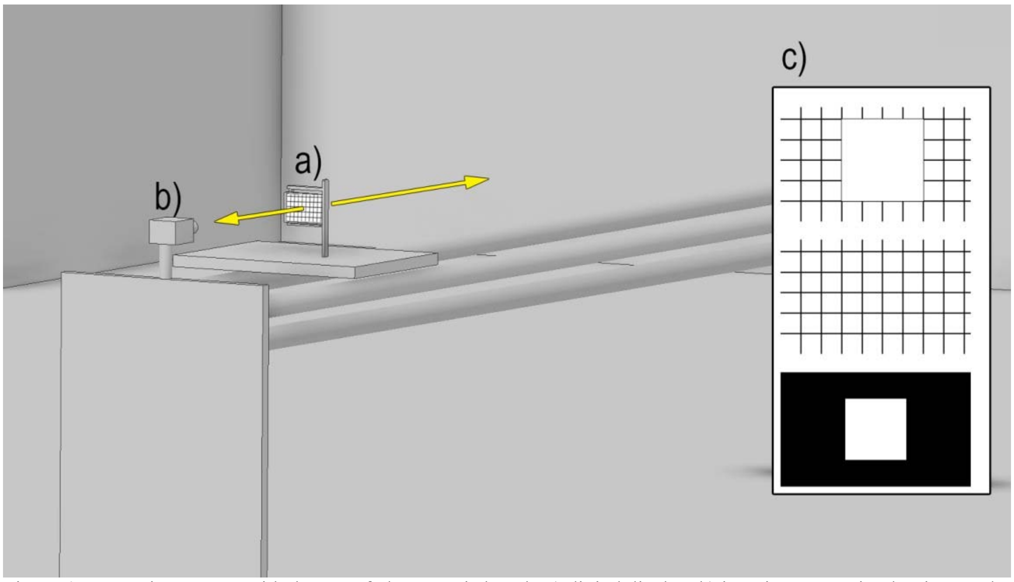

Figure 4. Measuring system with the use of photometric bench: a) digital display, b) imaging measuring luminance device, c) test panels to measure luminance

The used ILMD is the device equipped with monochromatic CCD of 1030x1380 resolution, with the lens of fixed focus of 50 mm[12]. Thanks to this, the field of view of single pixel at a level of 0.0073 degree both in horizontal and vertical plane as well as the field of view of the whole set covering the angular area of 7.5 degrees vertically and 10 degrees horizontally were obtained. The measurements were repeated many times, modifying, in every next measuring cycle, the distance at which the image was sharpened. The example measurement results for one of the measuring cycles carried out are shown in Fig. 5. In the presented case the distance, for which the measurement was taken with a proper depth of field, was set at 2m.

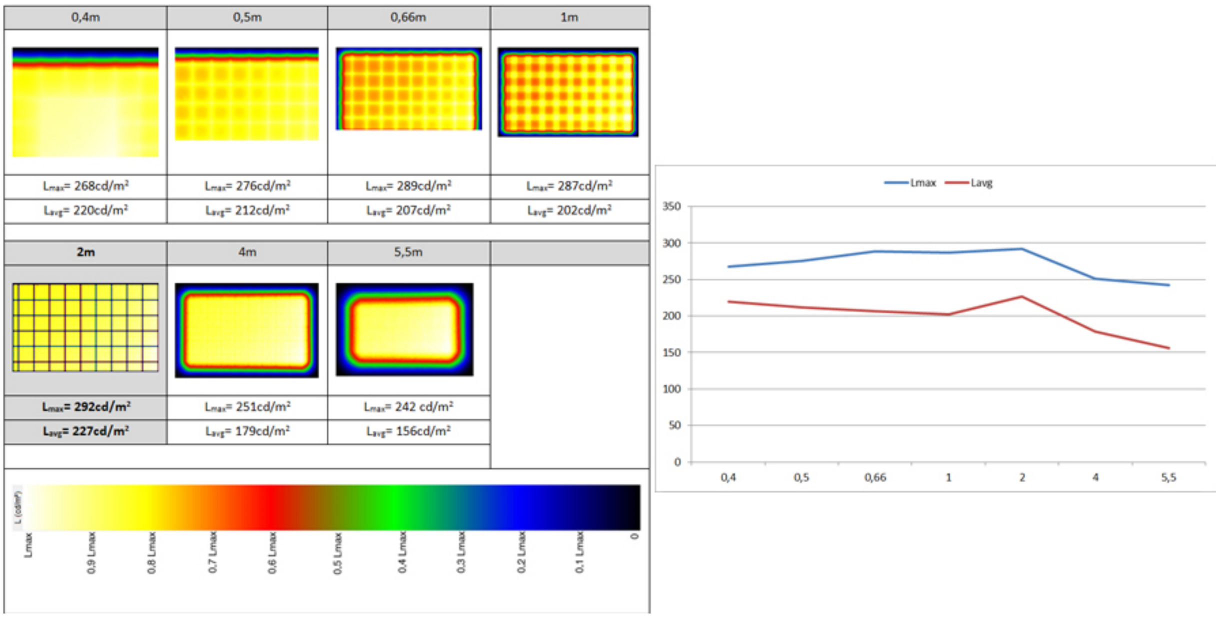

Figure 5. Selected measurement results covering the luminance distribution changes, values of the maximum and average luminance depending on the distance. The distance of sharp measurement was determined at 2m – indicated in the figure.

The analysis of the results shows that the values of maximum and average luminance for the whole OLED display were subject to some essential changes while modifying the measuring distance. Only the reference image for the distance of 2 m was characterised by a high specificity and had a depth of field permitting for a precise readout of brightness nuances and right separation of dark lines at the background of bright display (Fig. 5). By changing the measuring distance of 50%, the details are irreversibly lost, and the black lines of the luminance value close to 0cd/m2 stop being visible. Instead of them, the area of luminance falling within the range of 20% of the maximum luminance appears. What is interesting, the lines, after nearing to the object, have a higher luminance than the bright background of the measuring display (Fig. 5 – 1 m). Analysing the maximum and average values of luminance, we also see changes. With the relatively low examined range of changes in distances (5.5 meter and 40 cm versus the initial distance of 2 m), the noticeable luminance changes are close to 20%.

It is also certain that these changes are not small. One fact should be explained; when the object is nearing to the device, it stops being in the frame. This type of measurements was carried out completely consciously so that the real measuring conditions could be reconstructed accurately and the dependence without placing the whole illuminating object in the frame could be investigated. The analysis of the diagram covering the measurement results (Fig. 5) shows that in the presented example the direction of changes in values of the maximum and average luminance in the analysed case is of the same feature.

In this paper, part of the research that is being continued is presented. The aim of the analyses is to draw up and complete the measuring guidelines permitting us to carry out the right luminance measurements regardless of their purpose.

CONCLUSION

The done research shows that the imaging measuring luminance devices, apart from the big advantages, require a high vigilance and critical evaluation of the received results. All measuring cases connected with the parameters directly referred to the human impressions, for instance, discomfort glare evaluation [11], need adjusting the measuring system to the parameters and features of the human eye [3]. The typical resolution of the human eye was defined at 1 angular minute [5] and this value should exactly be the starting point for ILMD configuration. Basically, a proper component selection comes down to adjustment of lens focal to the value of resolution and physical dimensions of ILMD sensor and single photo-cell [1]. In the era of increasingly widespread use of ILMD in Lighting Technology, measurement accuracy plays a very important role. Everybody is aware that such parameters as a discomfort glare level are of a key importance and influence both security and comfort of the people being in the artificial lighting environment. The dynamic development of LEDs and reflector luminaire designs with discharge light sources do not allow us to ignore the discomfort glare-related problems. Especially in connection with the fact that the luminances of these light sources are within the range of 10^6 – 10^8 cd/m2[4].

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On Site Photometric Characterisation of Concrete Pavements with COLUROUTE Device

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***Abstract*— The standard tool for characterizing road surface photometry is the reduced luminance coefficient table (or R-table), as defined in the seventies by the CIE. Since these tables are no longer representative, measuring road photometry is necessary for optimizing a lighting installation and ensuring luminance level and uniformity. The objective of the study was to characterise and follow on site the photometric characteristics of different concretes with time and traffic. A first experiment was done with two concrete formulations (broomed and water jet scrubbed concrete) located around a very circulated concrete mixer plant. The photometric characterisation of these pavements was done with the portable reflectometer COLUROUTE device during three years. The selected surface treatment was applied in a tunnel and the photometric characteristics were measured during 30 months. It was shown that the concrete pavements are more diffuse and clear than classical pavements. Their use could generate significant energy saving.**

***Index Terms*—Concrete, Energy saving, Exterior Lighting, Pavement photometry, Portable reflectometer.**

INTRODUCTION

Designing a lighting installation involves accounting for site-specific geometric parameters and photometric characteristics of both the light sources and the road surface. By knowing the photometric characteristics of a pavement, the design of public lighting installations can be optimized in terms of positioning and energy saving. The reflection properties of the pavement material are expressed as a table of reduced luminance coefficient (or r-table) [1], [2]. To simplify the calculation, a classification based on the specularity coefficient S_1 is made and standard tables are defined by the CIE. CIE 2001 [2] recommends a scaling of the chosen table according to the measured brightness coefficient Q_0. Since the photometric characteristics are generally not known, one standard R-table is used for the design of lighting without any rescaling [3]. This generates important errors as shown in [4], [5]. Moreover, studies have shown that there is an important evolution of photometric characteristics with time and that these tables are no longer representative [6], [7]. In this context, measuring road photometry is necessary for optimizing a lighting installation and ensuring luminance level and uniformity.

Concrete pavements are said to be more diffuse and clear than classical pavements [8]. The aims of the study were the followings: photometric characterisation of concrete pavements with time and traffic, comparison of laboratory and on-site measurements and calculation of the amount of possible energy saving. This work was done within a collaboration of 6 years between the French cement and concrete pavement associations CIMBETON and SPECBEA and the Cerema, which was in charge of the measurements and the technical evaluation. The section 2 of this paper describes the CIE methodology of photometric characterisation, the portable device COLUROUTE and the two experiments. The results obtained in the pilot study and in a highway tunnel are in the section 3.

MATERIAL AND METHODS

A. Introduction To Road Lighting

The r-table is a two-dimensional table with a number of standardized combinations of the incidence lighting angle γ and orientation angle β, the boundaries of which define the solid angle Ω (Fig.1a). The angle of observation α is set at 1°, which corresponds to a driver looking at about 100m [1]. The reduced luminance coefficient r is defined by:

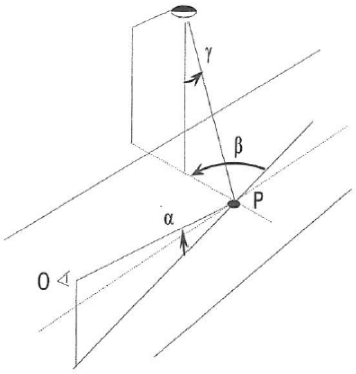
$$r(\beta,\gamma) = L(\beta,\gamma) / E_h.\cos^3\gamma = q(\beta,\gamma).\cos^3\gamma \quad (1)$$

with L the observed luminance in cd/m² and E_h the horizontal illuminance in lux.

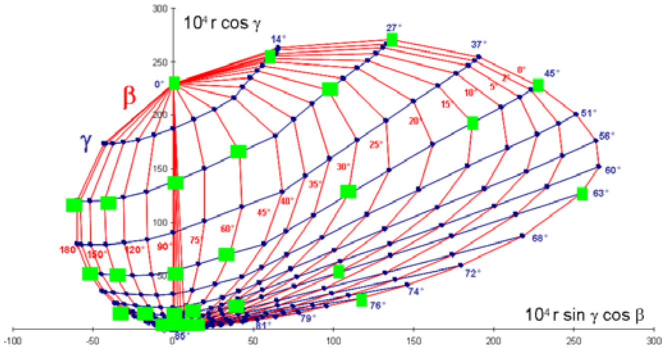
The characterisation of a pavement is given by its degree of specularity S_1 and its total reflectivity Q_0 (also called brightness). These two parameters are calculated from the previous matrix called r-table. The reflection indicatrix is a graphic representation of the r-table (Fig. 1b). Its volume informs on the brightness factor of the pavement Q_0., given

$$Q_0 = \int_0^{\Omega} \frac{q(\beta, \tan\gamma)\cdot d\Omega}{\Omega}. \qquad (2)$$

Its form is an indicator of the specularity factor S_1, given $S_1 = \dfrac{r(\beta = 0, \tan\gamma = 0)}{r(\beta = 0, \gamma = 0)}$. (3)



a.



b.

Figure 1. a. The photometric characteristics of the road surface depend on the angles of observation α, sight β and incidence γ (following [2]). O represents the driver and P the point of observation. b. Representation of a pavement reflection indicatrix. The angle of sight β is in red, the angle of incidence γ is in blue and the location of COLUROUTE illuminating angles are in green.

B. COLUROUTE Device

The portable measurement device named COLUROUTE (french acronym “COefficient de LUminance des ROUTEs”), was developed by the Cerema and complies with the CIE recommendations [9]. With this instrument (Fig. 2a), the luminance coefficients of a road surface are measured on site, in daylight and without sampling.

COLUROUTE is equipped with a sensor directed at the measurement surface with an angle of 1° and has twenty-seven sources set to illuminate successively this surface with different combinations of angles β and γ (Fig. 1b). These angles were chosen judiciously to allow the calculation of the specularity factor S_1 and to reconstruct by interpolation the complete reflection table of the road surface. Calibration is performed on site using reference plates measured with a laboratory goniophotometer [10] (Fig. 2b). The outputs comprise the reduced luminance coefficient table (r-table), the average luminance coefficient Q_0 and the specularity factor S_1. With this portable device it is possible to analyse a great number of areas and increase the number of interventions without damaging the road.

a. 

b. 

Figure 2. a. COLUROUTE device of the Cerema (Strasbourg). b. Goniophotometer of the Cerema (Clermont –Ferrand).

C. Experimental Setup

The aim of this pilot study was to follow the photometric characteristics of different concretes with time and traffic during 3 years and to choose a formulation for a tunnel pavement. The photometric characteristics of the two pavements were mesured on site with COLUROUTE device and in laboratory on core samples with the Cerema goniophotometer. It was performed around a circulated concrete mixer plant near Lyon in France (Fig. 3a). The new concrete pavement was composed of local aggregates alluvial whose color is a mixture of brown and beige more or less clear. Two surface treatments were used to obtain two different macrotextures: broomed and water jet scrubbed concrete. The circulation was composed of trucks carrying fresh concrete from the plant. The concretes surfaces were always watered to avoid dust. We assume that the presence of sand and water accelerates the corrosion.

The Sinard tunnel (length 980 meters), located South of Grenoble in the A51 highway, is one of the few in France to have a concrete pavement (Fig. 3b). It is an unreinforced, undowelled concrete pavement on a draining concrete subgrade. The concrete surface course was broomed across the traffic lanes using a hard brush, to provide the microroughness required for the grip of tires on the pavement (Fig. 3c). The surface concrete contains crushed materials to provide increased grip of tires after relative wear due to surface sweeping on newly laid concrete. The photometry of this pavement was measured periodically during 30 months with the COLUROUTE device.

a.  b.  c. 

Figure 3. a. Localisation of the pilot study. b. View of the Sinard Tunnel c. Picture of the broomed concrete (initial state)

RESULTS

A. The Pilot Study

In the pilot study, there were 3 measurements per pavement (M1, M2, M3) with COLUROUTE device every 6 months and there was one core sample taken for the laboratory measurements. All the results are shown in the Table 1 for the scrubbed concrete and in the Table 2 for the broomed concrete.

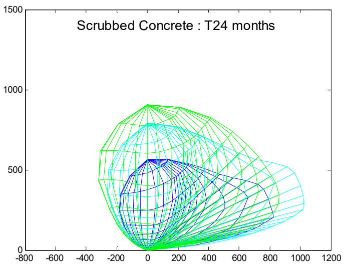
TABLE I. RESULTS FOR THE BROOMED CONCRETE, ***M*** IS FOR MONTH.

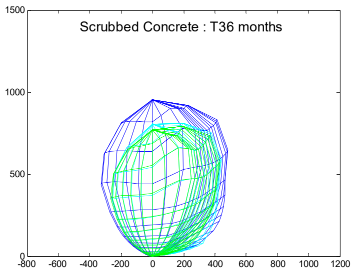
	Brightness coefficient Q_0					Specularity coefficient S_1				
Scrubbed concrete	***T0***	***T3m***	***T12m***	***T24m***	***T36m***	***T0***	***T3m***	***T12m***	***T24m***	***T36m***
COLUROUTE M1	0.090	0.088	0.095	0.154	0.165	0.11	0.12	0.44	1.51	0.50
COLUROUTE M2	0.084	0.094	0.095	0.199	0.152	0.12	0.10	0.86	1.36	0.54
COLUROUTE M3	0.089	0.120	0.096	0.187	0.139	0.20	0.13	0.46	1.03	0.46
GONIO on core	0.088	0.121	0.142	no core	0.157	0.23	0.72	0.86	no core	1.03

TABLE II. RESULTS FOR THE SCRUBBED CONCRETE, ***M*** IS FOR MONTH.

	Brightness coefficient Q_0					Specularity coefficient S_1				
Broomed concrete	***T0***	***T3m***	***T12m***	***T24m***	***T36m***	***T0***	***T3m***	***T12m***	***T24m***	***T36m***
COLUROUTE M1	0.141	0.120	0.112	0.191	0.181	0.09	0.14	0.27	0.43	0.30
COLUROUTE M2	0.120	0.149	0.140	0.176	0.136	0.08	0.16	0.28	0.36	0.25
COLUROUTE M3	0.152	0.105	0.117	0.139	0.175	0.08	0.14	0.33	0.51	0.24
GONIO on core	0.099	0.123	0.166	no core	0.138	0.09	1.10	0.80	no core	0.42

Whatever the methodology of measurements, the brightness increases with time for both pavements and reaches around 0.15. With COLUROUTE measurements, the specularity of the scrubbed concrete increases significatively (class R3 pavement) after 2 years (Fig. 4a) but returns to a class R2 pavement after 3 years (Fig. 4b). For the broomed concrete, the specularity remains low (class R1 pavement, Fig. 5). The specularity obtained in laboratory on the core samples is generally higher (Fig. 4c and 5c) than on the field. This is probably due to the presence of residual dust around the cement plant that could have an impact on the on site measurement. However, the goniophotometer and COLUROUTE measurements have shown that the specularity of the broomed concrete is lower than the scrubbed one.

a. 

b. 

c.

Figure 4. Reflection indicatrix of the scrubbed concrete measured with COLUROUTE device on site after 24 months (a) and 36 months (b). The three measurements are represented in blue, cyan and green. Measurement made on a core extracted after 36 months and measured with the laboratory goniophotometer (c). The axes are as defined in Fig. 1b.

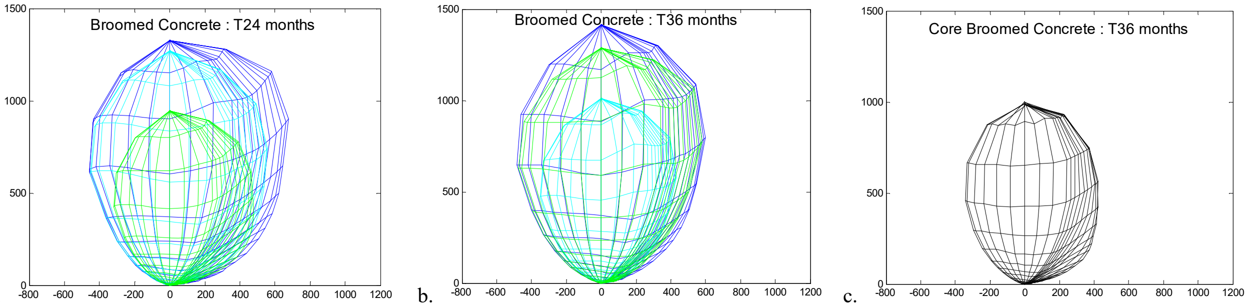


Figure 5. Reflection indicatrix of the broomed concrete measured with COLUROUTE device on site after 24 months (a) and 36 months (b). The three measurements are represented in blue, cyan and green. Measurement made on a core extracted after 36 months and measured with the laboratory goniophotometer (c). The axes are as defined in Fig. 1b.

The photometrics measures show an important effect of erosion with time and traffic as illustrated by the pictures taken on each COLUROUTE intervention (Fig.6). The broomed surface looked like a water jet scrubbed concrete after two years (Fig. 6b,d).

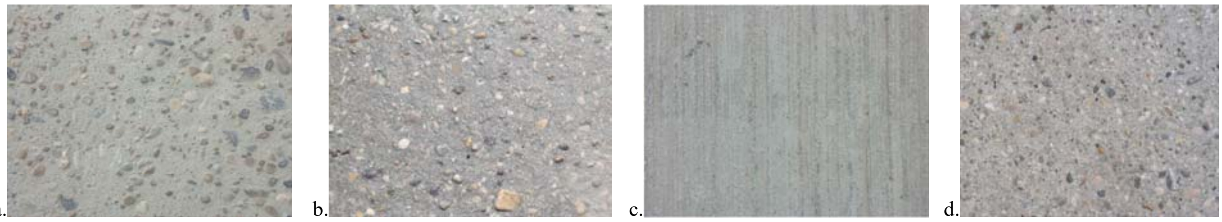


Figure 6. Pictures of the water jet scrubbed concrete (a. initial state, b. after two years). Pictures of the broomed surface (c. initial state, d. after 2 years).

Since it is easier to obtain uniform illumination with diffuse pavements, the surface treatment chosen in the Sinard tunnel was a broomed one because of its lower specularity.

B. Experiments on the Sinard Tunnel

Since it was not possible to extract core sample on the A51 highway, only COLUROUTE device was used to make on site measurements on the right lane of the pavement during 30 months. They were performed on the central and on the tyre lane. At each intervention, the specularity was relatively homogenous but there were differences on the brightness factor Q_0 that could reach 30%, as illustrated in the Fig. 7. At the initial state (Fig. 8a), the broomed concrete road surface was not very specular (class R2), probably because residual curing compound was still present. After 6 months of traffic, the pavement surface had an average brightness of 0.1 and was very close to R1 pavement types (Fig. 8b). There were more specular areas, in particular on the left tyre tread and on the centre lane. After 18 and 30 months of traffic (Fig.7 and Fig. 8c), the pavement remained of class R2 but was brighter than typical R2 pavements (the average brightness was 0.10 at 18 months and 0.09 at 30 months).

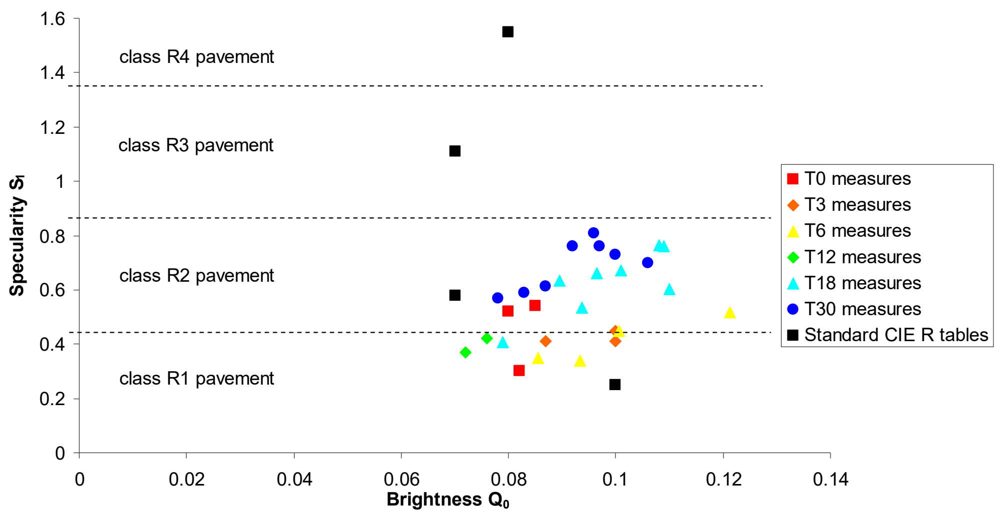


Figure 7. Representation of the photometric characteristics of the standard R tables (in black) and of all the measures done with COLUROUTE device in Sinard tunnel. In red for T0 measures, in orange for T3 measures, in yellow for T6, green for T12, light blue for T18, blue for T30.

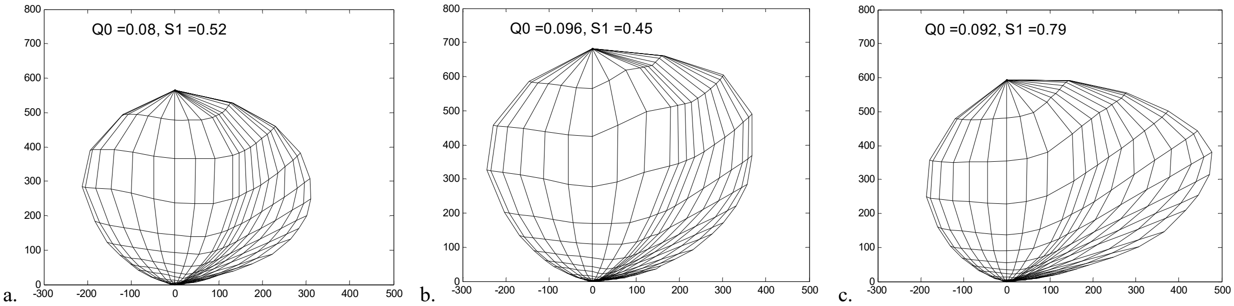


Figure 8. Photometric solids of the road surface in the Sinard tunnel, measured using COLUROUTE on new pavement (a), on a wheel track after 6 months (b) and 30 months (c) of traffic.

The energetic impact of the choice of such a concrete pavement is analysed with DIALUX software on a classical road installation with Philips Iridium gen3 Led and a lantern spacing of 29m (height 8m). Calculations were made in three conditions: using the standard R2 table, using the standard R2 table rescaled according to a 3 years old classical French black pavement from [5], and with a rescaling according to Q_0 obtained after 30 months with COLUROUTE. To achieve the class M3 requirement [11], 54.7W lantern are necessary for the standard R2 table, 70.6W for the classical bituminous pavement and 38W for the Sinard concrete (Table 3.). The corresponding electrical consumption confirms that using a lighter pavement generates substantial energy saving.

TABLE III. RESULTS OF THE DIALUX CALCULATION AND CORRESPONDING ELECTRICAL CONSUMPTION

Description of pavement	Q_0	Light Power in W	Consumption in kW/km	Energy saving
Standard R2 table (reference)	0.070	54.7	1.89	0%
R2 table rescaled with a classical bituminous pavement	0.054	70.6	2.43	-29%
R2 table rescaled with Sinard T30 concrete pavement	0.092	38	1.31	31%

CONCLUSION

The pilot study was used to choose between different surface treatments of concrete. There was an accordance with the results measured on core samples in laboratory and the portable device COLUROUTE. Differences are sometimes due to the process of sampling. In the pilot study located near a cement plant, there was residual dust that was removed during the extraction. Whatever the type of measures, the broomed surface is always less specular than the scrubbed concrete. The results obtained in the pilot study and on the circulated tunnel were consistent. The broomed concrete pavement is and remains bright and its specularity stays moderate, despite the effect of traffic.

The energy consumption study has shown that taking into account the real characteristics of the concrete pavement used in the Sinard Tunnel, the lighting electric power could be reduced by 46% compared to a classical French bituminous pavement. This emphasises the importance for the project owner to properly take into account the choice of pavement characteristics regarding its photometry when defining tunnel and road specifications.With on site measurements, more measurements are done and the mean result is more representative than just one or two core sample. There is still necessity to define how many measurements shall be done and how to handle them. These aspects will be addressed during the European Empir project called SURFACE which is beginning.Acknowledgement

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Mobile Methods of Rated Lighting Parameters of Illumination Measurement - Luminance and Illuminance.

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***Abstract*—The main objective of the road lighting is to provide safe and comfortable conditions for vehicles and pedestrians. The control of outdoor lighting rated parameters luminance and illuminance is the most effective way to assess lighting quality. For ensure high-quality, fast and safe measurements of rated parameters, according to the recommendations [1], was created a mobile lighting laboratory.**

***Index Terms* — outdoor lighting, luminance, illuminance, mobile methods of measurement, safety.**

PROBLEM DESCRIPTION

At present days, the measurement of rated parameters of the road surface are required to produce both traditional stationary and mobile methods in accordance with the legislation of the Russian Federation [2] - [7]. The method of measurement fixed more common, but difficult and time-consuming, and therefore expensive. In addition, to ensure the safety of the personnel performing the measurement, it requires the overlap of traffic on the site measurements. Therefore, considering all the difficulties and limitations, measuring the luminance and illuminance methods of the stationary mass is not held. Mobile methods of measurement of normalized parameters on the roads avoid the above problems, a modern means of measurement and processing of measurement results, ensuring the implementation of a mobile method gives the most reliable results. This greatly increases the performance measurements, which allows monitoring of lighting systems within their lifetime. The traditional stationary approach to rated parameters measurements is complex and laborious, and therefore expensive. Besides that for ensuring the safety of the personnel performing the measurements, it is necessary to divert traffic in the test area. Therefore, considering all difficulties and limitations, stationary methods of luminance and illuminance measurement are not widely used. Mobile methods of rated road lighting parameters measurement allow evading the above problems, and modern measurement equipment and data processing techniques that implement the mobile method allow to obtain the most reliable results. Among other things the mobile method increases the measurement productivity, that in turn makes it possible to monitor lighting systems during their lifetime.

The main objective of road lighting is to provide visibility of objects on the roadway surface. The most appropriate visibility parameter is the road surface luminance level to which the human eye reacts. However for its measurement it is necessary to meet certain conditions: the measurement area should be straight and (without any intersections with other lighted roads) and have a length of at least 60 m plus three spans between supports, the area surface should be clean, dry, uniform and well-trodden (at least six months in operation). In those areas where the luminance measurement can’t be carried out because of the failure to comply with at least one of these requirements we should measure the road surface illuminance.

MOBILE METHOD OF MEASUREMENTS

The essence of mobile method is that measuring devices (luminance meter or photometric illuminance sensors) are placed in a certain way on a vehicle (car) and connected to the recording device and the data received from them are automatically stored and processed with the help of proper soft- and hardware. The whole measurement process is carried out while the vehicle moves along the measured part of the road and this makes it possible to avoid the necessity for traffic interruption, which leads to traffic jams. At the same time, it is necessary to comply with a number of requirements: the movement should be carried out as far as possible with a constant speed of no more than 60 km/h, strictly along the lane. Applied equipment should be able to choose the integration time for the luminance meter and the number of measurements per time unit for illumination measurement system. To accurately track the position and speed during the measurements, the mobile system is equipped with a GPS receiver and a speed sensor.

A. Road surface luminance measurements by mobile method.

Mobile luminance measurements are carried out with a CCD-based imaging luminance meter LMK 5 [8] corrected for the spectral luminous efficiency function V(λ). The camera is installed in the car at a height of 1.5 m above the road surface (Figure 1) according to the requirements of the applicable Russian standards that are harmonized with European standards.

Figure 1 - Example of arrangement of an imaging luminance meter in a car for luminance measurements by the mobile method

The luminance measuring camera allows to record and store on the computer hard disk the luminance image that falls within the camera field of view. Image processing is carried out in the laboratory conditions after the measurements. In order to get measurement results manually a test area is designated on the luminance image by a specially designed computer program (Figure 2), and control grid points are marked in this area in accordance with the standard. The program automatically calculates the rated luminance parameters in each control point as well as the values of its road surface distribution uniformity (the ratio of the minimum brightness to its average value for all polygon control points) and the longitudinal value (the ratio of the minimum brightness value to the maximum on the current lane).

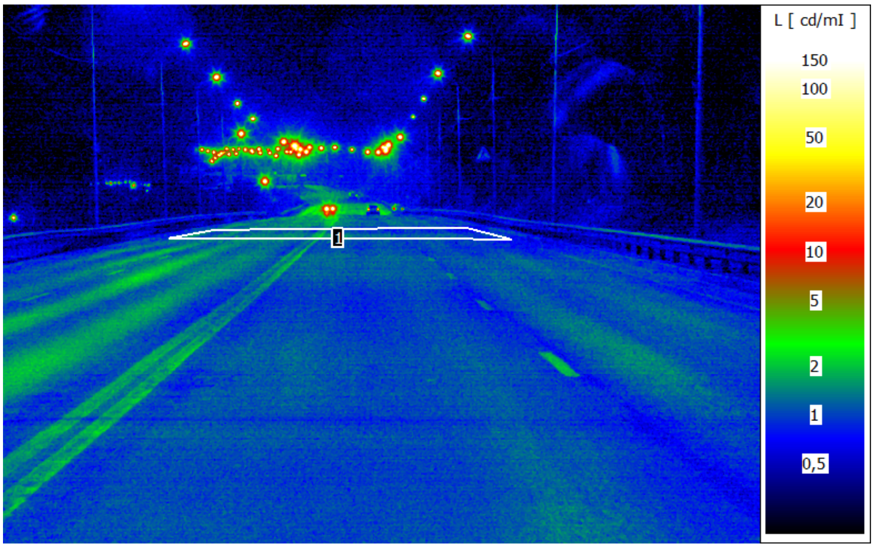


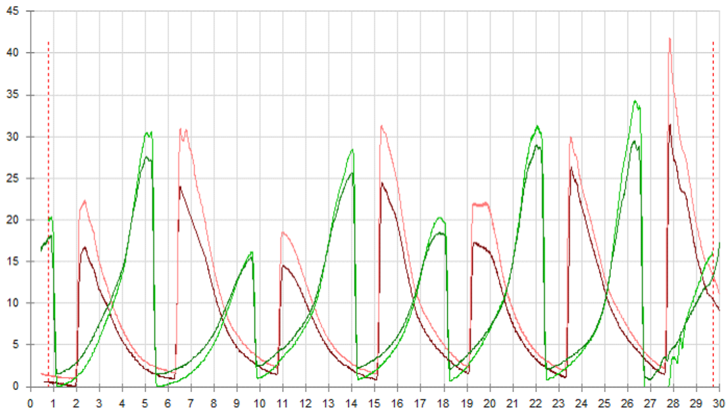
Figure 2 - Colour image with a designated test area (white)

B. Road surface illuminance measurements by mobile method.

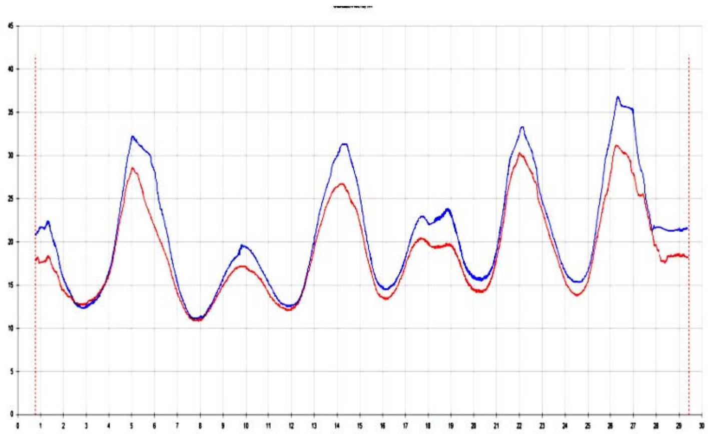
For mobile illuminance measurements in accordance with the recommendations of CIE 194:2011, four photometric heads are installed outside the car so that their receiving surfaces are parallel and as close as possible to the road surface (Figure 3). Sensors mounted at the front and at the rear of the car record the signals from luminaires that are located ahead and behind the moving car correspondingly. This is achieved with the help of sensor screening elements correspondingly. Sensor's data are stored while driving at preset time moments. It should be noted that in Europe there are similar operating systems, for example, [9] - [11].

Figure 3 - The assembled system for mobile measurement of illuminance

When processing the data a special program combines the signals obtained from corresponding front and rear sensors (two paires) at the time when they were in the same point of space. An example of the program in the processing shown in figure 4.



a)



б)

Figure 4 - Processing the results of measuring the illuminance of the road surface
(a - is measurement results obtained from all sensors, b - is the results obtained from processing after data is reported)

THE ERROR OF MEASUREMENT

The created system meets all safety requirements [12]-[14]. The luminance and illuminance measurements accuracy is estimated [15]-[17]. The total error of the method for measuring the brightness of the road surface is ± 6%, and when measuring the illumination ± 9%.

Using the newly created mobile laboratory has been performed for a relatively short period of time the patient volume measurements in many cities of the European part of Russia, including Moscow.

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Exploration of Light-Induced Variations in Cognitive Task Performance in Real Life

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Abstract— **Research has shown that light can induce moderations in cognitive performance. To date, most of the effects of cognitive task performance have been demonstrated in the controlled confines of the laboratory. How and to what extent light affects cognitive task performance in the field during person's daily routine is still largely unknown. To this end, a field study was performed to explore - as a first step - the effect of light exposure on cognitive task performance in everyday-life situations. The results of the current study highlights the relevance of studying light-induced variations in real life, and the results indicate that effects of light on task performance during individuals' daily routine may depend on type of task.**

***Index Terms*—Cognitive task performance, light, real-life**

Introduction

Multiple studies have shown that bright light can induce acute alertness-enhancing and vitalizing effects during daytime, both in the laboratory [1-3] as well as in the field [4]. While the effects on self-report measures are relatively robust, findings on cognitive performance tasks have revealed mixed results with positive, null, and even negative effects of exposure to bright vs. dim light during regular daytime working hours [5-7]. These effects are suggested to be dependent on – among others - the type of task and/or timing of the light exposure [3,5,6]. For instance, a recent laboratory study [6] revealed that while performance on a sustained attention task (auditory Psychomotor Vigilance Task; PVT) benefitted from exposure to bright light (1000 lux vs. 200 lux at eye level), results on a task requiring inhibitory capacity (auditory Go-NoGo task) and working memory (visual 2-back task) revealed some performance-undermining effects of bright light exposure. Moreover, Huiberts et al. [5] reported some improvements in performance on relatively easy working memory task (Forward Digit Span Task; FDST) under bright light (1000 lux vs. 200 lux at eye level) while performance on a more difficult version of this task (Backward Digit Span Task; BDST) as well as on a 2-back task was lower in the bright light condition in the afternoon. Moreover, no significant light-induced effects on the 1-back or 3-back task were reported in that study [5]. Another study showed that potential beneficial effects of bright light exposure on sustained attention may particularly occur in the morning [3].

To date, effects on objective task performance have mainly been reported in the laboratory. Yet, how – and to what extent - effects on task performance manifest during the daily dynamics in the field is largely unknown. In the current study, we therefore explored the effects of light exposure on individuals' performance in real-life situations. To this end, natural occurring variations in light exposure, task performance, affective state, and sleep were assessed for three consecutive days during the regular routine of healthy, day-active persons.

Method

A. Design

A correlational field study was performed as a first step to explore potential light-induced moderations in task performance during individuals' regular daily routine.

B. Participants

Thirty-one Dutch speaking subjects participated in the study, of which 17 were male and 14 female with a mean age of 24 (SD = 8.6; range 18 to 57). The participants were recruited through the J.F.Schouten School for User-System Interaction Research database of the Eindhoven University of Technology.

e. Measurements

The measurements consisted of cognitive performance tasks and questionnaires, combined with wearable sensors.

1) Cognitive performance tasks

Three performance tasks were employed, assessing different cognitive capabilities: sustained attention (PVT); inhibitory capacity (Go-NoGo task), and working memory (2-back task). All tasks were visual tasks administered on a mobile phone, and took 1 minute to complete.

During the 1-minute PVT task, stimuli (asterisk) were presented on the screen for 200 ms with an inter-stimulus interval of 1 to 5 seconds. Participants were instructed to respond as fast as possible to the stimuli by pressing the menu-button on the mobile phone. Participants' mean response time to stimuli was used as performance indicator for this task

The Go-NoGo task was very similar to the PVT, except that the stimuli consisted of targets (asterisk) and non-targets (plus-sign). Eighty percent of the stimuli were targets, and 20% of the stimuli were non-targets. Mean response time to targets as well as the number of correct responses were used as indicators for reaction time and accuracy on this task.

Participants were asked to only respond to targets. During the 2-back task, stimuli (letters: a, b, f, h, k, m, r, x) were presented one by one on the screen. Each letter was displayed for 200 ms and the inter-stimulus interval was set at 800 ms. Participants' mean response time to targets and the number of correct responses were used as performance indicators for the 2-back task.

2) Experience sampling questionnaire

The experience sampling questionnaire consisted of eleven items probing participants' affective state in terms of their level of vitality (4 items: '*energetic*', '*lacking energy*' (reversed), '*alert',* and '*sleepy*' (reversed)), tension (3 items: 'tense', 'calm' (reversed), and 'relaxed' (reversed)), positive affect (2 items: '*happy*' and '*satisfied'* , and negative affect (2 items: 'sad' and 'cheerless'). For each item, participants indicated how they felt on a scale ranging from 1) 'not all' to 4) 'completely'. In addition, three items adopted from [8] were administered to measure state self-control on a 5-point scale from 1) 'not true' to 5) 'very true'. These items measured different aspects of self-control strength: ability to concentrate on something ('Right now, it would take a lot of effort for me to concentrate on something'), general lack of willpower ('I feel like my willpower is gone'), and ability to control one's urges ('I am having a hard time controlling my urges'). Moreover, participants reported on the amount of social interaction, physical activity, mental effort, time spent outdoors, and food intake during the hour prior to completing the questionnaire.

i. Sleep diary

In the sleep diary, participants completed a short questionnaire regarding their sleep timing, sleep quality, and affective state after awakening. The questions from the sleep diary were adopted from the Karolinska Sleep Diary [9]. The items for affective state were the same as the ones employed in the experience sampling questionnaire.

ii. General questionnaire

Participants completed a general questionnaire which consisted of questions regarding their age, gender, chronotype, general sleep quality, general level of fatigue, trait vitality, neuroticism, general health, subjective light sensitivity, and eye discomfort. Chronotype was measured with the Munich Chronotype Questionnaire [10]. General sleep quality was assessed by means of the Pittsburg Sleep Quality Index [11]. General level of fatigue was assessed with the 20-item Checklist Individual Strength [12] probing different aspects of fatigue (subjective feelings of fatigue, concentration problems, motivational deficits, and low physical activity) during the two weeks prior to completing the questionnaire. Trait vitality was measured with the 7-item Trait Vitality Scale [13], general health with 5 items from the Dutch version of the SF-36 Health Survey [14], and eye discomfort was assessed with eight items probing various eye symptoms such as itchy eyes, dry eyes, and teary eyes. Neuroticism was assessed with a subscale of the Dutch translation of the Big Five questionnaire [15].

iii. Wearable sensors

Wearable sensors (Daysimeter and Actiwatch) were administered to objectively quantify participants light exposure and physical activity patterns, respectively. The Daysimeter was worn on a pair of glasses or headband (see [4] for additional information about the light exposure measurements). Participants wore the Actiwatch at wrist during their waking episode.

f. Procedure

During an introductory meeting, participants signed an informed consent, picked up the materials (smartphone, wearable light sensor, Actiwatch, and sleep diary), and received instructions regarding the study protocol. Moreover, participants received a link to an online questionnaire probing personal characteristics of the participants (such as chronotype and subjective light sensitivity).

During the three consecutive sampling days, subjects wore the wearable sensors, completed short cognitive performance tasks and reported on their affective momentary state by means of an app on a smartphone, and kept a sleep diary. The experience sampling questionnaires and performance tasks were administered on a regular basis during individuals' daily routine (one questionnaire and one task every hour between 8 am and 8 pm). After the three days, participants returned the materials, and they were debriefed, thanked and received a compensation for their participation.

RESULTS

Multilevel analyses were performed to assess whether the average amount of light at eye level (in lg lux) during the hour prior to the task was a significant predictor for cognitive performance, controlling for structural variations in task performance as function of time of day and sleep duration of the prior night. Moreover, additional analyses are performed to investigate whether we could replicate results regarding the correlation between light and vitality as reported in an earlier study [4]. It should be noted that we cannot disclose all results here, as we are submitting the study to a peer-reviewed scientific journal. Therefore, only some preliminary results will be highlighted in this abstract, while more results will be presented at the conference.

Results on task performance revealed significant faster response times to targets on the Go-NoGo task when participants were exposed to more intense light during the hour prior to the task ($B=-17.90$; $F(1,237)=10.78$; $p<.01$). In contrast, response times on the PVT and 2-back task did not significantly correlate with prior light intensity (both $p > .10$). In addition, results revealed no significant effects of hourly light exposure on accuracy on the Go-NoGo task and 2-back task in terms of number of correct responses (both $p > .10$).

DISCUSSION

The current study highlights the relevance of studying light-induced variations on human cognitive functioning in real life. In line with the previous studies performed in the laboratory, the results indicate that effects of light on task performance during individuals' daily routine may depend on the type of task. Future research employing longer tasks, a more diverse range of tasks, and/or manipulation of the light settings is needed to determine whether - and to what extent - light can support performance in real-life situations.

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The Impact of Dynamic Lighting on Cognitive Processes

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***Abstract* — In this work, the variation of lighting parameters (illuminance and correlated colour temperature) was used as a prestimulus to investigate effects on cognitive processes. To synchronize the pre-programmed lighting scenarios with the stimulus presentation, a control unit with a short response time was implemented into a LED lighting unit with precisely controllable luminous intensity and correlated color temperature. We investigated effects of recurrent variations in illumination on performance and if the deviation from a standard illumination condition can trigger a neuronal response in the brain to path the way for the following conflict stimulus. In our experiment the Stroop condition showed a strong effect on the reaction time of the subjects whereas no significant difference in reaction time occurred between the two different lighting conditions.**

***Index Terms* dynamic lighting, cognitive processes, performance, reaction time**

INTRODUCTION

The impact of light on humans is subject of current research in chronobiology and psychology. However, experiments with light as a visual stimulus to prime users have not yet been carried out. Nowadays “dynamic lighting” is commonly understood as lighting systems that change their parameters over the course of a day [19]. Such lighting systems change according to pre-programmed settings and usually adapt the light to circadian rhythms. These kind of lighting systems are nowadays mostly based on Solid-State Lighting (SSL), predominantly on light-emitting diodes (LED). Thanks to their high efficiency, their compact design and their long life LED can be used very flexible. Those lighting systems are increasingly digitally controllable, integrated with sensors, and connected to mobile devices or even the internet. Systems with a digital control unit are nowadays called intelligent lighting systems. The use of intelligent lighting systems hold great potentials, because they can address personal, chronobiologic and psychologic needs of individuals. Lighting concepts focussing on the health of people are called "Human Centric Lighting” (HCL). The day and night rhythm (circadian rhythm) of natural light serves humans as a synchronization of their inner clocks [2]. LED lighting systems simulating natural lighting situations include for example the "Virtual Sky” at Fraunhofer IAO in Stuttgart [17].

Light is not only the basis of any visual perception but it also influences our well-being and our performance [3–7, 11, 14, 20, 22, 23]. The aim of this work is the development of a dynamic lighting scenario that supports cognitive processes when carrying out activities that require concentration. The focus of this research are effects of ultradian changes in correlated color temperature (CCT) and illuminance on concentration.

Cognitive processes that occur when sudden environmental changes confront an individual with inconsistent information are critical to cope with daily life. A change of the visual environment like for example the lighting situation, the blinking of an LED or the appearance of a word on the screen are visual stimuli that require the activation of cognitive processes for further processing. Light stimuli are processed via two networks in the brain, the classical visual system and the non-visual system [21]. Both networks are involved in neural processing. The stimulus processing of a single stimulus in the human brain can take up to 600 ms. During the first 150 ms, elementary processes of vision are running. As soon as the stimulus reaches the visual cortex, the second stage of the processing, the visual object recognition begins where gamma activations are induced in the brain, to retrieve and compare information from other brain regions [9].

DYNAMICS AND ATTENTION

Certain neuronal activities occur when humans are exposed to visual stimuli. Attention is defined as a measure of concentration to a certain stimulus. Humans have a limited recording capacity. To capture the flood of stimuli, only a fraction of the stream of photons entering our eye is consciously perceived. The human brain filters unvarying information of a visual scene from our perception. The opposite happens when a change occurs. Since our brain is designed to adapt to changes in our environment, every change in the environment causes an activating potential for our cognitive processes. Filter mechanisms in our brain are designed to draw our attention to a change in our environment [15].

Usually two cognitive processes are involved in experiments involving attention: the perception of the signal and the response to it. If a subject has to make a choice before he reacts, the process will delay his reaction time. How quickly the brain can give a cognitive response to a stimulus is not only due to its complexity, but also to the quality of the stimuli. The following dependency between the intensity of an optical stimulus and the reaction time can be established: The response time of the person increases, the closer the intensity of a light stimulus comes to the visual perception threshold [12]. Also a larger lighting area can reduce the perception threshold [18].

Cognitive processes can be influenced with the help of the so-called "priming-effect": During the processing of the first stimulus, the so-called "prime" or "prestimulus", memory contents are activated which determine the path for the target stimulus (target) which can lead to a shortened reaction time [13]. Conflict-related cognitive processes are important in order to adapt to a sudden environmental change that confront individuals with inconsistent information. This priming-effect causes an increase in the so-called mismatch negativity (MMN). MMN is the second negative peak of event-related potentials in an EEG measurement. The processes underlying MMN seem to have an important role in the selection and storage of relevant information. The occurrence of MMN after visual stimuli, however, is still controversial.

LIGHTING AS A STIMULUS AND RELATED WORK

The majority of research on visual stimuli uses stimuli presented on displays. Lighting has not yet been used as a prestimulus [10]. Stimuli by light differ in their effect from local visual stimuli, since the threshold of perception of a visual stimulus is dependent on its spatial distribution. With increasing size of the spatial distribution of a visual stimulus, humans are more sensitive to alternations [18]. One challenge in this work was to design a lighting system that provides a maximum priming effect while not distracting the subject from the task. A light stimulus that fulfils these requirements must have a uniform luminous density in order not to steer the subjects' attention into a certain direction. The mean threshold of perception is theoretically a change of illuminance by 14 % (photopic vision) [16] [8]. To amplify the stimulation by light, a change in correlated color temperature can be used additionally.

Related research showed that deviant auditory prestimuli facilitate the processing of stimulus-related conflicts, providing evidence for a conflict-priming effect [13]. A task-irrelevant auditory stimulus and a task-relevant visual stimulus were presented successively. The auditory stimulus consisted of a standard or deviant tone, followed by a congruent or incongruent Stroop stimulus. The goal of the Stroop task is to decide if the meaning of a colored word and its actual color are either the same (congruent) or different (incongruent). It was shown that after deviant prestimuli, performance was better for incongruent than for congruent Stroop stimuli. This research suggests that memory contents in the brain are activated which path the way for a target stimulus and hence lead to a better performance. Whether these relationships also apply to visual stimuli from a lighting unit is our research question.

We investigated whether a prestimulus induced by deviating light influences the immediate reaction time of the subject. We hypothesized that the deviation of illumination improves performance in a following task where the subject has to react to a conflict stimulus, due to a conflict-priming effect of the brain which is caused by breaking a regularity principle. In our case we expected decreased reaction times after the prestimuli.

EXPERIMENTAL SETUP

In our experiment we used specifically configured LED-panels with adjustable correlated color temperature. Figure 1 shows the experimental setup with three luminaires (modified BelvisoAct C2 from Trilux). White walls in the environment were used in our experimental setup.

35 healthy subjects between 20 and 67 years (averaged 28.5 years) were encouraged to perform the Stroop task under standard and deviating lighting. 500 milliseconds before the presentation of Stroop stimulus, the change in illuminance (ΔE = 14 lx vertically at eye-level; from 124.5 to 138.7 lx) and correlated color temperature (ΔCCT = 225 K; from 3500 to 3725 K) took place for every sixth Stroop stimulus in random order. This change of illuminance and correlated color temperature was perceptible. The changes in illumination were precisely adjusted to the events of the Stroop task in order to determine changes in reaction times caused by the conflict priming effect.

All Stroop words were shown to the subjects on a screen in front of them. The reaction time was measured for each stimulus under two conditions: with a light-Prestimulus and without a light-Prestimulus. Under both lighting conditions the subjects had 90 - 180 lx at the eye

Subjects had to press two different buttons on a response pad. The motor response from the subjects were sent to the experimental computer without delay. We determined reaction times and the error rate. The Stroop task included the colored words “red”, “green”, “blue”, “yellow”, “pink” and “white”. For the congruent condition these words were presented in their respective color. There was a maximum of three incongruent words in succession. Subsequently, the mean reaction time for all stimuli conditions (groups) within one subject was determined. A total of 144 words were presented to subjects, 24 of which with a priming light stimulus.

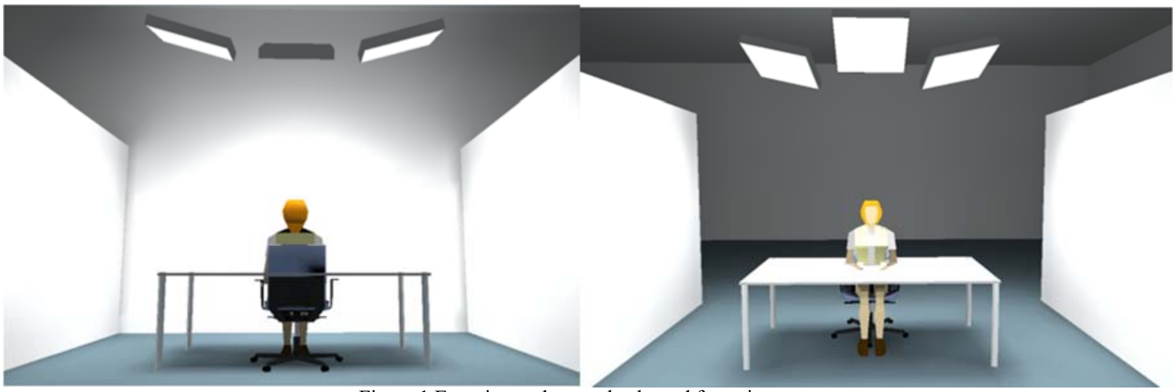

Figure 1.Experimental setup, back- and frontview

To increase the processing time between congruent and incongruent stimuli by the “Oddball-effect”, incongruent words were presented only half as often as congruent words. Each volunteer was given a different random order of words. To prevent any rhythm in the presentation cycle the timing of the presentation of the next stimulus was randomized, too. The entire test of the Stroop task took 15 minutes.

Figure 2 provides an overview of the lighting parameters used in standard lighting and during the deviant illumination. It also shows a network diagram of the relative spectral efficiency (RSE) for each individual photoreceptor in the human eye. The RSE values were calculated with the interactive dashboard of “SpeKtro” according to research from Maria L. Amundadottir [1]. A low value (RSE < 1) means a low stimulus potential and a higher value (RSE > 1) has a higher stimulus potential relative to the total irradiance of the light source. The largest changes in the RSE values caused by the deviating illumination occurs for the S-cones and the ipRGCs.

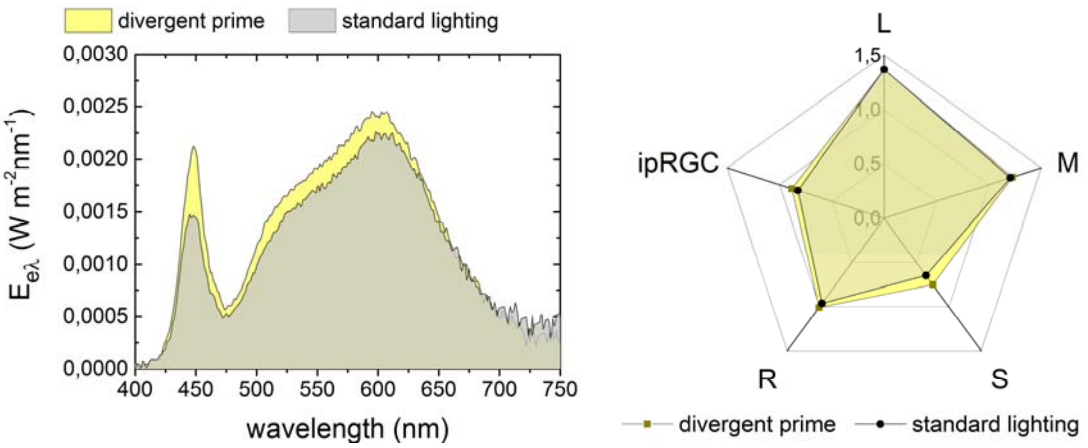

Figure 2. Illuminance changes, spectral characteristics (left) and relative spectral efficiency for each photoreceptor (right)

With illuminance changes and changes in CCT, not only the visual, but also the non-visual effect of light changes.

As a measure of the non-visual effect, table 1 shows the melanopic action factor $a_{mel,V}$ and the melanopic daylight-equivalent Illumination (MDEI).

TABLE I. VISUAL AND NON-VISUAL LIGHT PROPERTIES THE STANDARD LIGHTING CONDITION AND WITH PRIME

lighting condition	**lighting parameters**			
	E_v (lx)	***CCT (K)***	***$a_{mel, v}$***	***MDEI (lx)***
no prime	124,5	3500	0,49	66,4
with prime	138,7	3725	0,54	79,3

The melanopic action factor and the MDEI were calculated with the Human Centric Lighting Toolkit V14.21 according to DIN SPEC 5031-100: 2015 with the maximum value of the photometric radiation equivalent of K_m = 683 lm / W.

RESULTS

For statistical analysis the software ORIGIN was used. All variables were tested for normal distribution using Shapiro-Wilk test. All normally distributed data of reaction times were analysed with a two-factor ANOVA for repeated measurements. The first factor being the Stroop condition (congruent vs. incongruent) and the second factor the lighting condition (standard lighting vs. deviating light). The Stroop condition showed a strong effect ($F (1, 34) = 80.11$; $p < 0.05$) for the reaction time of the subjects. On average the response to the incongruent visual stimulus was slower (869 ms) than the response to the congruent stimulus (779 ms), see table 2. The lighting condition showed no significant differences ($F (1, 34) = 0.94$; $p = 0.34$) in reaction times. To test our hypothesis, the illumination conditions for each Stroop condition were tested with a post-hoc significance test (ANOVA with repeated measurements for one factor). The mean reaction time to the congruent stimulus after the deviating light was shorter (764 ms) than for standard lighting (779 ms). This difference in reaction time, however, is not significant ($F (1, 34) = 0.06$; $p = 0.81$). The mean reaction time to the incongruent stimulus was slower (898 ms) with deviating light compared to standard lighting (869 ms). This difference, however, is also not significant ($F (1, 34) = 3.01$; $p = 0.091$). The deviations of the reaction times for the incongruent target stimulus between lighting conditions are below the significance level of $p = 0.05$.

TABLE II. REACTION TIME, STANDARD DEVIATION AND THE QUARTILES FOR BOTH CONDITIONS

Stroop condition	**lighting condition**	**reaction times, and standard deviation**	
		$\bar{x}$ (ms)	***SD (ms)***
incongruent	with prime	898	213
	no prime	869	189
congruent	with prime	764	194
	no prime	779	167

Table 2 shows mean reaction times and standard deviation for both lighting conditions. Figure 3 shows the statistical evaluation (with quartiles) of reaction times of the Stroop task for the two lighting conditions.

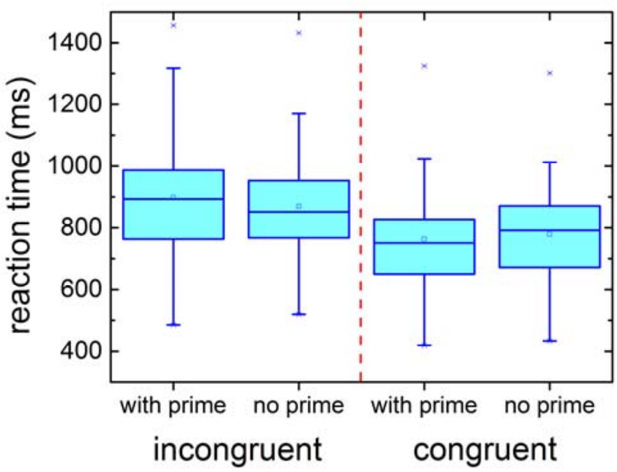

Figure 3. Reaction times with and without priming light

CONCLUSION

We hypothesized shorter reaction times after a light stimulus serving as a prime to cause an increase in the so-called mismatch negativity (MMN). In our experiment, however, no significant difference in reaction time occurred after the visual prime. Possibly no regularity principle was ever violated. Thus, our visual prime caused by dynamic light did not path the way for a conflict priming effect in the brain. For further investigations it would be interesting to carry out EEG measurements while dynamic light is presented to subjects.

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The Myth of Baker-Miller Pink: Effects of Colored Light on Physiology, Cognition, and Emotion?

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***Abstract*—Besides aesthetic aspects, color can have impact on human perception and behaviour. A special pink hue, the so-called Baker-Miller pink, is assumed to induce calming effects. In this study, we evaluated pink and white lighting conditions with N = 29 subjects, through tests of attention, measurements of skin conductance and emotional state ratings. With an exposure time of 15 minutes including measurements, no color effect was found in skin conductance and attentional performance. There was also no difference in ratings of emotional valence and arousal between the two lighting conditions. Although, subjects rated Baker-Miller pink light significantly less activating than white light. A significant sex effect showed that women preferred pink light more than men. These results indicate that there are indeed differences in subjective perception of white and Baker-Miller pink light although they cannot be found in objective measures of physiological and cognitive processes.**

***Index Terms*--arousal, attention, Baker-Miller pink, light color, skin conductance**

INTRODUCTION

In everyday life, color is one of the most omnipresent aspect of peoples' sensory perception. Beside aesthetic aspects, like color harmony, people tend to share color specific associations. Green, for example, is commonly considered as the color of hope, blue as the color of tranquility. Red seems to be more ambiguous, being the color of love and danger at the same time. The omnipresence of colors and their associations raises the question, if color can cause specific effects on humans' perception and behavior. In the 1970s Alexander Schauss proposed a pink hue, the later called Baker-Miller pink, which he regarded to unfold a broad impact on humans within 15 minutes exposure [1]-[2]:

- faster reduction of physiological arousal compared to other colors, from a heightened level of physiological arousal,
- reduction of muscle strength and,
- as consequence of these two effects, the reduction of aggressive behavior.

First observations with pink colored prison detention cells seemed to support these effects [2]. As a result, prison detention cells all over the world were painted with Baker-Miller pink [3]. Following laboratory experiments produced conflicting results. Two studies found a significant muscle strength reduction when suspects were exposed to a pink compared with a blue board [4]-[5]. Other similar studies with slight methodical improvements could not replicate this effect [6]-[8]. No significant differences in blood pressure, pulse and attentional performance after exposition to Baker-Miller pink vs. white could be confirmed [6]. A recent study investigating the effects of prison detention cells painted in Baker-Miller pink found no aggression reducing effects [3]. Based on these results, one should doubt the proposed effects of Baker-Miller pink.

Nevertheless, latest psychological research revealed color effects on psychological processes. The *color-in-context* theory [9] provides a theoretical framework on how the measured color effects on cognitive performance and emotion are caused. The authors suggest that color effects are caused by classical conditioning and biological predispositions. The effect is shaped by the psychological context of presentation. As an example, the color red can decrease performance in an intellectual achievement situation [10], whereas viewing red in a competitive sports context is associated with enhanced performance [11].

By virtue of this knowledge, the present study was designed to investigate possible effects of Baker-Miller pink colored light on cognition, physiology and emotion with up-to-date methods. In the exploratory study design, differences between a Baker-Miller pink colored light and a neutral white light were investigated. In focus of interest were (1) cognitive performance, operationalized by a test of attention, (2) physiological arousal, operationalized by skin conductance, and (3) emotional valence and arousal, operationalized by self-report. Additionally, we measured the participants' individual color preferences.

METHODS

A. Participants

The sample consisted of 29 Fraunhofer IAO Stuttgart employees aged from 20 to 50 years (M = 28.07, SD = 6.05, 15 females). Each individual had normal or corrected-to normal vision and no color deficiencies. Participation was voluntary and could be withdrawn at any time. All participants were informed about the procedure and purpose of the experiment and gave written consent in advance of participation.

B. Materials

The laboratory was a windowless room with constant temperature (21°C) and noise (20 dB). A vertical 2.85m x 2.25m diffuse light wall, developed by Fraunhofer IAO, with a total of 6912 LED lights, emitted the colored light. In the CIE 1931 color space, the Baker-Miller pink colored light was located at x = 0.3947 and y = 0,2931 and thus almost identical with Baker-Miller pink as wall paint color (x = 0.3946, y = 0.2978). A neutral white light served as control condition. Illuminance was measured on eye level and was comparable for both, pink light (228,91 lux) and white light (224,87 lux). The spectral characteristics are shown in Figure 1.

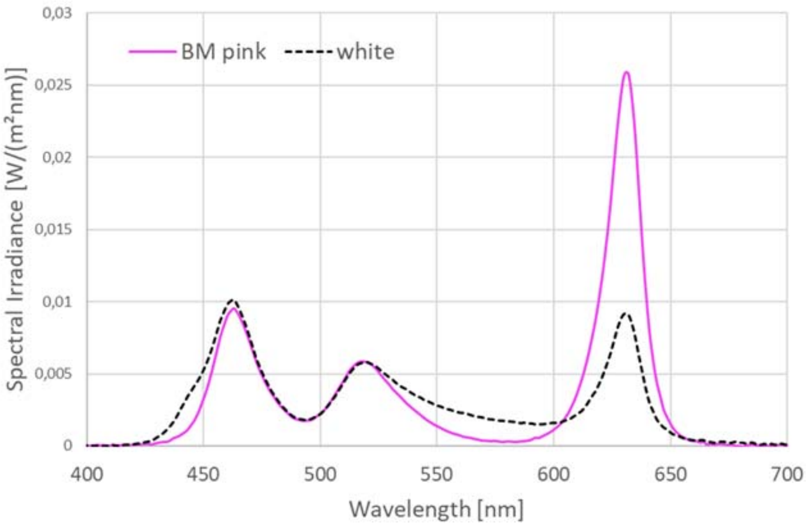

Figure 1. Spectral characteristics of Baker-Miller pink and white light color

Participants were seated in front of the diffuse light wall, at a distance of 1.60 m. The light wall occupied a viewing angle of approximately α = 85.67°.

C. Design

In order to compare Baker-Miller pink colored light with white light, a 2x2 mixed design with light color as within-subject factor was adopted. Sequence of color presentation (pink-white vs. white-pink) was balanced and included as between-subject factor. Dependent variables were measured through physiology, cognition and emotion.

Physiological arousal was operationalized by skin conductance in microSiemens (µS), a convenient measure of sympathetic arousal [12]. The BIOPAC MP 150 sampled skin conductance at a rate of 40Hz, using two Ag-AgCl electrodes attached to the distal phalanx surface of the fore and middle finger of the nondominant hand. As cognitive measure, the d2-R test of attention, a paper and pencil based mental speed test, was used to assess concentration and attention performance. This cancellation test has a high reliability with Cronbach's Alpha ranging from 0.82 – 0.96 [13] and is considered as a valid measure of attention [14]. The derived parameter concentration power corresponds to the total number of correctly cancelled target characters. The parameter percentage of errors corresponds to the amount of errors divided by the total number of processed characters. The Self-Assessment Manikin (SAM) served as measure for emotional status [15]. Ratings of valence and arousal were registered using a 9-point Likert scale. Emotional status

and physiological arousal were both assessed three times during each color condition with time of measurement as additional within-subject measure (2x2x3 mixed design).
As additional subjective measures, two 5-item questionnaires registered perceived activation and visual fatigue via 6-point Likert scale. Another 5-item questionnaire was developed to assess general beliefs about the impact of the colors pink and white and colored light. The questionnaire also used a 6-point Likert scale and was completed at the end of the experiment. To test for color preference, participants were given an additional item: "This test will now be repeated with the light color of your choice (white or pink). Which color do you choose?"

D. Procedure

After completing the informed consent, electrodes were attached and baseline measurements of skin conductance (30 seconds), emotional status and visual fatigue were assessed during normal ceiling lighting. Throughout the experiment, measurements of skin conductance and emotional status were assessed simultaneously. After baseline measurements, the first lighting condition started. Participants were instructed to watch the light wall for 10 minutes. A task of counting a pulsating dot at the light wall ensured looking onto the wall while producing only mild cognitive load. This was followed by measurement of skin conductance and emotional status. Next, participants completed the d2-R test, followed by another measurement of skin conductance and emotional valence, the questionnaires about visual fatigue and perceived activation. At the end of the first light color condition, skin conductance and emotional status were measured a third time.
After a 5-minute break, the second lighting condition with the same order of measurements started. Finally, the light wall was switched off and participants completed the questionnaire concerning general beliefs about the colors and colored light. In total, the study lasted about 50 minutes. Only one person was tested at a time.

E. Statistical Analysis

Baseline-corrected values were used for further analysis of emotional valence and arousal as well as skin conductance. For each questionnaire, mean values were calculated. All variables were tested for normal distribution using Shapiro-Wilk test. Mixed Analyses of Variance (ANOVA) were calculated for each, skin conductance, concentration power, emotional valence and arousal, activation assessment and visual fatigue. Percentage of errors in d2-R test were analysed with Wilcoxon test. A χ^2-test investigated the association between sex and color preference. All results were retrieved from two-sided tests.

RESULTS

Age and sex were approximately equally distributed among the two sequence groups: The white-pink group consisted of 8 females and 7 males (age: *M*=26.67, *SD*=4.07); the pink-white group consisted of 7 females and 7 males (age: *M*=29.57, *SD*=7.51). As can be seen in Table 1, all dependent variables show only slight differences in physiological, cognitive and emotional measures between Baker-Miller pink and white light.

TABLE I. MEANS AND STANDARD DEVIATIONS FOR COGNITIVE, PHYSIOLOGICAL AND EMOTIONAL MEASURES, PERCEIVED ACTIVATION AND VISUAL FATIGUE

Measures		**Light color**	
		Baker-Miller pink *M (SD)*	***White*** *M (SD)*
Physiology	Δ Skin conductance (µS)[a]	1.64 (1.51)	1.61(1.55)
Cognition	Concentration power[b]	191.69 (39.47)	190.55 (40.09)
	Errors (%)	7.40 (7.31)	8.93 (9.65)
Emotion	Δ Valence[a]	-0.55 (0.94)	-0.37 (0.98)
	Δ Arousal[a]	-0.26 (1.65)	0.01 (1.20)
Perceived activation[b]		3.13 (0.76)	3.74 (1.05)
Δ Visual fatigue[a]		0.41 (0.64)	0.46 (0.71)

a. Skin conductance, emotional valence and arousal and visual fatigue are baseline-corrected: positive values indicate a higher level than at baseline, negative values indicate a lower level than at baseline.
b. Values of concentration power (higher values indicate better performance) perceived activation (1=not at all activating; 6=very activating) are absolute values.

Physiological arousal was investigated using a 2x2x3 (color x sequence of light color x time of measurement) mixed ANOVA to test for differences in skin conductance. Light color (pink and white) and time of measurement (three times

throughout one trial) served as within-factors, sequence of light exposure (pink-white and white-pink) served as between-factor. The color*sequence interaction was significant, $F(1,27)=5.67$, $p<0.05$, indicating a general skin conductance increase during the second lighting condition. The ANOVA revealed no significant main effects.
To assess effects on cognition, a 2x2 (color x sequence) mixed ANOVA, including light color as within-factor and sequence as between-factor, investigated concentration power in the d2-R test of attention. The significant interaction color*sequence, $F(1,27)=192.72$, $p<0.001$, corresponds to a clear learning effect throughout the second test execution. No significant main effects were found, meaning there were no performance differences caused by the different lightning conditions or by dissimilar groups. The nonparametric Wilcoxon test, testing for percentage of error differences during pink and white light exposure, indicated no significant difference.

Emotional status was evaluated with two 2x2x3 mixed ANOVAs which separately investigated emotional valence and arousal. For emotional valence, a significant interaction was found for time of measurement*sequence, $F(2,54)=3.36$, $p<0.05$. This interaction is based on a difference of valence ratings between group pink-white and group white-pink at the first measurement after light exposure. Group pink-white rated emotional valence significantly higher at this point than did group white-pink. There were no significant main effects. For emotional arousal, a significant main effect was found for the variable time of measurement. Pairwise comparisons showed an increase between measurement 1 (after 10 minutes light exposure) to measurement 2 (after d2-R test) as well as a decrease between measurement 2 and measurement 3 (after further questionnaires), independent of the light color. This interaction suggests that the participants were subjectively aroused due to the d2-R test and calmed down again towards the end of a light condition. No further significant effects were found in this ANOVA.

To assess perceived activation of the light color, a 2x2 (color x sequence) mixed ANOVA was conducted. A significant main effect was found for color, $F(1, 27)=11.40$, $p<0.01$, but not for sequence. These results show that white light was rated more activating than pink light, independent of the sequence of light color exposure. The additionally significant interaction color*sequence, $F(1,27)=7.18$, $p<0.05$, suggests that this effect was caused mostly by the group which was exposed to first pink light and then white light. The white-pink group showed no such difference in ratings of perceived activation. No significant effects in ratings of visual fatigue for light color or sequence were found in a 2x2 (color x sequence) mixed ANOVA. This shows that neither color put more strain on the participants' visual system than the other.

Discussion

The goal of this study was to investigate effects on physiology, cognition and emotion of Baker-Miller pink light compared with white light. Although subjective differences in perceived activation through light color were shown, no effects in physiology and cognition were found: Due to the light exposure, skin conductance as physiological measure showed increased values compared to baseline but did not differ between colors. Results of the d2-R test indicated strong learning effects but no differences between colors. There was also no color effect evident in the measure for emotional status. The only measure detecting a difference between colors was that white light was rated as more activating than Baker-Miller pink light. This effect should be interpreted carefully because only the group which was exposed to pink light first and white light second showed this effect. Therefore, these differences might have been caused by sampling artefacts.

However, some aspects should be taken into account. Importantly, color exposure time was limited to 15 minutes which might have been too short to induce detectable effects. But, since usually skin conductance reacts to changes in physiological arousal already after few seconds with a reliable latency of one to three seconds [16], it can be regarded as improbable to assume effects after longer exposure time. In addition, as the *color-in-context* theory [9] proposes, psychological context plays an important role in color effects. Of course, the present laboratory setting differs completely from a real-life prison setting, for which Schauss [2] reported results of calming and aggression reducing effects of Baker-Miller pink. Nevertheless, this is not the first study which fails in replicating the proposed effects, even in the same context [3], arguing against a specific prison context effect. But, social desirability cannot be ruled out to having impacted our effects: Previous research [17] indicated that especially female sex is associated with the color pink already starting in early childhood. In fact, post hoc analyses investigating a possible association between sex and color preference showed a significant sex effect ($\chi^2(1)=5.97$, $p<0.05$): Women clearly preferred the Baker-Miller pink light over white light while men showed a slight preference for white light suggesting that the context might have played a role.

In the current study, arousal levels were compared between colors. It is important to note that this does not test Schauss' initial hypotheses, which claims that, starting with a high arousal level, exposure to Baker-Miller pink leads to faster arousal decrease compared to other colors. Therefore, including the induction of a higher arousal level prior to color exposure should be considered in further research. Based on the current study examining also physiological and cognitive measures, the results do not support the proposed strong calming effects of Baker-Miller pink [2].

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Illumination Needs of Patients with Low Vision

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***Abstract*— Background: The low vision and not clinically blind people all over the world are about tens of millions due to WHO (World Health Organisation). Most of illumination regulations are made for people who have normal vision. For blind people there is no special lighting necessary. But low vision patients have still some useful visual function, which could and should be enhanced using special illumination features. According to WHO low vision is visual acuity less than 6/18 and equal to or better than 3/60 in the better eye with best correction. Beyond this the patients are –not clinically but- legally blind. Not being clinically blind the patients expect to see some more with any help than without any device. Methods: The limits of normal visual function determine the transition to low vision. There are many eye and systemic diseases, which reduce the visual function. The patients' disease, its stage, its change and/or progress over time, life quality expectancy, age and a lot of other factors are important for the evaluation of the lighting needs of low vision patients. Results: There are relatively high percentages of legally blind and low vision patients in society. There are hundreds of eye (diabetic retinopathy, age related macular degeneration etc.) , internal medicine and neurology diseases which can cause low vision. Some of them may have better visual function with special lighting measures like special colour temperature, special colour filters or monochromic light and direction of the light. The usefullness of the methods in each patient depends from his diagnosis and the progress of the disease at a certain time. Conclusion: The illumination suggestions for low vision and not clinically blind patients should be done by an ophthalmologist or technically precised by an illumination specialist in cooperation with an ophthalmologist.**

***Index Terms*— Color filters, color temperature, eye disease, low vision, systemic disease.**

VISUAL IMPAIRMENT AND BLINDNESS

Due to the data from WHO (World Health Organisation) 285 million people are estimated to be visually impaired worldwide. 246 million have low vision and 39 million are blind. 80% of all visual impairment can be prevented or cured [1].

People with a VA of 6/18 or better can read withot any extra device than glasses or contact lenses. Below this VA additional optical devices are needed to read. According to WHO low vision is visual acuity (VA) less than 6/18 (Snellen chart) and equal to or better than 3/60 in the better eye with best correction. Beyond this the patients are –not clinically but- legally blind [2]. Not being clinically blind these patients expect to see some more with any help than without any device.

ILLUMINATION REGULATIONS AND LOW VISION PATIENTS

Most of illumination regulations are made for people who have normal vision [3]. For blind people there is no special lighting necessary. But low vision patients have still some useful visual function, which could and should be enhanced using special illumination features. On the other hand some diseases causing low vision may be worsened by some wavelengths of the seen electromagnetic radiation. The regulations may be good enough for "normal" eye health people, but also not enough of even bad for low vision patients. So tailored illumination is necessary for most of the low vision patients.

THE DISEASES WHICH CAUSE LOW VISION

There are many diseases which can cause low vision. The origin of them may be the brain or the eye. Low vision cerebral origin is mostly in cases with serious cerebral diseases. In that cases more medical help is needed than illumination.

The diseases ocular origin which cause low vision can be seen in many tissues of the eye. They may be in cornea, iris, lens, retina, optic nerve head / glaucoma and optic nerve [4], [5], [6].

Cornea: There may be infections, scars, degenerations and dystrophies of the cornea, which is normally transparent, becoming less transparent like opal glass. These changes may be loca lor general. Light coming directly to the cornea may cause dispersion, so that the vision becomes blurry [5], [6].

Iris: It is the diaphragm of the optical system of the eye. Iris dysfunctions may result in very tiny aperture or fixed wide aperture, so the regulative and adaptive mechanisms of the eye to the illumination become difficult or are disrupted [5], [6].

Retina: It is the tissue of the eye where the photoreceptors are located. In this way it is the sensor of the eye. There are many diseases of the retina and underlying uvea which can change the visual function. The deterioration in “sensors” causes sometimes transient but mostly progressive damage the photoeceptor cells causing visual fiekd defects, change in color vision, decrease in contrast sensitivity. The area and the cells which are involved in each disease shows the extent and kind of deteoriation. It may be only central or peripheral or mixed. Due to involved cells it may caıuse damage to visual field, colour vision, contrast sensitivity e.t.c. Blue portion of light may be deterious for some patients (especially age-related macular degeneration patients) [5], [6].

Optic nerve head: There are infections, inflamations and glaucoma which can affect vision. Infections and inflamations may have a permanent, transient and / or progressive clinical course, causing chancing visual disturbances. About 2 % of the society over 40 years and 10 % of the society over 60 years have glaucoma. It is a progressive disease causing non-reversible damage to optic nerve fibers ending in blindness if untreated. Glaucoma has typical progression modes in visual field defects [5], [6].

Optic nerve: It is the nerval pathway between eye and brain. Optic nerve diseases may cause dramatic changes in vision, even blindness. Some inflamations of optic nerve cause beoınd typical visual field defects also colour perception defects in blue-yellow axis [5], [6].

Color vision deficiencies: They may be congenital or aquired. Congenital ones are mostly static and have a special pattern each. Aquired ones mostly the side effect of a disease which may be transient or permanent. Mostly there is no such pattern as the congenital ones [5], [6].

General diseases like diabetes, hypertension and other angioid diseases are prone to make changes in retinal vessels like edema and bleedings causing low vision. They may be also combined. The treatment of them may be only to stop the progression causing also permanent damage to retina like with lasers.

All the knowledge must be combined for each individual patient.

All eye diseases, systemic diseases and neurological diseases may come seperately or simultaneously. In older ages it is a fact that one has many diseases at the same time. It means also that these are in different stages changing with age and time. They are mostly also progressive, it means that the visual function may change over –sometimes short- time. It means the need for certeain illumination properties may change even in a short time.

For all these diseases one may need a tailored illumination in brightness, color temperature of the light source, color composition of the light (white LEDs have a high blue peak), direction of light, reflection on surfaces etc.

IV. SOME ILLUMINATION GIDELINES FOR LOW VISION DISEASES

These guideline is given in the book Bestimmen von Sehhilfen, but the severity of the disease should be taken into consideration when using this guide. These diseases are mostly rogressive diseases, so that the patients eye, the damage to the eye and the need for lighting changes over time.

TABLE 1. ILLUMINATION NEEDS FOR EYE DISEASES (DUE METHLING) [4]

Disease	Illuminance (lux)
Normal sighted	1.000-10.000
High myopia	10.000
High myopia & myopic retinopathy	3.000
Corneal diseases	380-3.000
Cataracta senilis	1.000-3.000
Aphakia after cataracta congenital	380-10.000
Aniridia	100-10.000
Retrolental fibroplasia	3.000-10.000
AMD (age-related macula degeneration)	10.000
Juvenil macula degeneration	380-1.000
Choriotretinitis	380-10.000
Diabetic retinopathy	1.000
Glaucoma simplex	10.000
Optic nerve atrophy	2.300-10.000

There are relatively high percentages of legally blind and low vision patients in society. There are hundreds of eye (diabetic retinopathy, age related macular degeneration etc.) , internal medicine and neurology diseases which can cause low vision. Some of them may have better visual function with special lighting measures like special colour temperature, special colour filters or monochromic light and direction of the light. The usefullness of the methods in each patient depends from his diagnosis and the progress of the disease at a certain time.

CONCLUSION

The illumination suggestions for low vision and not clinically blind patients should be done by an ophthalmologist or technically precised by an illumination specialist in cooperation with an ophthalmologist.

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***Abstract*— Background: There are already about 250 artificial vision pateints all over the World.Artificial vision is achieved for clinically almost blind patients who have retinitis pigmentosa at a terminal stage. The up to date technology is achieved via a retinal implant which turns light sensation in the extracorporal ligt sensors to electrical signals, which are transmitted to the healthy neural cell layers in the retina. The number of electrodes, the extracorporal imaging technology differs between implant systems. The resulting articial vision is un,que and different from other vision modalities (biologic vision,i machine vision, computer vision, etc.). The artificial vision patients mostly live in their normal daily enviroments. The candidates for artificial vision are chosen from people who had normal vision as a child or in youth, so they have the experience of "normal" vision. Artificial vision is a greyscale black and white vision. The numbers of phosphenes (light flashes) which are seen are limited. The horizontal diameter of visual field is limited to about 20 degrees. Methods: Different visual modalities are compared with each other. The features and handicaps of artificial vision should be known, to understand this new vision modality. This knowledge helps us also, to suggest lighting properties which may make artificial vision patients can have better use of their sight. Results: The seven levels of grey of black and white vision, the mixture of silhoutte and shadow in artificial vision, the limited angle of visual field and many other clinical and technical factors of artificial vision should be evaluated in every patient so effective lighting at home or work place may be suggested. Also the direction of illumination should be considered and suggested in artificial vision patients. Conclusion: Illumination may be very important for artificail vision patients. The suggestion for illumination features made by the collaboration of the clinician and lighting specialist may be beneficial for the artifical vision patients.**

***Index Terms*-- Artificial vision, black and white vision, illumination direction. shadow, silhouette.**

BLINDNESS / LEGAL BLINDNESS

For the legal blindness limit, it is enough that each eye has a visual acuity of less than 0,1. (One does not have to be as blind as not see the light.) The percentage of the loss of visual perception is calculated through many added parameters like visual field e.t.c. [1] , [2]. Clinically, blindness is non-existance of light perception. Clinically, vision-creating studies for the blind people have reached a certain level. [1] , [2] For the present day, iintraocular retinal mplants placed in the eye and retinal stem cell studies are leading techniques [3] , [4].

RETINAL IMPLANTS FOR SIGHT OF BLIND PEOPLE

Until today retinal or cerebral vision implants in clinically blind individuals have not been as successful as they should have been or they have caused major complications. Cerebral implants are intended to bypass the visual pathways extending from the eye to the brain and directly stimulate the visual cortex of the brain. Although the first trials were successful in terms of seeing, they were abandoned because of epileptic attacks. The implants that have been tried today are implanted into the eye. These implants are intended primarily to stimulate the photoreceptors or other two-fold neuronal cells located beneath them, from the three neurons that make up the visual pathways. There are implants placed between the choroid and the retina beneath the retina as well as the type of "nailed" implant coming from vitreous to the photoreceptors. [5]
In the first experiments the sensors that detect light wee impalnted directly into the eye. Today the systems that transmit signals from the light sensors mounted on a frame of glasses to the retina through the implant are applied. [4] [5]
Scientific studies in previous years had shown that blind individuals who are clinically unable to benefit from retinal implants. After cerebral implants had been disabled with the cause of epileptic attacks, the pateints with retinitis pigmentosa (night blindness), a disease that affects only the photoreceptor layer, were the candidates for prosthetic (implant) vision as long as they still have a certain amount of visual function [4] , [5].
However, new models cerebral vision implants are being tested in healthy individuals as simulations and are about to be passed to the reproduction stage [6].

VISION WITH RETINAL IMPLANTS (PROSTHETIC VISION)

Visualization with retinal implants is a new visual modality. It is different without seeing "natural" which is formed by our eyes and our brains. For this reason it must also be learned. This new learning is called vision habilitation in the

learning phase. (It is not rehabilitation, because it is not a re-learning of an old learned one.) The creation of color vision at this stage of visualization is not targeted at the first stage [4] ,[5] , [6].
The generated signal warning is detected by the HDR CMOS sensor in some implant systems. HDR (High Dynamic Range) is a system used mostly in photography. It is used to create a different and more detailed color (brightness, saturation) than when the sensor detects the light in the image (the capacity is much lower than the eye). The HDR CMOS sensor is important in creating images with enhanced contrast and color characteristics. The generated images are delivered to the retina neurons by the intraocular implant. There are 8 levels of light feeling created in today's technology, and it is planned to increase the number of stages in the future [4].
The name "phosphen" is given to the perceived light points (in the sense of seeing the light without the light itself) in the prosthetic eye, which is formed by electrical impulses given to the retina [4, 5]. It is necessary to distinguish this definition from the definition of photopsia used in ophthalmology . A neuron that is specially adapted to each sensation in the body can perceive the other senses in the sense that it is special for, with the perception threshold being much higher. For example, a light-sensitive neuron in retina may also sense the touch / pressure sensation. As a result, some blind babies may have visual perception of a light flash or seeing stars through as eye rubbing (oculodigital syndrome) or when a punch (overpressure) hits the eye [1] , [2].

Properties of a New Vision Algorithm Created by Retinal Implants

The most important discrimination criteria for the resulting vision are edge perception and contrast. For this reason, the sensor used should be formed with enough edge detection and contrast within the light detection limits. At this stage it is considered as the next stage to pass the stage of color vision [4], [5], [6].

Sensitivity of photoreceptors in the human eye and photographic sensors

The human vision system can adopt from to 10^{-4} candelas/m2 and up to 10^{5} candelas/m2. The amount of light at which one can see easily is between 350-2,000 candelas/m2.
The camera sensors can also create images when the analog system does not have 10 stops (2^{10}) of light. With digital system, this amount has been increased to 11-12 stops, but with the use of new type of sensors, it is possible to take pictures with more stops, especially by reaching the levels where human eye needs dark adaptation.
However, even after these improvements in the cameras' sensors, they have still much less perception than the human eye (from a starting point of illumination level). ($2^{10} = 10^{3}$). [1], [2], [7].

Gabor Filter and Gabor Patch

The researches carried out in the perception of vision; that the area itself is not visible, but it is caused by the appearance of the edges of the area. For this reason, it is necessary to create an edge perception in color or black and white. In robotic vision, the edge perception consists of shapes that resemble coffee grains, with layers of different gray (or color) saturation and luminosity intervening. The perception of the difference between the different layers by the eye creates edge perception in the visual perception [8].

Basic Thinking About Illumination Proposals That Will Create Edge and Contrast

The characteristics of the sensor to which the implant system used for precise detection is connected should be known. It should be examined whether the sensor's perception is different according to eye sensation, whether the color contrast in the used sensor is transferred as a black / white contrast to the sensor, whether the dynamic ratio is high or not.
The appearance of the shadow of the object, which is important for depth perception in normal vision, can be misleading in the phosphene perception, and can also act as a factor disturbing the perception of the vision. The resulting shadows can be perceived as an object, edge or contrast of an object that is not present in individuals living with prosthetic vision.
The direction of light coming from the sensor is important. In general, it should be known that the "glare" -like effects will occur in the sensor and the sensing will deteriorate. It is important that the light coming from the back or side of the sensor be transmitted properly so that the sensor can perceive it well and transmit appropriate data for its formation.
Because the sensor senses only light intensity rather than color contrast, the color temperature of the different lamps and the light spectrum they emit should be evaluated.
The environment (s) where the patient will live or live after the implant should be made compatible with this data.

Recommendations for Edge and Contrast Illumination for Patients with Retinal Implants

In order to have a good edge perception in the sensor. it is important to "draw" the edges of the objects that the patient / individual sees.
For this reason, it is important for the light to come from back of the patient as much as possible, so that the shadows are behind the objects which are intended to be seen by the patient.

The recommendations of one of the implant manufacturer companys is that the implanted individual should be able to perceive, for example, to see a cup standing on the table. For this to happen, the light should fall on it in a way to detect the shape of the cup, but the backlight must have enough light intensity contrast to produce at least minimal edge effect. A similar amount of light intensity on the object and the background will prevent edge and contrast perception.
On the other hand, a fully lateral light set so that no shadow is created on the table, will also help to perceive the position of the object.
The light sources used, the light temperatures and spectral characteristics of the lamps and the light spectrum that the sensor perceives must be compatible or harmonized.

RESULTS

Prosthetic vision has begun to be investigated after new technologies has been introduced. The difference from natural vision will be better understood by the research being done.
However, since there is a system that operates via the sensor, there is limited data transmission in the stage of non-visual light detection, limited by the sensor's capacity and transmission.
Using prosthetic vision, edge "perception" of the sensor and contrast enhancing lighting methods - without forming nay illusion (such as shadow, silhouette) – may increase the visual quality of the individual with prosthetic vision.

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Acute Diurnal non-Image Forming Effects of Light in Middle-Aged Participants

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***Abstract*— This study investigated acute non-image forming (NIF) effects of bright vs. regular office lighting on subjective alertness and vitality, and objective vigilance and working memory performance in healthy day-active subjects aged 46-70 years old. Participants ($N = 28$; $M_{age} = 58.2$; $SD_{age} = 6.7$; 14 males) came to the lab twice at the same time of day. They were first exposed to (roughly) a half hour of 120 lx at the eyes (practice and baseline), and subsequently to one hour of 165 lx or 1700 lx at eye level. They engaged in vigilance and working memory tasks and completed questionnaires on subjective alertness, vitality, and mood. Linear Mixed Model analyses were conducted to investigate the effects of Light (illuminance level) and Light * Time of day interactions on each of the outcome variables. Results will be presented and discussed at the conference, but cannot be disclosed in this paper because of a planned publication in a peer-reviewed scientific journal. The current findings do suggest differences between middle-aged and young people in acute subjective NIF effects which can be informative for choosing and designing indoor lighting for different age groups.**

***Index Terms*--Illuminance level, Cognitive performance, Alertness, Mood, Time of day**

INTRODUCTION

A considerable number of studies have focused on acute bright light-induced non-image forming (NIF) effects on alertness and performance in healthy day-active young people [1]-[3]. In general, these studies revealed alerting effects of relatively bright compared to dim or regular light exposure during the day. However, studies have also shown null or even detrimental effects of bright compared to regular indoor light exposure on cognitive performance [3]-[5]. Interestingly, the appearance of these diurnal NIF effects in relatively old people are largely unknown. Due to changes in the eye with age, such as yellowing of the eye lens and decreased maximum and minimum pupil sizes, the amount and composition of light reaching the retina changes [6], [7]. Because of this, it is likely that acute diurnal NIF effects resulting from light exposure also differ in a middle-aged compared to a young age group. Indeed, it has already been found that nocturnal light-induced suppression of melatonin is impaired in relatively old vs. young participants[8], [9]. Therefore, it is possible that middle-aged employees may also need higher light intensities or a greater amounts of blue light exposure during the workday to reach the same acute alertness-enhancing effects that have been found in younger subjects. The current study investigated such acute diurnal NIF effects of bright vs. regular indoor office lighting on subjective indicators of alertness, vitality, and mood, and objective vigilance and working memory performance in healthy day-active subjects aged 46 to 70 years old.

METHOD

A. Design And Participants

This study employed a 2 (Light: 165 vs. 1700 lx at eye level, within) x 2 (Time of day: morning vs. afternoon, between) mixed-model design. The order of the lighting conditions was counterbalanced across participants. Dependent variables included task performance (Psychomotor Vigilance Task (PVT) and Backwards Digit-Span Task (BDST)) and subjective self-reports of alertness, vitality and mood. The study ran from March 21st to June 10th 2016.

Twenty-eight participants ($M_{age} = 58.2$; $SD_{age} = 6.7$; 14 males) completed both the 165 lx and the 1700 lx condition. All participants had normal or corrected to normal vision (contact lenses or glasses). Participants who travelled across time-zones or worked night shifts during the month preceding the study were excluded from participation.

The study was performed in a simulated workstation at the Eindhoven University of Technology. There was no daylight contribution during the experiment. Characteristics of the recessed ceiling Philips Savio luminaires can be viewed in [10]. Correlated color temperature was kept constant in each condition at 4700 K.

B. Procedure

Participants came to the laboratory on two separate days at the same time; either in the morning (9:00–10:30) or afternoon (15:45–17:15). There were at least two days between the two sessions. Before participating in the study, participants completed online questionnaires on chronotype, global sleep quality, light sensitivity, general fatigue and trait vitality (possible confounding variables). Participants were instructed to keep their sleep timing two days before each laboratory session similar to their habitual sleep schedule.

During their first visit to the laboratory, participants were guided to their workstation and received instructions to apply the physiological sensors measuring heart rate (HR) and skin conductance level (SCL) (analyses will be reported elsewhere). Subsequently, participants were informed about the experimental procedure and completed a practice round of the performance tasks and the questionnaires. After the practice phase, the experiment leader returned to the laboratory to ask whether participants had any remaining questions about the tasks and/or study procedure.

In both sessions, participants completed four repeated measurement blocks of performance tasks. During the practice and baseline phase (first measurement block), light levels were 120 lx at eye level for every participant. After baseline, illuminance levels were set from 120 lx to either 165 lx or 1700 lx at eye level. Subsequently, participants completed three 18-minute measurement blocks during the light exposure. Participants reported on their subjective sleepiness, vitality, and mood at the end of the baseline phase and at the end of the final measurement block. Last, participants completed some additional general questionnaires (see section *C.*). A visual overview of the procedure can be viewed in Fig. 1.

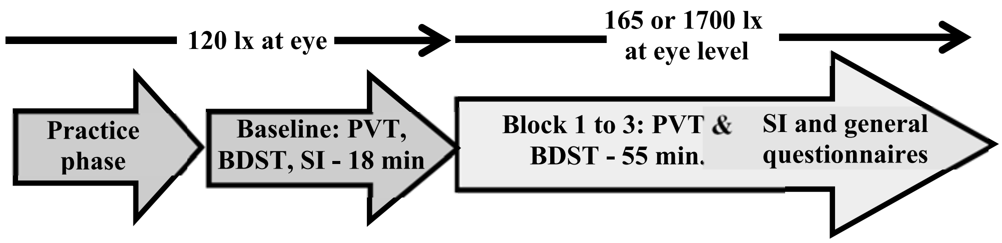

Fig. 1 Study procedure. PVT = Psychomotor Vigilance Task; BDST = Backwards Digit Span Task; SI = Subjective Indicators.

C. Measurements

Vigilance performance: a 10-min auditory PVT as developed by [11] was used to measure vigilance performance. During this task participants pushed space bar as fast as possible upon hearing a short beep (400 Hz) which were presented at random intervals ranging between 6 and 25 s. Average reaction speed during the task (1000/reaction time in ms) was computed and used as outcome measure.

Working memory performance: A Backwards Digit-Span Task (BDST) was used to measure working memory performance. During this task participants heard sequences of digits presented at a rate of 800 ms per digit with lengths differing from four to six digits for easy trials and lengths of seven and eight digits for difficult trials. They had to reproduce the full digit-sequence in reversed order by typing the correct numbers on the keyboard. Maximum response time to complete the sequence was 2 s plus 2.3 s for every digit in the sequence. The percentage of correctly reported full digit-spans per measurement block for easy and difficult trials were calculated and used as outcome measure.

Subjective sleepiness, vitality, and mood: Subjective sleepiness was examined using the Karolinska Sleepiness Scale (KSS;[12]), a 9-point scale ranging from 1 (extremely alert) to 9 (extremely sleepy - fighting sleep). Subjective vitality was assessed with four items (energetic, alert, sleepy (reversed), lacking energy (reversed) adopted from the activation-deactivation checklist [13]. Last, mood was assessed using three components, namely tension (using two items tense and calm (reversed)) from the activation-deactivation checklist [13]; a single item for positive affect (‘happy’) and a single item for negative affect (‘sad’). These items were measured using a 5-point rating scales from 1 (not at all) to 5 (very much).

Possible confounding variables: Potential confounding variables assessed before the start of the experiment included the Munich Chronotype Questionnaire [MCTQ; 14]; the Pittsburg Sleep Quality Index [15]; the Checklist Individual Strength [16]; Trait subjective vitality [17]; and a 3-item subjective light sensitivity scale adopted from [3]. After the final measurement block participants completed a short questionnaire probing sleep onset and offset, sleep quality of the preceding night, time spent outside, travelling time outside, caffeine and food consumption during the hour before the experiment and total consumption of caffeinated drinks since awakening.

RESULTS

As indicated in the abstract, we cannot disclose the current findings here as we are planning to submit the study to a peer-reviewed scientific journal. Linear Mixed Model (LMM) analyses including the levels 'Participant', 'Experimental session' and 'Block' were conducted to investigate the effects of Light and Light * Time of day on performance indicators and LMM's including the levels 'Participant' and 'Experimental session' were conducted to investigate the effects of Light and Light * Time of day on subjective indicators. The participant identifier variable was included as random intercept in the model and Block was assigned as repeated variable nested within Experimental session, nested within Participant. Interaction effects (Light * Time of day and Light * Block) were tested to examine whether possible effects of Light were more pronounced in the morning or afternoon, and/or whether they occurred immediately or more towards the end of the light exposure. Light * Block interactions were not included for subjective indicators as these were only measured once during the light exposure. In case a significant interaction effect was found, post-hoc tests were conducted to investigate differences between lighting conditions during morning vs. afternoon sessions and/or during each measurement block. All analyses were corrected for baseline values of the corresponding outcome variable as well as the some of the potential confounding variables. Because of significant differences between morning and afternoon sessions on general fatigue levels, total time spent outside on the day of the session and time spent in bed during the night before the session these variables (standardized values) were added as confounders to each of the LMM analyses.

CONCLUSION

The current study investigated acute diurnal NIF effects of illuminance level (165 lx vs. 1700 lx) on alertness and performance in middle-aged participants. During the conference, findings will be further discussed and compared to acute diurnal NIF effects found in younger subjects as investigated in [10]. Overall, the current results do suggest differences between middle-aged and young people in acute subjective NIF effects and give rise to further investigation of acute NIF effects in these age groups as results do not seem to be in line with previous studies examining acute NIF effects during night time light exposure in relatively old vs. young people [9]. Future research focussing on age-dependency of acute NIF effects can be informative for choosing and designing indoor lighting for different age groups.

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Health Effects of Biodynamic Lighting in Clinics

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***Abstract*—Using LED technology together with sensors and complex control algorithms, lighting systems can be tailored in a way to change the spectrum, intensity and spatial distribution dynamically according to the availability of daylight and different individual and application specific requirements. Hereby, it is expected to create a sustainable benefit for the users (i.e. "healthy" light). Together with clinics in Austria, several studies have been carried out to quantify beneficial light effects: with patients suffering from circadian disruptions and disorders of mood, physical activity and cognition, with mildly depressed geriatric inpatients, and with neonates and mothers in a puerperal ward. It is assumed that the inclusion of patients instead of healthy people facilitates the quantification of non-visual light effects. The latest research results of these studies and the conclusions for lighting design practice will be presented.**

***Index Terms*— biodynamic lighting, human centric lighting, non-visual light effects, LED lighting, circadian rhythms**

INTRODUCTION

In 2002, researchers described circadian entrainment effects of a small portion of human retinal ganglion cells containing the photopigment melanopsin [1], [2]. This photopigment maximally reacts to short-wavelength radiation between 460-490nm [3]. This discovery provoked worldwide basic research initiatives focusing on understanding and measuring immediate and long-term non-visual light effects on neurophysiological, endocrine, cognitive, sleep- and mood-related parameters in humans [4], [5]. Bright light effects as well as the impact of exposure to light spectra with selective spectral emission (e.g. narrow-bandwidth blue light) were investigated intensively. Additionally, the influence of exposure time, exposure duration, and previous light exposure were explored in more detail.
To date, there exists scientific evidence that chronic exposure to low daytime light levels and enhanced light levels during the night promotes disruption of circadian rhythms, which in the long run compromises human health.

Hospital patients must stay in highly controlled unfamiliar environments, every often accompanied with stressful medical treatments. Consequently, they suffer from impaired sleep and mood and disrupted circadian rhythms. Furthermore, patients are exposed to low indoor light levels during the day and regular light exposures during care procedures in the night, especially those who are critically ill.

Biodynamic lighting aims at generating beneficial effects on patients´ sleep, mood and circadian rhythms by complementing insufficient daylight exposure with bright artificial white light and by changing light intensity and colour temperature of artificial light sources during day- and night times. Bartenbach has designed biodynamic lighting system in hospitals in Austria, Denmark and Germany.

In the following, the state of science in non-visual lighting impact research done by international research groups and Bartenbach are summarized. In addition, biodynamic lighting system in hospitals, designed by Bartenbach, are described in more detail.

STATE OF SCIENCE

Currently, there is good evidence that light modulates non-visual processes during times of the day with little to no daylight (i.e. in the night, early morning and late evening). For these periods, acute effects of bright light and blue-enhanced light exposures on alertness, working memory and attention as well as on specific physiological parameters (e.g. night-time melatonin suppression and cortisol excretion in the early morning), were described extensively (e.g. [6]-[9]). Additionally, research could show that regular exposures to bright light at night disrupt human sleep and alter the

phase and amplitude of circadian rhythms. In the long run, these light effects probably compromise human health [8]-[15].
In contrast, bright light exposure in the early morning stabilizes circadian rhythms, decreases sleep inertia, enhances mood and thus promotes human health [16], [17].
To date, scientific evidence about non-visual daytime light effects is sparse. Up to now, moderate bright light effects on alertness, mood and cognitive performance were described [18]-[20]. However, reported outcomes of studies done in nursing homes and hospitals [21]-[24] are promising. Typically, these studies utilized ceiling-mounted diffuse light panels in specific room zones (e.g. lounge or bedroom) during the day with high light intensities (>1000 lux at eye level) for several hours to generate non-visual light effects.

OWN RESEARCH IN CLINICS

Bartenbach investigates non-visual light effects in clinics for more than 10 years (e.g. [25]-[28]).

Beneficial effects of biodynamic lighting were first investigated in two clinical trials in a puerperal ward in Austria (Department of Obstetrics and Gynaecology, Medical University Innsbruck). In these studies, increased maternal night-time melatonin levels and improved mood scores could be observed. Additionally, neonatal activity levels increased significantly in the morning and the weakly established neonatal circadian rest-activity cycle showed a phase advance of 105 minutes when being exposed to biodynamic light for 3 to 5 days [29].

In an on-going research project (short title: “psylicht”), a biodynamic lighting design was implemented in two wards of a regional psychiatric hospital in Austria (Department of Psychiatry and Psychotherapy A, Hall). In these wards, demented as well as depressed inpatients are treated.
Over a period of 24 hours, light intensities and light colours change automatically in all areas (i.e. bedrooms, bathrooms, corridors, staff´s rooms and lounge areas). These changes are coupled to prevailing rhythms of living (e.g. sleeping and eating times) and medical treatments. Basically, patients are exposed to high light levels (up to 1000 lx) of neutral-white light (4000 K) during the day. In the evening and night, bedrooms and bathrooms of the patients are illuminated with reduced light intensities (<50 lx) and warm-white light (2200 K).
Additionally, room lighting can be dimmed at any time and switching on pre-defined light scenes (e.g. for watching TV, having meals) is possible as well.
Furthermore, light intensities and colour temperatures in staff´s rooms are varied during the day analogue to the light scenarios in the patient´s areas to induce also beneficial effects of light on shift-working nurses and doctors.

Figure 1. Daytime and night-time room illumination in a lounge area

In this on-going clinical investigation, over the course of two years, potential light effects are quantified by means of actimetry and logging of light switching manoeuvres. Additionally, data from electronic health records (e.g. fixations, falls, medical treatment) will be analysed.

A preliminary data analysis on falls and fixations of demented inpatients was finished recently. For this analysis, data on falls and fixations occurring before and after the implementation of the new biodynamic light concept were compared. Although we could not observe a significant reduction in falls within our sample of 695 inpatients, injuries caused by falls were less severe under dynamic lighting. Additionally, none of the documented falls was caused by slippery under biodynamic lighting. Furthermore, fixation rates decreased as well.

A second preliminary data analysis measuring effects on diurnal activity levels of a smaller group of demented patients living either in bedrooms with dynamic light (n=20) or standard light (n=20) was run as well. For inpatients living in bedrooms with biodynamic light, we could observe reduced physical activity during the night, an earlier increase in morning activity, increased activity during resting periods around noon and decreased activity levels earlier in the evening.

An update of these data analyses will be given at the conference.

IMPLEMENTED BIODYNAMIC LIGHTING DESIGNS IN CLINICS

Bartenbach´s biodynamic lighting designs in hospitals are based on the following four components:

- **Utilize daylight as much as possible**: provide high daylight levels with excellent spectral quality to the patients and staff during the day; provide, if possible, a view to the outside environment; avoid visual impairment (glare) and high thermal loads
- **Complement insufficient daylight with high-quality artificial light**: provide daytime-specific variable light intensities and light colours;
- **Use sensor technologies**: provide artificial light when daylight light levels are low and persons are present
- **Install easy-to-use light-switches and -interfaces**: provide the option, to individually control ambient light levels

In September 2015, a biodynamic lighting design was implemented in the psychiatric clinic in Slagelse, Denmark. A new lighting system was installed in the whole building with an area of 44,000 m^2 and 190 bed rooms. The lighting design in Slagelse (Figures 3-6) was awarded with the Danish Lighting Award in 2016 and with the MIPIM Award as "Best Healthcare Development" in 2017.

Figure 2 and 3.: Lighting at night with reduced short wavelength radiation

Figure 4 and 5: Daylight design in indoor areas
(Photographs: Karlsson architect / VLA, Photographer: Jens Lindhe)

In 2017, a similar biodynamic lighting design will be finished in clinic in Germany (Helmut G. Walther Clinic, Lichtenfels) with a total of 254 bed rooms (Figure 7).

Figure 6. Varying light colours during the day in a patient's bedroom in Lichtenfels (Germany)

Challenges In Designing Biodynamic Lighting – Lessons Learned

Biodynamic lighting designs are based on an intensive collaboration of multi-disciplinary working teams. Defining requirements for application-specific lighting control strategies, the utilization of daylight, merging day- and artificial lighting designs in an integrative control system which is embedded in a building automation system are a few hot topics to be solved.

Furthermore, technologies for biodynamic lighting designs currently suffer from limitations in inter-operability, are very expensive and commissioning processes are complex and need intensive teamwork of complementing industries. Last, but not least, evidence for beneficial effects of biodynamic lighting designs is weak today. Therefore, in 2015, the research initiative "Light B Health" was started by researchers at Bartenbach to critically discuss existing knowledge on non-visual light effects and to intensify research activities. Furthermore, this initiative should foster the establishment of an independent platform for researchers, companies and users to exchange experiences and knowledge about mechanisms and effects of current and future biodynamic lighting designs. Finally, guidelines and best practice solutions for these lighting designs will be specified.

CONCLUSIONS

Biodynamic lighting designs have gathered a lot of interest in research communities and the lighting industry the last years. Bartenbach has already implemented biodynamic lighting designs in hospitals as well as in offices and other application areas and conducted studies to quantify potential beneficial light effects.

Biodynamic lighting designs need intensive collaboration between architects, lighting designers and the lighting industry to integrate day- and artificial light components, sensor technologies and user-friendly interfaces.

Since scientific evidence for beneficial biodynamic lighting effects is weak now, further high-quality research is needed. Therefore, Bartenbach has started the research initiative "Light B Health", a platform for all interested persons, to build up knowledge on biodynamic lighting effects.

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Influence of Light Condition on Medication Care in a Hospital

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***Abstract*—Medication errors in hospitals can lead to life threatening situations. In the process of medication care, many errors can occur. Good lighting might prevent some of these errors. The study presented in this paper investigates whether the light condition can contribute to improve the visual performance in hospitals. The specific focus is on the area where medication is being sorted and prepared for patients at the ward. Light measurements, a survey among nurses and a visual acuity test demonstrates that the amount of light has an influence on the visual performance but that nurses do not seem to be aware of this.**

***Index Terms*—hospital errors, Patient safety, medication-rooms, light conditions, nurses**

Introduction

Medication dispensing follows a long route before it reaches the patient. In this process human mistakes are easily made. This can result in life threatening situations. According to Jones [1] patients are at risk due medication errors. These errors are caused by difficult-to-read medication labels, the increasing age of the nursing population and the poorly lit work environments. Appropriate lighting enhances the visual performance. Mistakes in medication could for example originate from insufficient lighting, disadvantageous spectral distribution or distracting lighting. Since the main focus in a hospital lies with the patients, keeping dim lighting during night check-ups enhances the patients sleep but at the same time pose challenging light conditions for nurses to perform their visual tasks. These tasks include, but are not limited to, reading the dose, telling apart different pills and checking whether the infusion is still working properly. The impact of the light conditions becomes even larger for average aged and older nurses whose vision is deteriorated by presbyopia or eye fatigue. Therefore it is crucial to provide a lighting situation that enhances the visual performance of nurses managing medication. Graves and colleagues [2] performed a semi-structured interview among 16 registered nurses in a hospital. They inquired about their attitude towards the influence of light on their work performance. They concluded that most nurses are unaware of how light can enhance the patient safety and on how they can influence their own light condition. Although several studies stress the importance of good lighting for preventing medication errors, actually only one research paper was found which assessed the influence of light on a medication related task, in this case capillary refills [3]. This study among 309 care professionals found that a statistically significant amount of less errors occurred between capillary refill assessments in (day) light conditions than in dim light conditions. The number of undetected refills during the light conditions was 3.9% while under dim conditions it was 66.7%. Since the two different light conditions occurred during daytime and nighttime respectively, it remains unclear whether these large differences can be solely attributed to the visual performance or whether stress or reduced alertness during the evening/night might have an impact as well. In a study on the influence of daylight and darkness on medication errors by nurses in Alaska, the researchers concluded that darkness was one of the four predictors of the risk of medication error [4]. More than half of all medication errors occurred during the first 3 months of the year. Interesting is that there was a 2-months delay between the level of darkness and the rate of errors. This would indicate that medical errors are not only related to the visual performance.

The research presented in this paper focusses on the preparation and dispensing of medication. The main research questions is to assess the attitude of nurses towards the lighting conditions in the hospital they work and relate that to the actual light condition. The second question is to what extent impacts the current light level the nurses' visual performances.

Method

In two different hospitals (henceforth called H1 and H2) in the Netherlands the current light conditions in the medication rooms of different wards were measured. A survey among hospital nurses was conducted, enquiring about their perception of the light conditions with a special focus on their activities related to the medication process. A visual acuity (VA) test was carried out on two positions in the medication room where the preparation and sorting of medication takes place. The two positions represent a darker and a brighter light condition respectively.

The lighting design and room lay-out of the medication-rooms in H1 were all identical, except from the Intensive Care unit. In H2 not every medication room and lighting design was similar. For this reason, the study was carried out in wards with a different lay-out and lighting design, on three different floors of the same building volume (these will be referred to as H2-A, H2-B, H2-C). The activities related to the medication process were similar in both hospitals. All measured medication rooms had no window connected to daylight, except the IC-unit in H1.

A. Test Locations

Hospital H1 was completed in 2013; its design complies with the healing environments principle. The key concept behind healing environments is that the interaction between patient, care professionals and its environment positively contributes to the healing process and/or wellbeing [5]. One example of applying this principle is that the medication rooms on all different wards are at the same in position, and have the same size and lay-out. The only exception to this rule is the medication room of the Intensive care (IC) -unit. The other hospital (H2) was completed in 1973. Since they were in the middle of a large renewal project, some of the wards had recently been renovated. The measurements took place in three different wards; two non-renovated (H2, A and H2, C) and one renovated (H2, B). **Napaka! Vira sklicevanja ni bilo mogoče najti.** shows the floor plan and layout of the medication-room of the different wards.

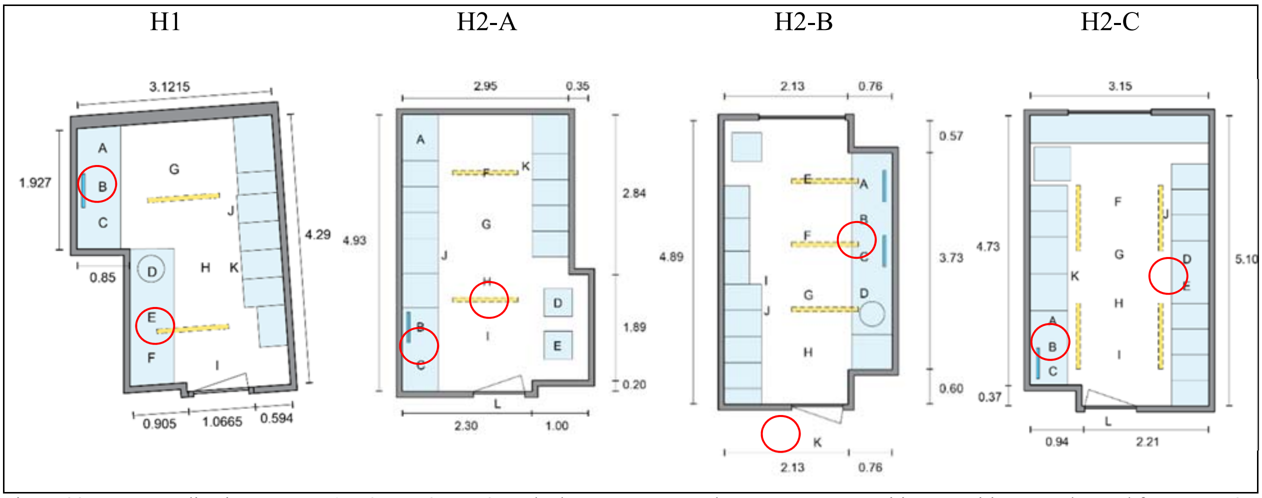

Figure 23 Layout medication rooms H1, H2-A, H2-B, H2-C, the letters represents the measurement positions. Positions J and K and for room H2-B, I represents a vertical measurement position at eye-height. The yellow lines indicate the position of the luminaires in the ceiling. The VA-tests were performed at the positions indicated with the red circle. In H2-B no dim position was identified and therefore this measurement was performed at the nurses' station.

B. Participants

With the approval of the head of the ward, nurses on duty were asked to voluntary participate in the study which took ~45 minutes of their time.

i. Survey

In total 29 participants (26 Female, Mean age 31.7 a, SD 10.8 a), worked in different hospitals (31.3% in H1, 68.7% in H2). The mean work experience was 10.7 a (SD 10.3 a).

ii. Visual acuity test

The total number of people who participated in the VA-tests was 32. 28 female and four male. Mean age was 33.3 a, SD 10.6 a), worked in different hospitals (37.5% in H1, 62.5% in H2). The mean work experience was 10.9 years (SD 10.2 a). Of the 17 participants who wore glasses or contact lenses, 8 of them were corrected for farsightedness or both farsightedness and myopia.

C. Survey

A survey was conducted to establish the attitude towards the lighting. This survey was executed as a structured interview. This approach allowed to confirm that the questions, especially the ones about the lighting characteristics, were interpreted correctly.

D. *Visual Acuity Test*

The VA was tested with a two-sided 'Logarithmic visual acuity chart 2000 "new etdrs" ' by Precision Vision®. One randomly chosen side was used for the darker condition and the other for brighter light condition (see Figure **23** for the test positions). The reading distance was kept 40 cm, measuring from eye to chart. The lighting on the chart, per individual test was measured since the lighting was not identical in all medication rooms nor at all measured positions.

In H1 the average illuminance on the two task areas was 240 lx and 610 lx. In H2, the illuminances in H2-A were 190 lx and 280 lx, in H2-B were 252 lx and 808 lx and in H2-C, 310 lx and 560 lx. The difference between both lighting conditions are presented in Figure **24**.

The results are presented in LogMAR (**Log**arithm of the **M**inimum **A**ngle of **R**esolution). An observer who can resolve details as small as 1 minute of visual angle, scores LogMAR 0 (the base-10 logarithm of 1 is 0). A value of 0 indicates normal vision, a negative value indicates that smaller details are readable (better vision) while a positive value indicates worse vision. In this study, the value of the smallest correctly read sentence was used. The VA of the nurses was tested with the vision correction they used at that time.

E. *Light Measurements*

Light measurements were performed in the different medication rooms. The following aspects were measured:

1. The illuminance (E) and the correlated colour temperature (T_{cp}) were measured on the relevant task areas (see Figure **23**): Horizontally at the desk(s), on the floor as well as horizontally and vertically close by the storage closets for medication. For the VA-test, the E and the T_{cp} were measured on the chart on the positions where testing took place. The illuminance spectrometer Konica Minolta CL-500A was used to take the measurements.
2. The luminance distribution inside the rooms was determined by using a Canon EOS50D digital single-lens reflex camera with a Sigma 4.5 mm fisheye lens and the software BPS-Radiance-image (2014)

F. *Analysis*

Data statistics were carried out in Microsoft Excel (2013). A one tailed paired t-test was used to identify whether a significant difference in VA was found between the results under the darker and the brighter condition. A p-value < 0.01 was considered significant. IBM SPSS statistics 23 was used to analyse a correlation between the VA and illuminance and VA and T_{cp}. A Pearson one-tail test was therefore carried out.

RESULTS

A. *Light Conditions In Relation To The Attitude Towards Lighting*

The nurses expressed no explicit complaints on the amount of light in the medication room. 81% considered the lighting good. Although the measurements revealed a rather large difference in horizontal illuminance at desk level between the different medication rooms, this was not experienced as such by the nurses (see Table 1). The correlated colour temperature was considered cold by 38 % of the participants while 6% found it warm. The remaining 56% were neutral. The measured T_{cp}, in all medication rooms was < 3100 K. A T_{cp} of 3000 K is considered warm white while a T_{cp} of 4000 K is considered cool white. When asked about the amount of daylight, 40% wanted to have more daylight, one person wanted less daylight, while the rest considered the amount of daylight in the ward good. Due to the lay-out of the wards, the patient rooms are connected to two sides of a hallway with the nurses station centred in the hallway with at the end a window. The patient rooms all have windows.

TABLE 1 AVERAGE HORIZONTAL ILLUMINANCE IN THE MEDICATION ROOMS

	Average horizontal illuminance [lx]		**Perceived light condition by nurses (number of participants)**
	Desk	***Floor***	
Recommended[6]	500	100	
H1	397	325	Good (8) Dim (1)
H2-A	195	315	Dim (2) Good (3) Bright (1)
H2-B	839	483	Dim (1) Good (6) Bright (1)
H2-C	521	773	Good (6)

B. Visual Acuity

Each participant was asked to participate in a VA-test on a relatively dark and a bright position in the medication room. Since not all medication rooms were identical the light conditions and the difference between both light conditions are not identical either. Figure 24 shows the VA difference per participant indicating the difference in illuminance between the dark and light condition. Figure 25 displays the difference between the VA per participant set-out against the age of the participants. For both graphs, a negative value indicates better vision under the higher illuminance while a positive indicates the opposite. A value of 0 indicates no difference.

Interpreting the graphs reveals, that most participants (15 out of the 32) had a score under zero, indicating that the VA was better under the highest illuminance. For 14 participants the score remained the same and 3 participants scored better under the dark conditions. A paired samples t-test allowed to compare the visual acuity results under the darker and the brighter condition, within subjects. There was a significant difference between VA under the darker condition (M=0.04, SD=0.01) and the brighter (M=-0.01, SD=0.01) condition; (t(31)=3.30, p=0.001). When performing a Pearson test, no significant correlation was found between VA and illuminance level, and VA and T_{cp}.

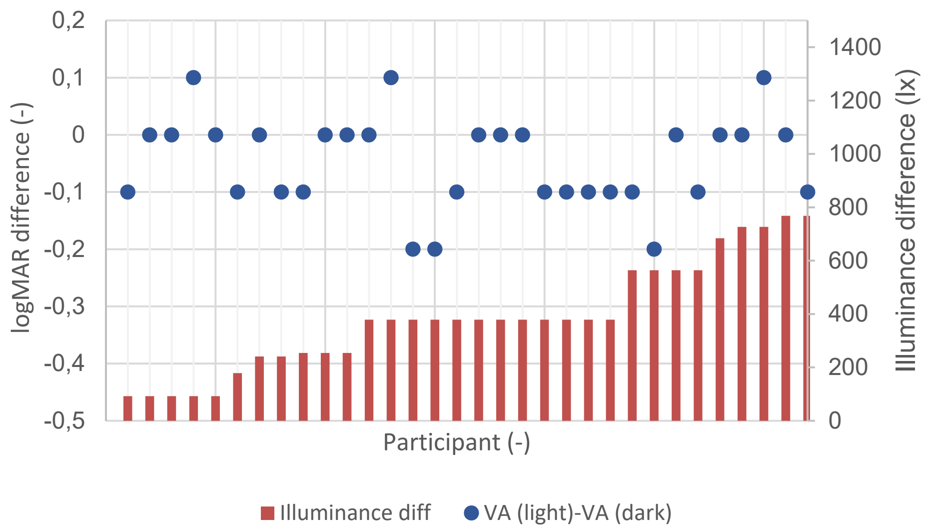

Figure 24 Difference in VA per participant and illuminance. The bars indicate the difference in illuminance between the darker and the lighter condition.

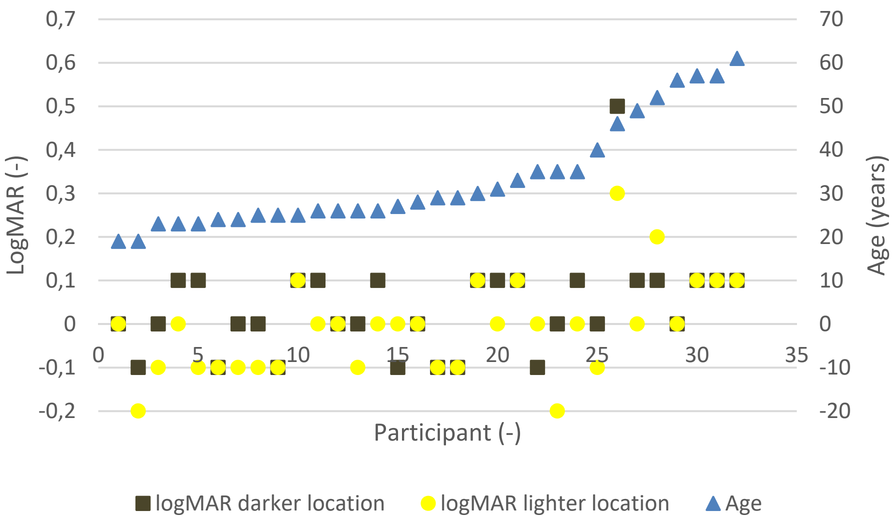

Figure 25 VA light and dark condition ordered per age of participant.

Discussion and Conclusion

The results indicate that although large differences in light conditions have been observed in different medication rooms, the majority of the nurses perceive the lighting as good. This also holds true when the illuminances are lower than the recommended levels according to the standard. That this might be a case of unawareness can be concluded from the results of the VA-test. For nearly half of all participants, the visual performance was significantly better on a relatively bright position in comparison to a relatively dark position in the medication room.

When considering the process of mediation care, dealing with sometimes very small letter sizes, appropriate lighting might therefore contribute to lower the error rate. In a follow-up test, the light parameters illuminance and correlated colour temperature will be varied in order to find the most suitable light condition for reading different prints on different types of medication packages.

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Determination of Veiling Luminance for Peripheral Visual Objects

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***Abstract*— An experimental set-up that measures location based retinal stray light levels in humans is described. The experiment uses the psychophysical Direct Compensation Method to determine the equivalent veiling luminance on the retinal periphery. The experimental results will be used to adapt the CIE disability glare equations for spatial dependency.**

***Index Terms*— disability glare, flicker, peripheral retina, psychophysics, stray light**

Introduction

A. Glare

Commonly, people experience glare when looking at oncoming headlights. They sense an actual discomfort or a visual impairment, caused by an inappropriate distribution of light sources or excessive contrast in the field of view. The reduction of visual quality makes glare rating an important aspect of traffic safety assessment. The European Standard (EN 13201-2) defines glare index classes and criterions for the restriction of glare [1].

Generally, glare can be divided into two main types, discomfort glare and disability glare, which differ in their effect on human perception. Discomfort glare is a description of subjective glare. Complaints may be expressed as discomfort, annoyance, fatigue, and pain [2]. Disability glare, which is also known as physiological glare, is glare that impairs vision. It is caused by retinal stray light due to intraocular scattering of the incident light [3]. Stray light veil causes loss of retinal image contrast. The functional effect of retinal stray light on vision makes it an important criterion for the road safety assessment, since the effects of glare sources in the field of view can be quantified by disability glare.

The impairment by glare sources arises from optical scattering of the incident light at the human eye's imperfect optical media, resulting in a broad distribution of stray light on the retina (Fig. 1). The intensity of the stray light veil is used as a measure of glare and is expressed as the equivalent veiling luminance. This is the luminance of a uniform patch of light that changes the contrast threshold by the same amount as the glare source [4]. The equivalent veiling luminance can be quantified using psychophysical measuring concepts.

B. CIE General Disability Glare Equation

We can calculate the stray light distribution by determining the equivalent veiling luminance and measuring the illuminance at the examined eye in the plane perpendicular to the viewing direction. This calculation is based on the General Disability Glare Equation [5], a mathematical model for retinal stray light developed by the CIE. It was created from the experimental data of several stray light studies [3], [6], [7].

Several anatomical and physiological factors can be included in this calculation. These influencing factors are mainly based on properties of the intraocular stray light sources (cornea, lens, translucency of the eye wall, reflection on the retina, see Fig. 2) [3]. The most important factor is the angular distance between the glare source and the visual target. The closer the target is to the glaring light source, the stronger the stray light veil, which is placed over the retinal image of the target. In addition, the translucence of the eye is dependent on the eccentricity of the glare source.The aging of the ocular lens leads to its opacification and pathologically to the formation of a cataract. Thus, incident light is more scattered with age. The pigmentations of the fundus and the eye wall also influence the intraocular light scattering.

C. Issue

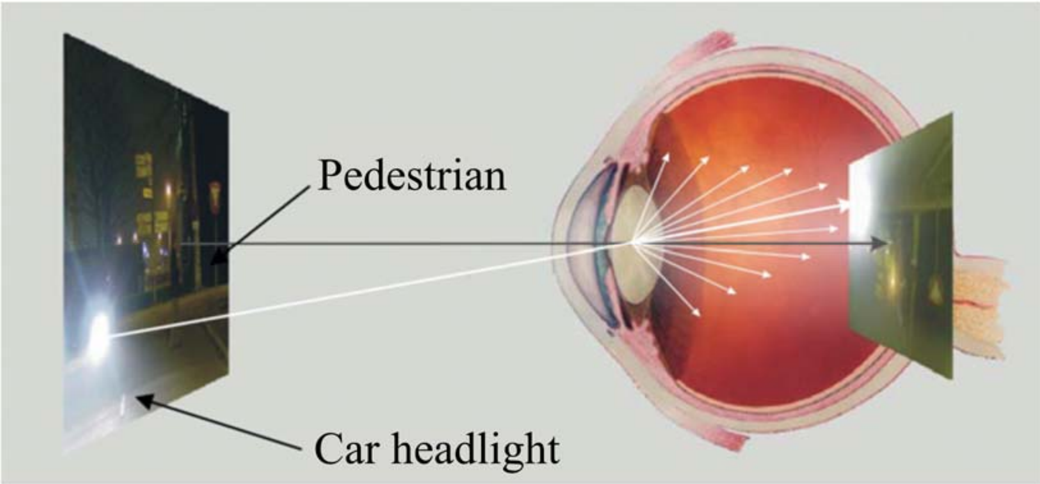

Figure 26. Illustration of retinal stray light with the image of the outside world (left) and its projection on the retina (right). [2]

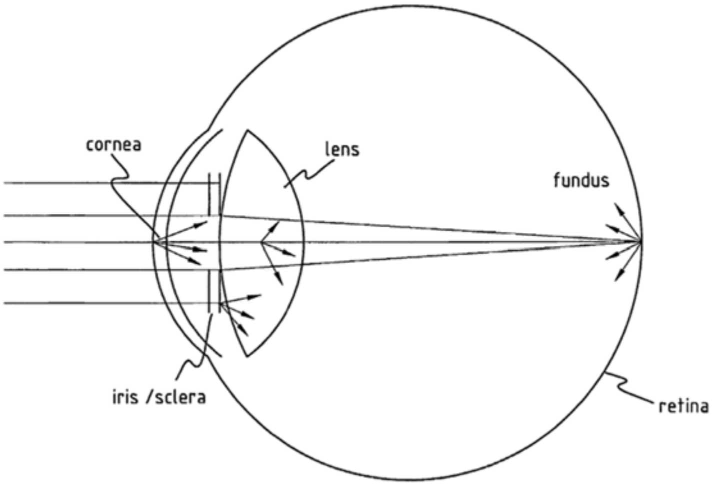

Figure 27. Ocular stray light sources [12]

The CIE General Disability Glare Equation is based only on foveal investigation. Whether and how the distribution of the scattered light for peripheral retinal locations changes is unknown. The first study on extrafoveal stray light originate from Stiles and Crawford in 1937 [8]. They have shown that the common mathematical model describes light scattering on the retina insufficiently, and therefore does not provide sufficient prediction for peripheral visual tasks [9]-[11]. Uchida and Ohno [13] used a visual target, which should be detected in the peripheral visual field, in their investigations on the adaptation field. The perception of the subject was disturbed by a glare source with varying intensities and glare angles. Aim was the measurement of the contrast detection threshold for the estimation of the adaptation state of the observer. The setup was realized by a LCD screen, which represents the target and the background, and an LED glare source. Their results support Stiles and Crawford's statements on the changing distribution of stray light at the retina [8].

However, in most road traffic hazards, the important visual objects, e.g. a pedestrian in dark clothes, located in the peripheral field of vision (on the sidewalk). They are not situated in the line of sight (on the street) and therefore outside central vision.

Nevertheless, only mathematical models of foveal vision are used for safety assessments [1]. To verify their validity, investigations like the approved stray light studies must be carried out with a method adapted to peripheral measurement targets.

RESEARCH HYPOTHESIS

- The equivalent veiling luminance differs for foveal and extrafoveal vision in case of constant angular distance between glare source and target.

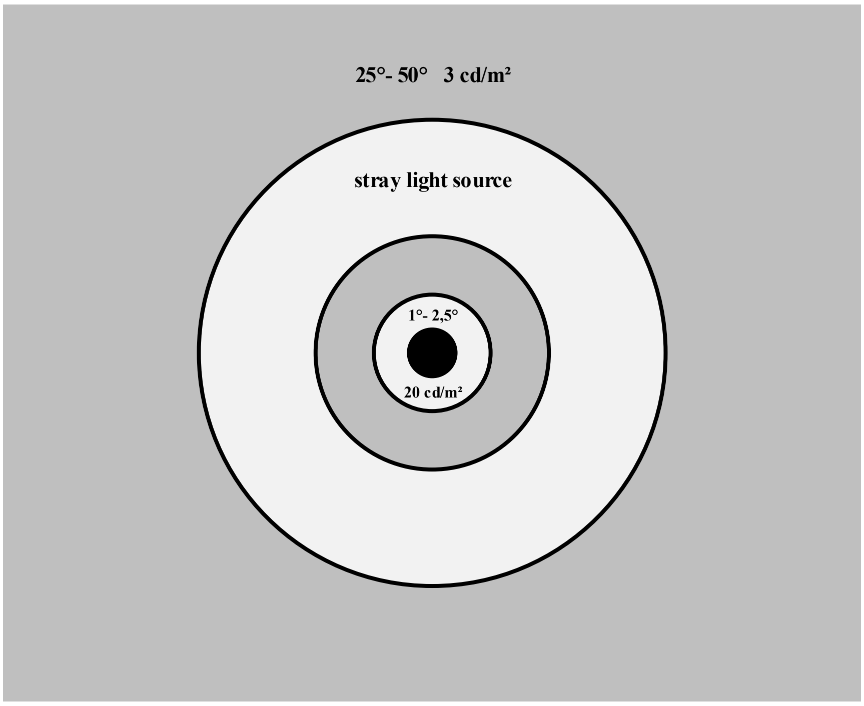

Figure 28. Spatial configuration of the screen from the Direct Compensation Method by van den Berg and Spekreijse (adapted from [14]). In the centre is the dark test spot, which presents an adjustable, antiphase flickering compensation light. It is surrounded by a bright separation ring and a low intensity annulus. The glare source ring flickers with a frequency of 8 Hz.

- The equivalent veiling luminance of an extrafoveal glare source is distributed asymmetrically over the retina.
- With an adaptation of the Direct Compensation Method, introduced by van den Berg and Spekreijse [14], the equivalent veiling luminance of a glare source is determinable for peripheral targets.
-

METHOD

A. Direct Compensation Method

A Dutch research group under the direction of van den Berg published the Direct Compensation Method, a stray light measuring technique, in 1986 and applied it on many studies to investigate retinal stray light. This method estimates the foveal amount of scatter directly for different glare source eccentricities [14].

The subject monocularly observes a screen with a circular arrangement of fields (Fig. 3). In the centre is the target, a dark test spot, with a 2 degrees' diameter. In the surrounding area is the glare source, that can be presented at four effective distances from the centre (effective radii range from 3.75 to 30 degrees). The glare source flickers with 8 Hz, a frequency that is in the range of maximum flicker sensitivity in human vision. [6, 7]

The incident glare light causes a flicker perception in the dark test spot due to intraocular light scattering. The subject's task is to minimize or clear this flicker perception by adjusting the luminance of the test spot with a dial. The point of flicker disappearance is named compensation point, because the flickering stray light is "compensated" by the test spot luminance. This luminance corresponds directly to the portion of scattered light spread over the foveal retina. The test spot is surrounded by a time-invariant and bright intermediate ring. This suppresses the flicker perception in the area adjacent to the test spot, to ease the performance of the task.

B. Requirements for The Experimental Setup

Due to the method and aims of measurement, certain demands should be stated on the setup's design. First, a flickering glare source is required. The flicker frequency of the glare source should be set to be good perceivable. The test spot flicker must be precisely in antiphase to the glare source flicker, so the flicker perception can be cancelled. In addition, the luminance amplitude of the test spot must be adjustable by the subject.

In the original Direct Compensation Method, the test spot is centred on the screen and should be fixed by the subject. By this arrangement, the equivalent veiling luminance can be determined only for the fovea. In the case of a modification for extrafoveal targets, both the source and the test spot must be positioned in the entire visual field to perform

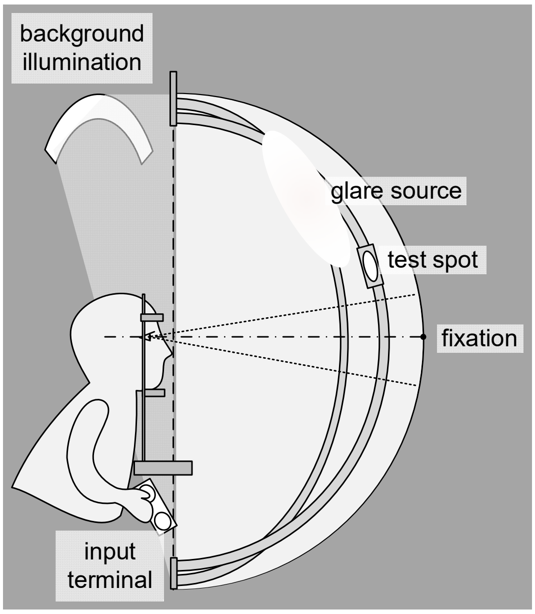

Figure 4. View of the experimental setup. The fixed subject is placed in front of an illuminated half sphere, presenting three visual stimuli: a flickering glare source, an antiphase flickering test spot and a stable fixation point.

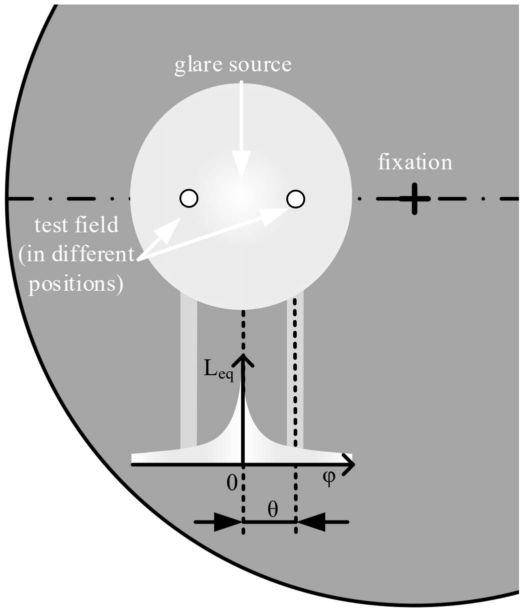

Figure 5. Detail of the setup showing a possible glare source-test spot constellation during a trial. The point-shaped glare source stays fixed with distance φ to the fixation point in the center of the hemisphere. The test spot is positioned on a circle around the glare source with fixed distance θ. The graph shows the profile of equivalent veiling luminance regarding

Figure 6. Fixation object proposed by THALER et al. [15]

investigations in the retinal periphery. In addition, a central fixation point must be installed for the subject. Observation of the fixation should be controlled by an eye-tracking camera for error correction.

C. Stimulus Presentation

The planned experiments will use an adapted setup of the Direct Compensation Method. The subjects are placed in the centre of a white hemisphere with a diameter of 1.5 meter (Fig. 4). Their head is fixed by a chin rest. The subjects are looking at a fixation point. The hemisphere represents the field of view with a constant, uniform adaptation background luminance, so that the subject will adapt to a defined level. The lighting system of the background is mounted above the subject.

Two LED light sources will be presented. Both, test spot and glare source, are mechanically attached to the hemisphere and can be set at any spherical position. They flicker in antiphase and are aligned to the subject. The test spot luminance amplitude can be adjusted by the subject via a control dial. The luminance of the glare source is controlled by the investigator.

D. Fixation and Eye Tracking

The method of measurement necessitates a stable retinal image of the glare source and the test spot and a minimization of fixational eye movements. For that purpose, an eye-catching fixation point should be presented to gain high accuracy. Also, the subject is encouraged to maintain the visual gaze at the centre of the hemisphere. Thaler et al. propose a target shape looking like a combination of a bull’s eye and a cross hair for experiments that require a stable fixation (Fig. 6, [15]). For monitoring the fixation stability, the subject’s eye movements are controlled by eye tracking.

DATA ACQUISITION

The experiments present different constellations of glare source and test spot positions in the visual field (Fig. 5). During trials the glare source stay fixed and the test spot will be positioned in an orbit around the glare source to “scan” the location-dependent distribution of the retinal stray light veil. The combination of the scanned data allows reconstructing the retinal stray light distribution.

We use a psychophysical method to determine the location-dependent equivalent veiling luminance. The subject’s task is to find the compensation point, the point of vanishing flicker perception at the test spot. It is an absolute threshold. Therefore, threshold matching methods are most suitable for data acquisition. To find the threshold we use the ascending and descending method of limits. In the ascending method, the test spot luminance amplitude is increased from zero to flicker disappearance. In contrast, in the descending method the too high test spot luminance amplitude is reduced to the point of flicker disappearance. Six compensation points are determined in each of the three ascending and descending runs. The thresholds are averaged to determine the equivalent veiling luminance of the experiment.

PLANNING THE TRIALS

After the completion and calibration of the setup a pilot study for verification of the measuring method takes place. After positive results a cross-sectional study is accomplished with glare source-test spot constellations and different subject properties (e.g. age, eye colour, cataract). The data analysis leads to adjustment supplement of the CIE General Disability Glare Equation for local dependency and, therefore, to a mathematical modelling of disability glare in peripheral vision.

ACKNOWLEDGEMENT

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Discomfort Glare Caused by Several LED Sources

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***Abstract*—Most analytical models of discomfort glare are only valid when one source is present in the visual field. Some of these models were generalized to predict discomfort glare when several sources are simultaneously switched on. Nevertheless, they do not take into account the distances between light sources when they are simultaneously switched on. The present work studies the effect of the distance between two sources on the discomfort glare in central and peripheral vision. The results demonstrate that the relative position of the sources to each other does not impact the discomfort glare.**

***Index Terms*—Automotive lighting, Borderline between Comfort and Discomfort (BCD), Discomfort Glare, Psychophysics, Road lighting.**

INTRODUCTION

In the current context of energy transition, the LED technology is nowadays employed in most lighting applications [1]. Nevertheless, it is necessary to control the drawbacks of LEDs: these sources are very small (compared to previous one), which lead to high levels of luminance and to more discomfort glare [2]–[4]. In exterior lighting at night, people are often surrounded by light sources (street lighting, automotive lighting), which is likely to cause discomfort glare. Discomfort glare is an important issue, notably on the road, where people do not have to be disturbed nor distracted.

Many models were proposed in previous work in order to predict the mean level of discomfort glare depending on the photometric and geometric characteristics of the visual scene. Most of them estimates the mean level of discomfort glare generated by only one light source, described with its mean luminance, its solid angle seen from the observer's eyes and its position in a uniform scene, which was characterized by the background luminance [2]-[7]. Then, in order to deal with more than one light source in the visual field, some authors tried to generalize their one-source model [5][6][8]. They all tested the additive hypothesis: the individual contribution of each source to the discomfort glare were added [6][8]. Thus, these models do not consider that potential interactions of light sources simultaneously switched on, and notably the distance between sources, could have an effect on discomfort glare. Bennett [9] showed that the higher the number of light sources, the higher the discomfort glare. In a road lighting installation, he found that the closest light source brings the most important contribution on the discomfort glare. Similarly, de Boer and Schreuder [10] found a small decrease of discomfort glare (+0.5 in the de Boer scale) when the number of visible light sources was about halved in a road lighting installation.

In this context, the present work studies the effect of the distance between sources on discomfort glare. Furthermore, perception of details is not the same in central vision and peripheral vision. Thus, if there is an effect of the distance between sources on discomfort glare, it could be different depending on the vision. We focus here on the effect of the distance between two sources on discomfort glare. More precisely, the aim of the present study is to test two assumptions:

- The distance between two sources has an effect on discomfort glare;
- This effect is different in central and peripheral vision.

The remainder of the paper is organized as follows. The experimental protocol is detailed on Section 2. Results are presented in Section 3. Section 4 will conclude with a general discussion about these results and the limit and perspectives of this work.

MATERIAL ET METHOD

A. Panel

Thirty-six participants took part in the experiment (23 men and 13 women). They were aged between 21 and 58 years old (M=34.5, SD=10.4). A preliminary test was conducted on visual acuity with an ErgoVision (Essilor) for each participant. All participants had an acuity above 5/10.

B. Equipment

The experiment was carried out in a dark room. A digital RGB LEDs strip was stuck on a white screen horizontally (Fig. 1). All the LEDs are identical : they have a diameter of 4 mm and they are all separated with a distance of 16 mm (center to center). Participants sat at a distance of 1.6 m from the screen in order to see the LEDs with a solid angle about 5.0×10^{-6} sr (Fig. 2). During all the experiment, they were asked to look at a target in front of them, which was stuck on the middle of the LEDs strip (Fig.1). The chin of each participant was fixed by a head rest in order to ensure a reproducible line of sight (Fig. 2). A halogen lamp was located behind the participants at a distance of 1.55 m in order to create a relatively uniform background luminance of 1 cd/m², which is the recommended value for street lighting from European standard EN-13201 [11].

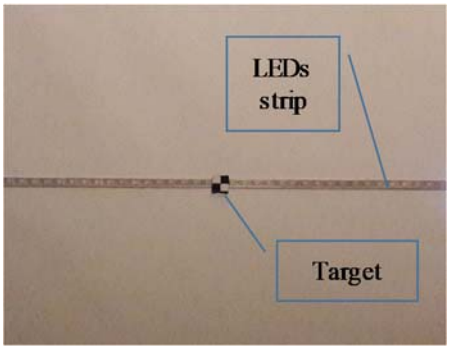

Fig. 1. Photograph of the experimental set-up (front view).

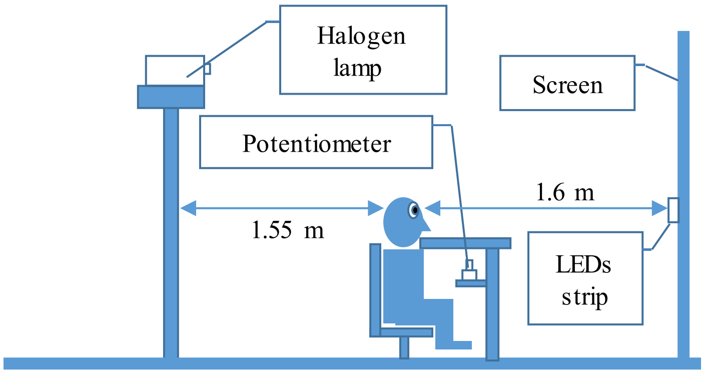

Fig. 2. Framework of the experimental set-up (side view).

C. Experimental Design

The main idea of this experiment was to collect photometric characteristics from stimuli that generate a constant level of discomfort glare. The criterion of *Borderline between Comfort and Discomfort* (*BCD*) was selected because it was broadly used in the literature [5][9][12][13] and defines a discomfort level which can be easily understood by the participants.

To test our assumptions, different stimuli with two light sources simultaneously switched on with different inter-distances were presented to the participants (Fig. 3 (c)). For each type of vision (central and peripheral), a two-source stimulus was composed of:

- A stationary source: the illuminance E_{ST} and the eccentricity of which were fixed. It was always the source the closest to the target ;
- A variable source: the illuminance E_V* of which was collected.

E_V* was set by the participant in such a way that the two-source stimulus caused a sensation of discomfort glare at *BCD*.

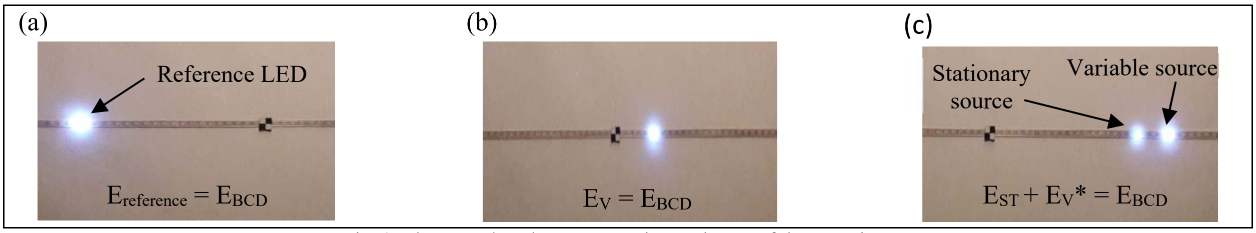

Fig. 3. Photographs whose summarize each part of the experiment:
(a) show the location of the Reference LED; (b) is an example of single-source stimulus; (c) is an example of two-source stimuli.

To vary the distance between the two sources, the position of the variable source was changed. However, previous work showed that eccentricity of the light source has an effect on discomfort glare [5][6][8][12][13]. In order to compensate for this effect, the illuminance E_V from each of these variable sources switched on alone was preliminary collected at *BCD* for each participant (Fig. 3 (b)). The dependent variable of this experiment was the mean illuminance ratio:

$$Illuminance\ ratio = \frac{E_{Vi}\ *}{E_{Vi}} \tag{1}$$

Where:

- E_{Vi}* is the illuminance of the variable light source i (lx) that allows the participant to feel at the *BCD* when the variable source is simultaneously switched on with the stationary light source (Fig. 3 (c));
- E_{Vi} is the illuminance of the same variable light source *i* (lx) at *BCD* when it is switched on alone (Fig. 3 (b)).

To study the effect of the distance between two light sources on discomfort glare, a comparison between the different ratios was made: if there is an effect, these ratios should be different across distance.

The illuminance of the stationary source E_{ST} for each participant was chosen in order to generate roughly half of *BCD* (Fig. 3 (b)). We have consider that in some models of discomfort glare [6][7], the contribution to glare is proportional to the source illuminance. Consequently, the illuminance of the stationary source was fixed to half of the illuminance set at BCD when it was switched on alone:

$$E_{ST} = \frac{E_{V,ST}}{2} \tag{2}$$

This experimental design included two experimental factors:

- The type of vision with two modalities : central vision and peripheral vision ;
- The distance between the two light sources with four modalities: 0.6°; 1.2°; 2.3° and 4.6°.

The characteristics of the stimuli are provided in Table 1.

TABLE 2. CHARACTERISTICS OF THE STIMULI

Source name	Eccentricity (°)	Type of vision	Distance from Stationary source 1 (°)	Distance from stationary source 2 (°)	Range of vertical illuminance for the LED alone (lx)
Reference LED	11,3	Borderline			[0.003; 0.222]
Stationary source 1	2,3	Central			[0.003; 0.240]
1.1	2,9	Central	0,6		[0.003; 0.237]
1.2	3,5	Central	1,2		[0.003; 0.235]
1.3	4,6	Central	2,3		[0.003; 0.232]
1.4	6,9	Central	4,6		[0.003; 0.239]
Stationary source 2	11,3	Borderline			[0.003; 0.222]
2.1	11,9	Peripheral		0,6	[0.003; 0.218]
2.2	12,5	Peripheral		1,2	[0.003; 0.211]
2.3	13,6	Peripheral		2,3	[0.003; 0.221]
2.4	15,9	Peripheral		4,6	[0.003; 0.209]

D. *Experimental Protocol*

The experiment was divided into three successive parts. For each part, participant were asked to focus the target (Fig. 1). Before the start of each part of the experiment, each participant was given a training in order familiarize the participant with the notion of *BCD* and the experimental protocol.

During the first part, the participants were asked to adjust with a potentiometer (Fig. 2) the brightness of the Reference LED (Fig. 3 (a)) until they found the BCD. This particular LED, was the same for all participants and was located 11.3° left from the target (Fig. 3 (a)). The characteristics of the Reference LED are detailed in Table 1. The participants were invited to adjust the illuminance of the Reference LED at BCD (Fig. 3 (a)). This was repeated six times. Then, the average illuminance was collected for each participant and the Reference LED was set to this value for the rest of the experiment.

During the second part, participants were asked to adjust the brightness of each of the LEDs of Table 1 presented alone, at *BCD*. To do this, the single-source stimulus was switched on alternatively with the Reference LED illuminated at the participant's BCD. Thus, participants had to vary the illuminance of the source until they felt the same sensation of discomfort glare as the one generated by the Reference LED. The Reference LED and the single-source stimuli were alternatively switched for 1-second periods. These sequences lasted 20s (10 alternations of two 1-second periods). Each of the 10 single-source stimuli in Table 1 were presented three times, in order to minimize the data variability.

The last part of the experiment was composed by 24 stimuli, with again three repetitions of each of 8 different stimuli. These two-source stimuli presented two LEDs simultaneously switched on with different inter-distances (Fig. 3 (c)): a stationary source and a variable source. The participants were asked to adjust the illuminance of the variable source E_V* so that the degree of discomfort glare generated by the two sources together was at *BCD*. The same comparison with the Reference LED at BCD as in the second part of the experiment was asked. This time, participants had to compare the two-source stimuli with the Reference LED in order to feel the same degree of discomfort glare from each side. In this part, each stimulus lasted 14s (7 alternations of 1-second periods for each side). The illuminance of the stationary source was set according to (2) based on the mean illuminance of E_V obtained in the second part of the experiment.

All stimuli of the two parts were presented in a random order for all participants. Before each part, participants received a training in order to get accustomed to the task. The details of the different LEDs are listed in Table 1.

Results

Five participants were detected as outliers by a hierarchical ascendant clustering and were removed from the data. Fig. 4 shows the mean ratios $E_{Vi}*/E_{Vi}$ (with standard deviations) for the different distances between two sources and for each vision. This results show that the mean illuminance ratios are almost constant whatever the distance between two sources and the vision: the mean illuminance ratio is about 0.84 in central vision and about 0.80 in peripheral vision.

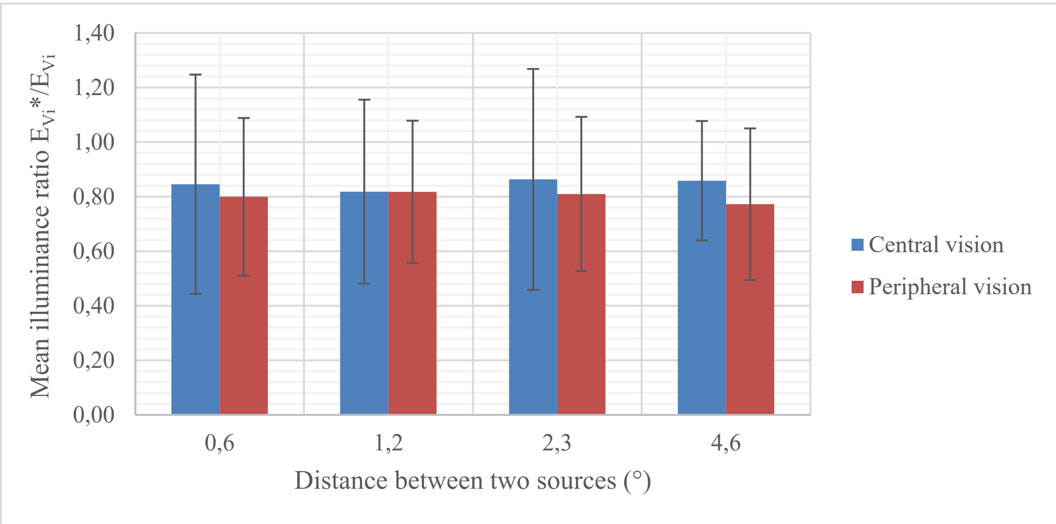

Fig. 4. Mean illuminance ratios $E_{Vi}*/E_{Vi}$ as function of the distance between two sources (°) in central (left in blue) and peripheral vision (right in orange)

A repeated measures ANOVA was performed with two intra-subject factors: the vision range (with two modalities: central vision and peripheral vision) and the distance between the two sources (with four modalities: 0.6°; 1.2°; 2.3° and 4.6°). Normality was satisfied according to the Kolmogorov-Smirnov test. Sphericity was checked with the Mauchly test, and the Greenhouse-Geisser correction was employed for distance because sphericity was not reached. The analysis of the mean illuminance ratio $E_{Vi}*/E_{Vi}$ did not yield a significant effect of vision ($F(1,30)=1.87$, $p=0.18$) or distance ($F(2.20,66.14)=0.07$, $p=0.95$). There was no interaction vision*distance either ($F(3, 90)=0.42$, $p=0.74$).

Discussion

The great dispersion in the results (Fig. 4) come from the inter-individual variability: each participant has their own sensitivity to discomfort glare. This variability may affect the ANOVA's results, but the variability is inherent to the issue of discomfort glare (data collected are subjective answers from participants).

The results from the present experiment suggest that there is no effect of the distance between two sources on the discomfort glare in the distance range of [0.6; 4.6]°. Moreover, the vision range does not affect this result. Therefore, it reveals that the relative position of the sources to each other does not impact the discomfort glare. Thus, the issue in term of discomfort glare when there are more than one light source in the visual field is therefore only related to the number of sources but not to their spatial arrangement.

The mean illuminance ratios $E_{Vi}*/E_{Vi}$ was about 0.80. According to our hypothesis, mean illuminance ratios of 0.5 were expected, because the stationary source for each type of vision was fixed at $E_{BCD}/2$ in order to "halve" the discomfort glare level. But the participants adjusted the variable sources at 80% E_{BCD} to feel at *BCD* with two sources, meaning that the stationary source contributed to 20% of the total discomfort glare. This shows that there is no additivity of illuminance in the discomfort glare. In some models of discomfort glare, the contribution to glare is proportional to the squared source illuminance [2][3]. Thus, it may be interesting in future work to consider E_{ST}^2, E_V^2 and E_V^{*2}.

Our findings are related to two sources with fixed values of solid angle and background luminance. Similar studies could be conducted with more sources and other parameters values to support our findings.

Finally, in this experiment, characteristics of one source with different positions and various two-source stimuli which generate the same level of discomfort glare were collected. Based on these collected data, characteristics of one equivalent source that generate the same level of discomfort glare as two sources simultaneously switched on could be predicted in future work. Such a model could be useful to simplify situations where several sources are simultaneously switched on to one equivalent source, notably in automotive lighting.

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The Treatment of Light Scattering in a Volume and Application to Foggy Traffic Situations

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***Abstract*—Usually, light simulations are conducted with ray-tracing based methods. As long as light scattering occurs only at the interface between two media, this works very well. Against that, the scattering in media like fog occurs not at an interface but in the volume. To treat volume scattering with ray-tracing, a large amount of rays have to be taken into account with means a lot of computational effort. We invented a calculation method which is not based on ray-tracing, simple, potentially fast and based on physical principles. This method and first experiments for a physical proof are presented in this contribution. This work has to be seen in the context to our research on comprehensive virtual evaluation methods for vehicle lighting which takes adverse weather and physiological efforts like glare and perception into account.**

***Index Terms*-- volume scattering, light simulation, glare, perception, headlamp**

INTRODUCTION

New headlamp functions can increase the perceptibility range for the driver, but it has to be validated that glare is minimized in order to ensure traffic safety. Therefore, CAGE (Computer Aided Glare Evaluation) was developed as a tool evaluating the glare potential of a headlamp system on a vehicle early in the development process in order to optimize the headlamp system. A study [1] revealed that reflections from a wet pavement are contributing to glare more than the direct light emitted from the headlamps. CAGE already considers a wet pavement during adverse weather, but the rain itself or fog will also affect perceptibility and glare. In consequence, we are making research on the calculation of light distributions in a scattering volume.

Conventionally, light simulations are performed with ray tracing based methods. This works very well for refraction and scattering at the interface between two media. In a medium like fog, the scattering occurs not at an interface but at every point inside the volume. This means that a huge amount of rays have to be considered which means a lot of computing efforts when the volume scattering is treated with ray tracing.

In [2], a fast alternative method was published for the calculation of spatial light distribution that does not use ray-tracing methods, but is physically exact. E.g. in [2] the illuminance distribution is calculated from the headlamp on the pavement and on a virtual screen in 25m distance to the headlamp in dependence of the fog density. Although the method in theory is valid, and the calculation results are plausible, an experimental proof was not stated yet.

In this contribution, we present experiments in order to prove this new calculation method experimentally. We designed a test set-up for the simulation of repeatable fog states and made measurements of spatial illuminance distributions emitted by a well-defined light source in order to prove the theory and to determine the parameters which correlates to the fog density.

Additionally, it is to mention that the method works for any kind of radiation in a uniform scattering and absorbing medium, but we focus on the application in photometry.

THEORY

Before we start with the deduction of the method, some definitions have to be done:

$$\tilde{n}(\lambda) = n(\lambda) - i\kappa(\lambda) \quad (1)$$

defines the optical properties of a specific material and is called the complex refraction index with n as refraction index, κ as absorption index, λ as wavelength of the light, and i as complex identity.

$$c_m(\lambda) = \frac{c}{n(\lambda)} \quad (2)$$

is the velocity of light in the material, c the velocity of light in vacuum. The relation between the absorption coefficient and the absorption index is not obvious so we refer to textbooks on optics like [6]:

$$K(\lambda) = 4\pi\, n(\lambda)\kappa(\lambda) \quad (3)$$

Beer's law describes the decay of the light intensity during it passes a distance d in the medium:

$$s_{d,absorb}(\lambda) = s_0(\lambda)\, e^{-K(\lambda)d} \quad (4)$$

Eq. (4) is modified by inserting (2), (3), and the propagation time $d = c_m t$:

$$s_{s,absorb}(\lambda) = s_0(\lambda)\, e^{-4\pi\kappa(\lambda)ct} \quad (5)$$

Since the tracing of the rays is extensive in real space when volume scattering occurs, we first calculate the light distribution in the momentum space. In momentum space, all photons with a wavelength λ which propagate in the direction (θ, ϑ) at $t = 0$ are found at $\vec{p}_{\lambda,\theta,\vartheta} = \hbar\vec{k}_{\lambda,\theta,\vartheta}$. With proceeding time, photons will be scattered out from $\vec{p}_{\lambda,\theta,\vartheta}$. Since the scattering is elastic, these photons will change their propagation direction but not their absolute value of momentum respectively their wavelength $|\vec{k}| = \frac{2\pi}{\lambda}$. This means that the photons will move on a sphere with radius $|\vec{k}|$ in momentum space. Inspired by the diffusion equation, which is also based on scattering processes, we described in [2, 3] the intensity distribution in momentum space with:

$$s_{scatter}(\alpha_{mom}, t, \lambda) = s_0(\lambda) \frac{1}{4\pi a(\lambda)t} e^{-\frac{\alpha_{mom}^2}{4a(\lambda)t}} e^{-4\pi\kappa(\lambda)ct} \quad (6)$$

α_{mom} is the angle between a specific point on that sphere and (θ,ϑ), $s_{scatter}(\alpha_{mom}, t, \lambda)$ the number of photons with wavelength λ per solid angle at α_{mom} and t. $a(\lambda)$ is mathematically the full width at half maximum of a Gaussian and correlates to the density of fog. When no absorption occurs, the factor $e^{-4\pi\kappa(\lambda)ct}$ coming from Beer's law (4, 5) can be neglected to 1. Eq. (6) was not found in a rigorous deduction but by considerations of physical analogons. Therefore, it has to be checked which is one of the topics of this contribution, and we will find below that it has to be modified. Equation (6) describes the light intensity distribution in momentum space, but the point of interest is the real space. The relation between the basis in real and in momentum spaces as is $k_{\perp,\parallel} e_{\perp,\parallel} = 2\pi$ which arise from Fourier transformation, further is

$$k_\perp = |\vec{k}| \sin \alpha_{mom}, \qquad k_\parallel = |\vec{k}| \cos \alpha_{mom} \qquad |\vec{k}| = \frac{2\pi}{\lambda} \quad (7)$$

Corresponding to α_{mom}, α_{pos} shall be the angle between $e_\perp$ and $e_\parallel$: $\tan \alpha_{pos} = \frac{e_\perp}{e_\parallel}$. Combining with (7), the transformation results to

$$\alpha_{pos} = \arctan \cot \alpha_{mom} \quad (8)$$

Whereas in momentum space will only move on the *k*-sphere, the light will propagate in real space:

$$|\vec{r}| = c_m(\lambda)\, t \quad (9)$$

Finally from (6, 8, and 9), for every point in real space $(|\vec{r}|, \alpha_{pos})$ the intensity can be given. A counter argument against our statement is that because of the scattering not all photons will propagate on the fastest path as it is assumed in (9). This is correct, but also Eq. (6) applies for the photons that move on a longer path. So we find in $(|\vec{r}|, \alpha_{pos})$ a sum of Gaussians, and according to the central limit theorem, the sum of Gaussian will be a Gaussian like in (6), but not with $a(\lambda)$ but with $a'(\lambda)$ which can be found experimentally.

Now we explain how to come to photometric values. Since we consider fog as mixture from air and water droplets in the visible range of optical radiation, we neglect the wavelength absorptive factor in (6). Then (6) has to be integrated with λ and weighted with $V(\lambda)$ to $\bar{s}(t, \alpha_{pos})$. As stated before, the sum of Gaussians is a Gaussian and so the integral will look formally like (6) without wavelength dependence. $I(\theta, \vartheta)$ is the light intensity distribution of the lamp. Without scattering the illuminance at $(r_P, \theta_P, \vartheta_P)$ results from the photometric square law

$$E(r_P, \theta_P, \vartheta_P) = \frac{I(\theta_P, \vartheta_P)}{r_P^2} \quad (10)$$

When scattering occurs all elements of $I(\theta, \vartheta)$ will contribute to $E(r_P, \theta_P, \vartheta_P)$:

$$E(r_P, \theta_P, \vartheta_P) = \int_{\theta,\vartheta} \frac{I(\theta,\vartheta)}{r_P^2}\, \bar{s}\big(t, d(\theta_P, \vartheta_P, \theta, \vartheta)\big)\, d\theta d\vartheta \quad (11)$$

$d(\theta_P, \vartheta_P, \theta, \vartheta)$ is the angle between (θ_P, ϑ_P) and (θ, ϑ) and replacing α_{pos}. So illuminance distributions can be calculated with (11) in a scattering medium like fog.

APPLICATION EXAMPLE

Usually a headlamp is described by the LID, the light intensity distribution $I(\theta, \vartheta)$ in automotive applications. When inserting the LID in Eq. (11), the illuminance can be calculated point by point, e.g. the illuminance distribution emitted by a low beam in a typical mounting height of 0.65m on the road. This is depicted in Fig. 1 in dependence of the parameter $a(\lambda)$ which correlates to the density of the fog. When fog occurs, light is scattered above the cut-off in the region of oncoming traffic lane, and with increasing fog density the low beam distribution breaks down. These results seems to be plausible, but the calculation method has to be proven experimentally.

EXPERIMENTS

The central point which has to be questioned is the intensity distribution in momentum space, Eq. (6). In laboratory, we put up a simple box with a length of 6m. By evaporating water with ultrasound, we realize a thick, homogeneous fog. In order to have a simple light distribution, we use a laser that illuminates a screen on the wall of the box in a distance of 6m. The average luminance and the stray light is measured with a luminance camera outside the box. Of course, parts of the stray light is coherent and so interference effects are visible. In this early state of work, this is disturbing, nevertheless the laser spot is not a point but has a structured lateral intensity distribution, and so we do only consider ratios of stray light distributions, but in a more advanced state of work this interference patterns can help to characterise the droplet distribution [5].

So we apply four states of fog density and compare them with an initial state. Analysing the integrals of the luminance, it is noticeable that the total luminous flux on the screen decreases with increasing density of fog. This means that the missing flux is backscattered since no absorption occurs. As consequence, Eq. (6) underestimates the backscattering and so has to be modified.

In order to examine if the forward scattered light behaves like Eq. (6) pretends to, we look at lateral intersections of the luminance on the screens. We divide the luminance intersections by the ratios of the total luminous fluxes in order to compensate the backward scattering. For further explanation, please refer to Fig. 3. In Fig. 3a, Eq. (6) is plotted for a couple of parameters $a(\lambda)$. In Fig.3b, certain ratios of the curves are depicted. The measured ratios are drawn in Fig. 4. By comparing Figs. 3b and 4 we state that shapes of the theoretic curve and the measured curve are similar which indicates that the forward scattered light indeed can be described by Eq. (6). In addition, we estimated the ratios between the parameters $a(\lambda)$ in the respective fog density.

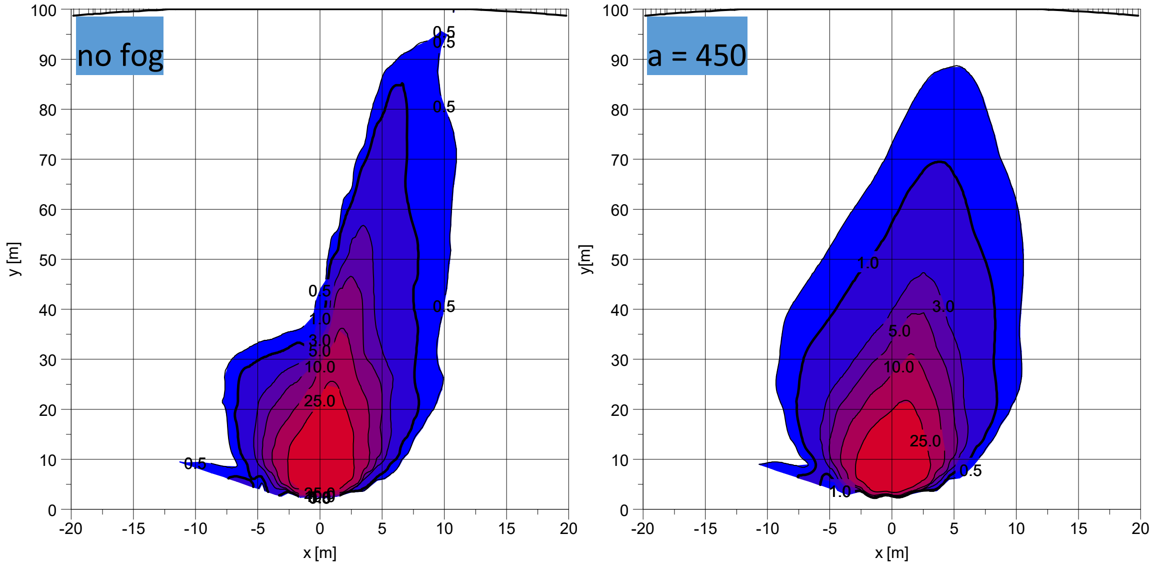

Figure 1: Low beam distribution on the virtual road calculated with our method, on the left side without fog, on the right side with fog.

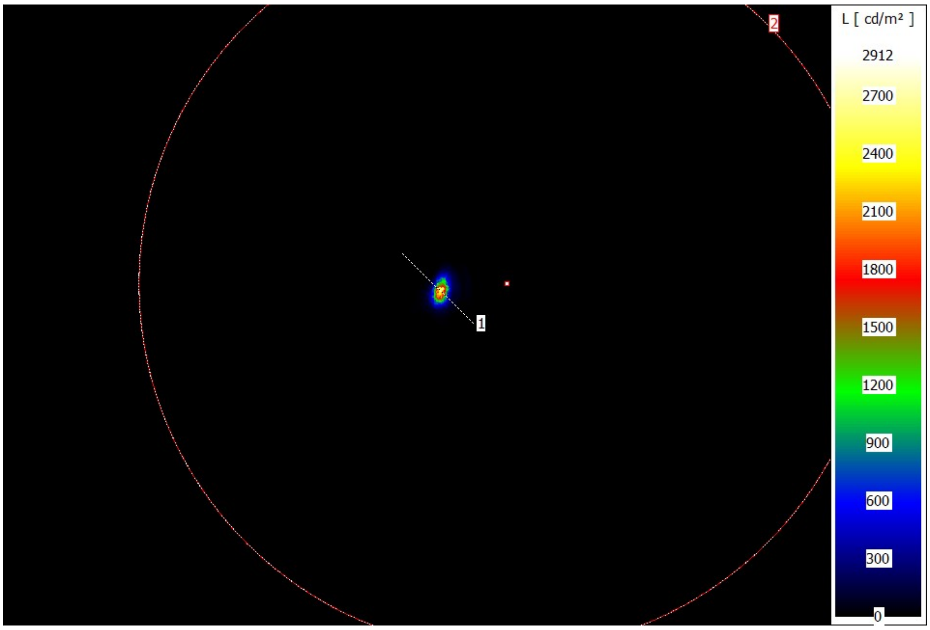

Figure 2: Experimental setup: the light reflex is measured on a screen on the wall of the box with a luminance camera outside the box.

TABLE II. ANALYSATION OF EXPERIMENTAL RESULTS: TOTAL FORWARD REFLECTED LIGHT FLUX AND PARAMETER *A*, CP. EQ. (6).

fog density state	***Ratio total forward scattered light flux (fog density state/initial state)***	***a(fog density state)/a(initial state)***
Initial state	1	1
state 1	0.92	1.08
state 2	0.82	1.13
state 3	0.67	1.17
state 4	0.45	1.25

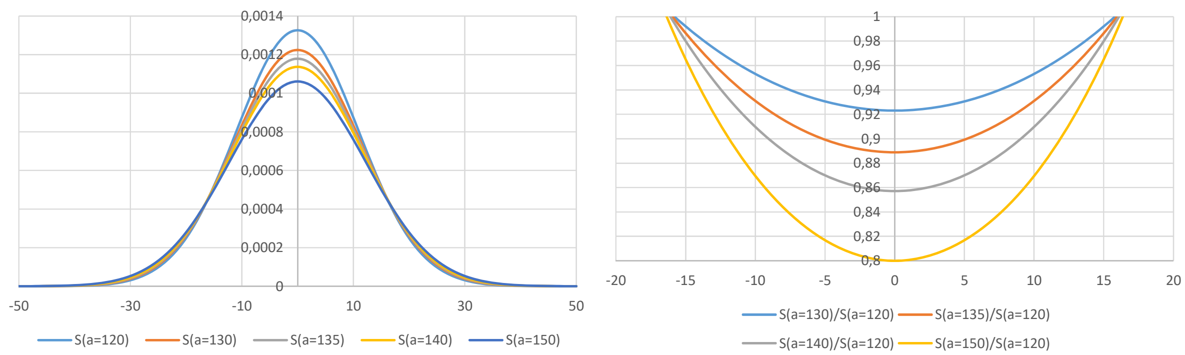

Figure 3: a) Plots of Eq. (6) in dependence of parameters *a* (left), b) calculated ratios *S(a=a')/S(a=120)*, please compare with results from the measurements in Fig. 4.

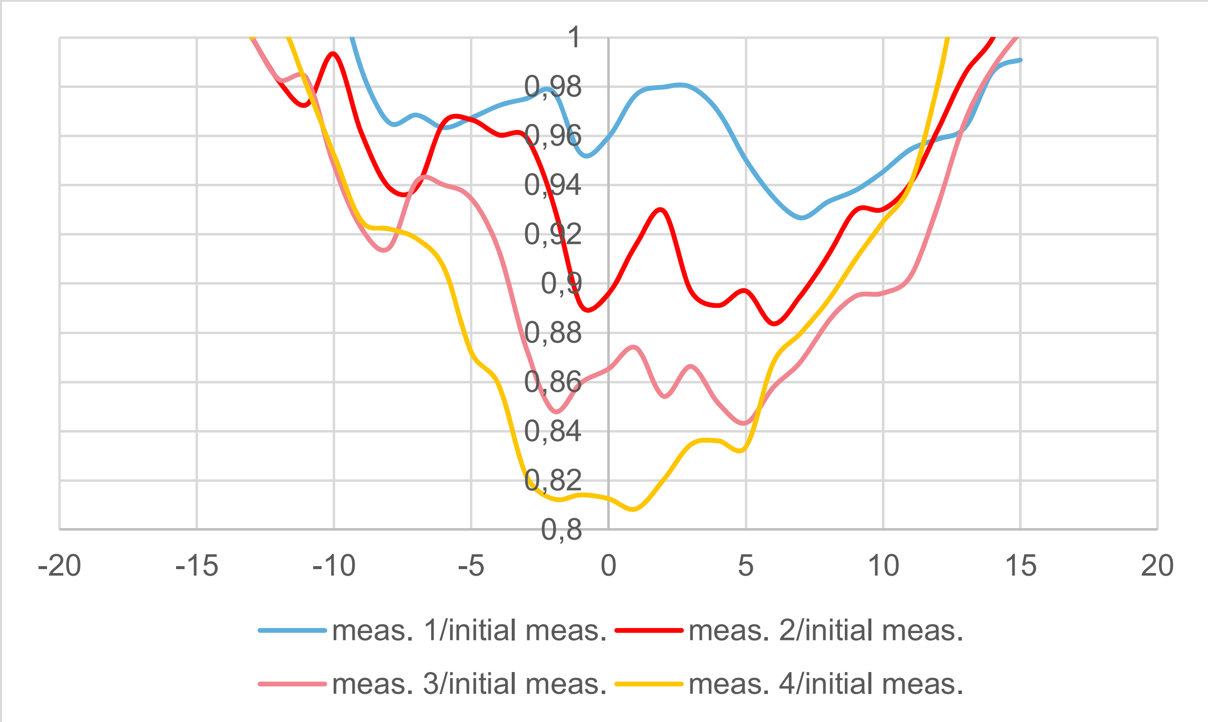

Figure 4: Ratios between the measured luminance intersection (cp. Fig. 2) with increasing fog density and the luminance intersection at initial state, please compare the calculated ratios in Fig. 3b.

Summary and Outlook

We invented a method for the simulation of spatial light distributions in a uniform scattering medium like fog. The method is abstract, but simple and potentially fast. In this contribution, we showed our first steps for an experimental proof, especially of Eq. (6) which describes the light distribution in momentum space. We found that Eq. (6) displays the line shape of the forward scattered light, but underestimates the backward scattering. This is not too surprising since backward scattering physically has a high probability, but it means that our first cut was too rough and Eq. (6) has to be modified which will be done after analyzing the spatial distribution of the backscattered light. The calculation process around this distribution function can be kept.
In the next step, the parameter $a(\lambda)$ has to be correlated with visual aspects. This is planned to be done camera-based by evaluating contrasts on visual targets in our fog simulation box.
From computational part, a further step will be to calculate luminance distributions in order to make statements on physiological recognisability and glare.
It is to mention that the method is generally applicable for radiation in a uniform scattering and absorbing medium and that is applicable also in general lighting. Our final aim of this work is to complement our virtual evaluation tools for vehicle lighting systems which are taking into account adverse weather in order to minimize glare, maximize recognisability and thus traffic safety.

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Disability and Discomfort Glare Caused by Today's Automotive Headlamps in Interaction with Road Conditions

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***Abstract*—Today's automotive headlamps are equipped with different light sources and optical systems. Nevertheless, all have to fulfil legal requirements to ensure good visibility conditions and to avoid glare. Consequently, they should cause disability and discomfort glare of similar magnitude. For that reason, we investigated the impact of today`s headlamps in interaction with a dry and a "wet" road. Three headlamps (different optical system and light sources) of one car and a newly invented adaptive low beam distribution were tested. Additionally, goniophotometer measurements were done for a legal approval and a comparison. The results reveal that today`s headlamps do not cause disability and discomfort glare of similar magnitude, but the newly invented adaptive low beam is quite promising. Therefore, we developed assessment methods which allow an early evaluation of headlamps during the development process. Furthermore, we recommend the need for new criterions to exploit the full potential of future headlamp systems.**

***Index Terms*-- adaptive glare free low beam, disability glare, discomfort glare, front headlamps, glare evaluation**

Introduction

Today's automotive headlamps are equipped with tungsten halogen (TH), xenon gas discharge lamps (HID), or LED light sources (LED) and have different optical systems. Nevertheless, all headlamps have to fulfil legal requirements to ensure good visibility conditions for the driver and to avoid glare to other traffic participants. Therefore, it can be assumed that each headlamp will cause disability and discomfort glare of similar magnitude in real traffic scenarios. For that reason, the hypothesis of the following study is: "Today's headlamps in interaction with road conditions cause different disability and discomfort glare, due to specific light distributions of each headlamp."

Theoretical Background

A lot of studies have been performed to analyse which disability and discomfort glare will arise due to the low beam distributions of different head lamp systems and their light sources. Just a few of them, like ROSENHAHN [1] and SCHMIDT-CLAUSEN and SCHWENKSCHUSTER [2] did also consider the effect of a wet road. Next, two studies will be mentioned in detail because of their relevance to the following contribution.

LOCHER and KLEY [3] performed a bifid study in the light testing facility of the Hella company where they put different headlamps in a distance of 50 meters to the subjects. As headlamps, TH reflection, TH projection as well as HID and LED headlamps were used. The subjects had to assess discomfort glare. Furthermore, disability glare was evaluated. As long as legal requirements were fulfilled and subjects were looking at their own lane there was no significant influence on disability and discomfort glare.

SCHILLER and KHAHN [4] focused on the rapid enhancement of automotive headlamps. Therefore, they tested headlamps of one car equipped with TH, HID and LED light sources under real traffic conditions. The headlamps had to be assessed by subjects on discomfort glare. Additionally, the glare illuminance was measured to evaluate the disability glare. The results reveal that LED headlamps achieve comparable results to HID headlamps. Nevertheless, HID headlamps are still best in class with respect to visibility. Moreover, they achieve the lowest discomfort glare assessment. With respect to the evolution of automotive exterior lighting design and optics should be considered because both aspects seem to have a higher influence on glare than expected.

Nevertheless, none of the mentioned studies focused on a wet road and its interaction with different low beam distributions. For that reason, the following contribution will assess the headlamps of one car under dry and wet road conditions on disability and discomfort glare. Additionally, an adaptive low beam distribution for wet roads will be evaluated.

Method

A. Experimental Set Up

The study was performed on the test track of IAV GmbH at the research and development center in Gifhorn, Germany. The test setup with two cars – to illustrate a real traffic scenario – is shown in Figure 5. . The study itself was performed without any cars. Consequently, no further parameters like the windscreen of a car or any electronical devices inside a car could influence neither the test nor the subjects` attention.

Bottom left of Figure 5. shows the position of the subjects (1, 2). A pair of TH headlamps were positioned two meters in front of them to illuminate the own roadside. A monitor in 50 meters distance at the right roadside showed a red dot. The subjects were instructed to look at it all the time. Therefore, the glare angle θ was 4.6° for each observer position.

Top right of Figure 5. shows the position of the headlamp that had to be assessed. The distance between the headlamp and the observer was set to 50 meters because it represents the "worst case" scenario on a dry road [5], [6]. The lateral distance between observer position 1 and the headlamp was two meters with respect to CIE 188:2010 [7].

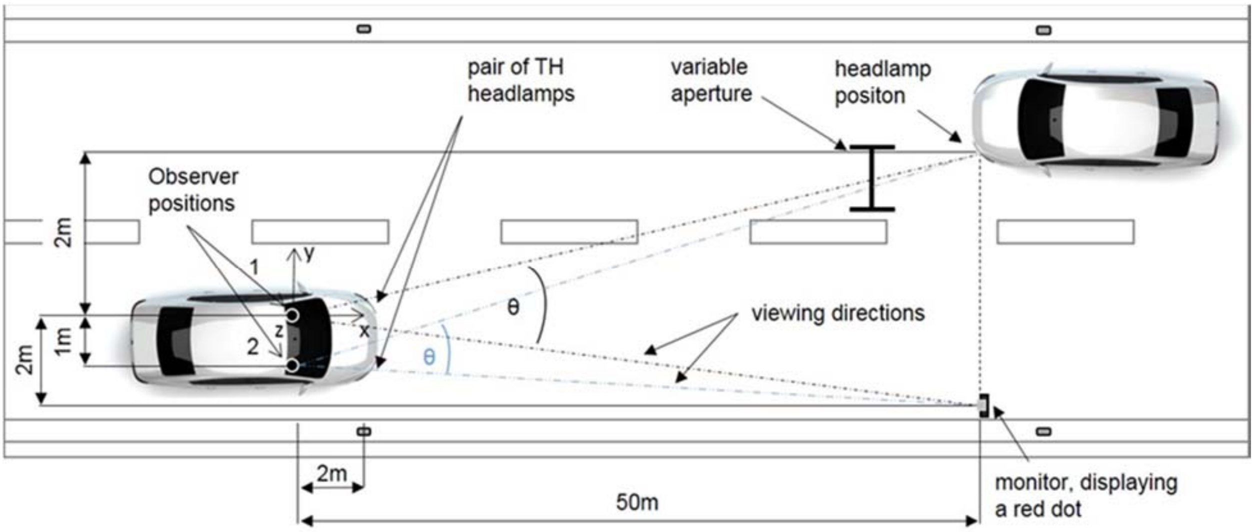

Figure 5. Test Set up (top view)

A variable aperture in front of the headlamp (see Figure 5. , top, right) enabled to present different glare scenarios and realised the adaptive low beam distribution. For that reason, the aperture was divided into three parts. The first part was responsible for the "direct" glare scenario. It was mounted below the standard height of the headlamps. Thus, just the headlamp itself was presented to the subjects. The second part was responsible for the "indirect" glare scenario. It was mounted above the standard height of the headlamps. Thus, just the luminous flux, which is reflected on the road, was presented to the subjects. The third part realised the adaptive low beam distribution. It was mounted below the standard height at the crossing of the geometrical trace between headlamp and observer position (see Figure 5.). If all of them were opened, a normal traffic scenario was presented.

The characteristic of a wet road was simulated by a plastic foil that was put on the road.[2]. Contrary to a wet road that has to be watered continuously, the plastic foil ensures stable properties during the study. Due to the fact, no real wet road was used for the study, it will be referred to in the paper as "wet".

B. Headlamps

All tested headlamps were serial ones that fulfil legal requirements. Each headlamp was dipped 1% downwards according to ECE regulations and were mounted on a desk. The desk was built up parallel to the road surface to readjust the headlamps` mounting position inside a car. The height was 0.65 meters. The constant supply voltage of the headlamps was 13.2V. TABLE III. provides more details about the headlamps. Headlamp D was the same as headlamp B with an additional aperture (see Figure 5.) in its optical path. It enables to hide the luminous flux that primarily raises the glare illuminance at observers' position due to the reflections on a wet road.

TABLE III. SPECIFICATION OF THE TESTED HEADLAMPS

Label	Optical system	Light source	Car mounting position	Remark
A	Reflection	TH	Left	Production head lamp
B	Projection	HID	Left	Production head lamp
C	Multi-Projection	LED	Left	Production head lamp
D	B (modified)	HID	Left	IAV adaptive glare free low beam

C. Subjects

The subjects were mechanical engineering students of the Technische Hochschule Nuremberg and participated voluntary. More information to the subjects are given in TABLE IV. .

TABLE IV. SUBJECTS` INFORMATION – DISCOMFORT GLARE ASSESSMENT

Gender	Number	Age (min)	Average	Age (max)
Male	25	19	22,4	33
Female	3	21	23,7	29

D. Test Procedure

All subjects got a short introduction about the procedure, the test setup and the way to assess the discomfort glare. Neither information about the glare scenarios nor the adaptive low beam distribution were given to them. Due to the number of subjects, they were grouped randomly into four groups and brought to the test track group wise to adapt to the mesopic conditions (> 10 minutes).

At the beginning of the study, the headlamps A and B and C were presented in glare scenario "total" as stimuli to each group. Afterwards the first team was seated at observer position 1 and 2 and headlamp A was presented in all three glare scenarios (sequence: "total", "direct", "indirect"). Afterwards the team had to leave and had to assess the discomfort glare. While team 1 took their assessment, the same headlamp was presented to team 2. This procedure was repeated for all teams of group I. Hereafter the headlamp was changed and the procedure started again. Consequently, it took four runs for each group. The sequence of presentation was randomized for each group (see TABLE V.).

After all groups had assessed the "wet" road the plastic foil was taken away, and group IV and I did the same procedure for a dry road again.

TABLE V. RANDOMISED SEQUENCE OF HEADLAMP PRESENTATION

Label	Glare Scenario	Sequence of presentation (randomized)			
		I	II	III	IV
A	Total (t)/ Direct (d)/ Indirect (i)	1	4	3	2
B		2	1	4	3
C		3	2	1	4
D		4	3	2	1

1) Disability Glare

The disability glare was evaluated using the measured glare illuminance at observer`s position. A photometer was mounted between the two subjects in a height of 1.2 meters. The lateral distance between the photometer and the headlamp was 2.5 meters. This lateral distance and the distance in longitudinal direction between observer and headlamp results in a glare angle θ of 2.86°. The equivalent veiling luminance was calculated, using Equation (1) [8]. E (lx) represents the measured glare illuminance, k is a specific parameter for the age (k=10 comply with the age 30) and θ is the glare angle. Since all parameters stay constant, except the glare illuminance, it is possible to make a statement on the differences in disability glare.

$$L(v_{eq}) = k * \frac{E}{\theta^2} \tag{1}$$

2) Discomfort Glare

Discomfort glare must not necessarily imply a reduction of visual performance. Nevertheless, it can lead to a distraction and influence traffic safety. For that reason, it has to be evaluated as well as the disability glare.

The discomfort glare was rated by using tablet computers. First, the subjects had to select the headlamp and road condition. Second, they had to evaluate all three presented glare scenarios by using slide controls (see Figure 2). Third, a question was asked, if they were looking at the red dot all the time. This should ensure that everybody was evaluating the glare situation at the same glare angle θ.

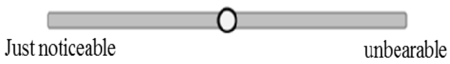

Figure 6.Discomfort glare – slide control

The style of the slide control was following a visual analogue scale (see 0). It was divided into 0.1 steps from 1.0 up to 9.0 in comparison to the De Boer scale [9]. Therefore, the ends of the slider got the same labels. The control was set in the middle as kind of "neutral" position. The subjects could move the control smoothly from right to left and vice versa. Having chosen the right rating, they just had to leave the control. By submitting their ratings, they were saved on the tablet computer digitally.

The discomfort glare ratings were analysed with regard to statistical significance. First, a Shapiro-Wilk-Test was used to check normal distribution. Since not all groups were normal distributed, the Wilcoxon-test, a non-parametrical test, was used. As confidence level α was set to 0.05. The results should point out the effectivity of the adaptive low beam for wet roads and if the differences between the average ratings of the headlamps are statistical significant.

RESULTS

A. Disability Glare

The glare illuminance was measured 14 times for the wet road and 7 times for the dry road for each assessed headlamp (A, B, C, D) and the three glare scenarios (t/d/i)).

Napaka! Vira sklicevanja ni bilo mogoče najti. shows all average values of the glare illuminance that were measured in case of a "wet" road. The results clarify the strong impact of a "wet" road on disability glare. The direct glare illuminance is lower than 0.12 lx. Due to the "wet" road it rises up to a maximum of 1.87 lx in case of the TH headlamp. Moreover, the results indicate the differences due to the specific low beam distribution of each headlamp. Especially the TH headlamp causes a very high glare illuminance that is 67% greater than the one of the HID headlamp. The HID headlamp causes the lowest glare illuminance. All glare illuminances that were measured for the glare scenario "indirect" correlate with the glare scenario "total". Consequently, the "indirect" scenario dominates the disability glare in case of a "wet" road.

Napaka! Vira sklicevanja ni bilo mogoče najti. shows all average values of the glare illuminance that were measured in case of a dry road. The results reveal that the impact of the "indirect" glare illuminance is very low. Primarily the direct glare illuminance dominates the disability glare. It becomes obvious that different headlamps and their low beam distribution lead to different results with regard to disability glare.

Napaka! Vira sklicevanja ni bilo mogoče najti. and **Napaka! Vira sklicevanja ni bilo mogoče najti.** verify the positive effect of the tested adaptive low beam distribution (headlamp D). In particular, in case of a "wet" road the glare illuminance is reduced to a minimum of 0.1 lx in total.

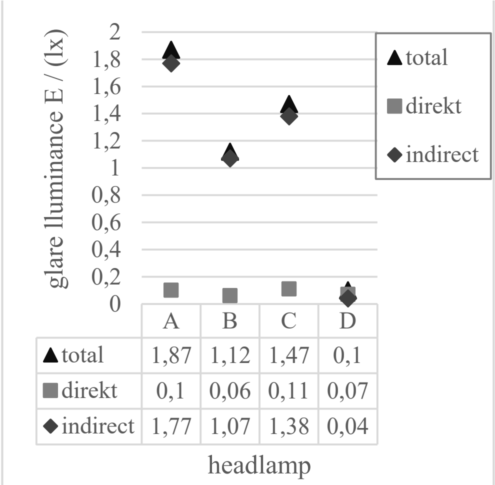

Figure 6. Figure 29 Glare illuminance – Average values for a "wet" road

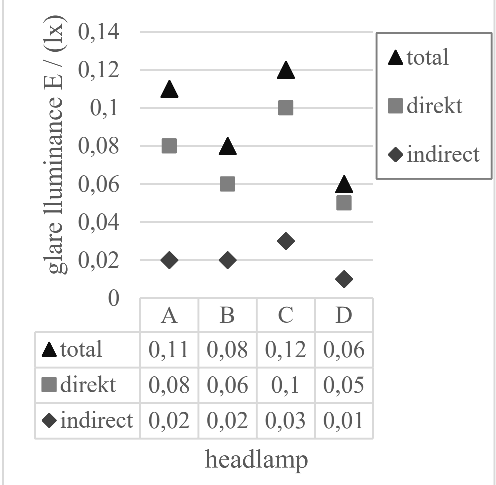

Figure 7. Figure 30 Glare illuminance – Average values for a dry road

B. *Discomfort Glare*

Figure 5 shows the average discomfort glare ratings and their standard deviations for all tested headlamps and glare scenarios in case of a "wet" road. Each headlamp, except headlamp D, get ratings lower than 5 de Boer. These ratings are not acceptable anymore and represent a disturbing situation, which will distract the driver. Looking to the results in more detail it becomes obvious that the "indirect" glare scenarios get a similar assessment than the "total" scenarios. The "direct" scenarios do not indicate to result in discomfort glare. A very positive effect on the discomfort glare ratings is achieved by the tested adaptive low beam distribution. In comparison to the normal low beam distribution (headlamp B), it is up to 4 de Boer steps lower at the "total" glare scenario and nearly reaches "just noticeable" ratings.

Napaka! Vira sklicevanja ni bilo mogoče najti. shows the average discomfort glare ratings and their standard deviations for all tested headlamps and glare scenarios in case of a dry road. In comparison with the ratings for a "wet" road, all ratings are greater than 5 de Boer. Looking to the results in more detail it becomes obvious that the "direct" glare scenarios get a similar assessment than the "total" scenarios. The "indirect" scenarios have no influence on discomfort glare and do not have to be considered for the discomfort glare assessment as long as the road is dry.

0 and **Napaka! Vira sklicevanja ni bilo mogoče najti.** verify that the TH headlamp (headlamp A) reaches the worst assessment on both road conditions in the tested distance of 50meters. The LED headlamp gets the best assessment on a "wet" road and the HID headlamp on a dry road. Since assessment methods are missing, these aspects are not considered during the development process of automotive headlamps.

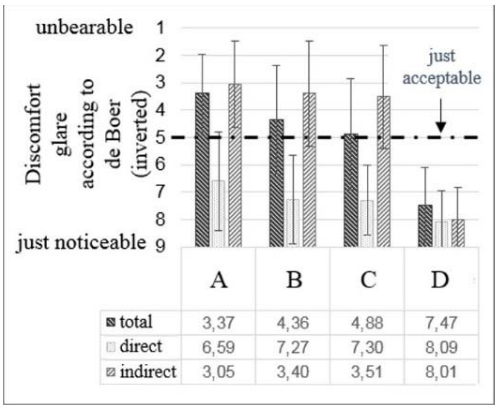

Figure 5 Discomfort glare – Average values for a "wet" road

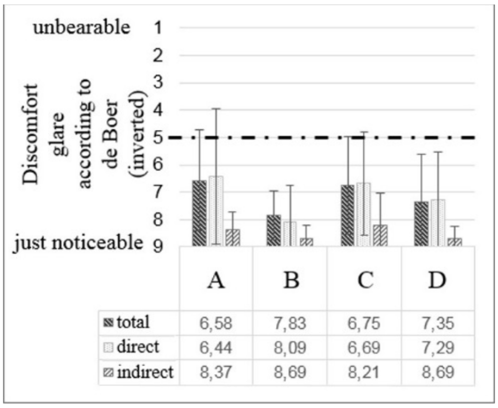

Figure 6 Discomfort glare – Average values for a dry road

Table 4 proves that just the average ratings for the glare scenario "total" between the serial headlamps A and B are significant. None of the average ratings for the tested scenario "indirect" are significant. Nevertheless, Figure 5 reveals that each headlamp is rated different. At last, the effectivity of the adaptive low beam distribution for wet roads is proven. All average ratings between the serial headlamps and the adaptive low beam are significant, except for glare scenario "direct" between system B and D. This scenario may not be different because it is the same headlamp that was presented. Consequently, it validates the used method.

TABLE IV. DISCOMFORT GLARE – STATISTICAL ANALYSES OF AVERAGE RATINGS FOR A "WET" ROAD (WILCOXON TEST, CONFIDENCE LEVEL: A = 0.05)

Compared average ratings	Glare scenario		
	t	d	I
A↔B	0.036	0.307	0.108
A↔C	0.076	0.557	0.851
B↔C	0.345	0.832	0.701
A↔D	< 0.0001	< 0.0001	< 0.0001
B↔D	< 0.0001	0.078	< 0.0001
C↔D	< 0.0001	< 0.0001	< 0.0001

DISCUSSION

The results of this study confirm that despite of legal conformity different headlamp systems of one car cause different disability and discomfort glare. In particular, if the road is "wet". One reason is the characteristic of each low beam distribution [10].

The results of the disability glare assessment reveal that the glare illuminance is up to 17 times greater in comparison with a dry road. Furthermore, the glare illuminance is dominated by the "indirect" glare scenario. At last, today's headlamps differ up to 67% in glare illuminance at observer`s position in 50 meters distance, due to their low beam distributions. The worst glare illuminance is measured in case of the TH headlamp, independent of the road condition. The lowest glare illuminance is measured in case of the HID headlamp.

The results of the discomfort glare assessment point out how different today`s headlamps are perceived. In case of a "wet" road the TH headlamp is perceived significantly more glaring than the HID-headlamp. Despite of its high correlated colour temperature of more than 5500 K the LED headlamp gets the best rating. In case of a dry road it is the HID headlamp, which is best in class. This is confirmed by the results of SCHILLER and KHANH [4].

The additionally evaluated adaptive low beam distribution for wet roads [10] enables a reduction of the glare illuminance from 1.12 lx down to 0.1 lx. Consequently, the disability glare is reduced to the level of a dry road. In comparison to the normal low beam distribution of headlamp B, it is up to 4 de Boer steps lower and nearly reaches "just noticeable" ratings. These differences are statistically significant and therefore verify the effectivity of the adaptive low beam distribution for wet roads.

CONCLUSION

Assessing the disability and the discomfort glare, many factors have to be taken into account, especially the road condition. For type approval, just the glare illuminance is considered. If the threshold value at point B50L and further threshold values below the cut-off-line are fulfilled the headlamp gets its type-approval. The presented study reveals that today's assessment as used for homologation doesn't assess the "real" glare potential, which occurs in daily traffic situations.

In summary, today`s headlamps with LED light sources cause the same if not less disability and discomfort glare than conventional TH headlamps. Nevertheless, HID headlamps are still best in class, due to its very low glare illuminance. More traffic safety and driving comfort is reached with the newly invented adaptive low beam distribution [10]. The disability as well as the discomfort glare is reduced almost to zero. To ensure the effectivity of such an adaptive low beam distribution new assessment methods are necessary that consider the interaction of today`s headlamps with road condition [10].

ACKNOWLEDGEMENT

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Investigating Impediments to Drivers' Hazard Detection Ability: Fog and Sudden Switch-Off.

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Abstract— **Road traffic accidents are a major cause of deaths globally. One goal of road lighting is to improve a driver's ability to see potential hazards after dark. Driving requires exposure to a range of situations that may impede the driver's ability to detect a hazard. Here we investigate how lighting mediates the impact of two such impedimentary situations on hazard detection. Three experiments were carried out using a 1/10th scale model simulation of a major road, in which participants had to detect potential hazards (a car moving into their lane and a suddenly appearing obstacle on the road) in two different situations – the sudden transition from a lit to an unlit area, and the presence of fog. Using a luminance above 0.1 cd/m^2 tended to improve detection performance, particularly under conditions of thick fog. A lack of overhead lighting produced worse detection, with detection being worst in the first 3 s after overhead lights were switched from on to off.**

Index Terms—**Driving; Fog, Peripheral detection**

INTRODUCTION

Road traffic accidents account for more than 1.2 million deaths globally each year, and are the leading cause of death amongst 15-29 year olds [1]. Reducing the number of these deaths is a key priority for national Governments, and the UN has set a target to halve the number of global road traffic deaths by 2020. The risk of a road traffic accident is greater after-dark compared with daylight [2], with reduced visibility being one cause of this. Road lighting is designed to limit this reduction in visibility and therefore reduce the frequency and severity of road traffic accidents after-dark. The illuminance provided by low-beam headlights reduces to less than 3 lux at about 80 m, and this only for a narrow width of less than 3 m on the road surface [3]. Road lighting can therefore illuminate potential hazards that are beyond the vehicle's headlights, and this may occur frequently on major roads where vehicle stopping-distances exceed the distance ahead lit by headlights [4]. Road lighting is therefore expected to reduce the frequency of road traffic accidents. For example, one study using Dutch road accident data found that road lighting reduced accidents by approximately 50% during hours of darkness [5].

A range of research has examined the effect of road lighting on the basic task of hazard detection, for example by presenting a target or hazard under different conditions of lighting (e.g. [6], [7]). Driving is a dynamic task undertaken in a range of conditions and situations however, and it is essential to know how road lighting influences hazard detection under this range of different conditions. Two such conditions that may impede a driver's ability to see a potential hazard ahead are a rapid change in road lighting conditions, and the presence of fog.

Not all sections of a main road are lit after-dark, due to cost-benefit considerations. Lighting is not always an effective countermeasure to some types of road collision [2] and thus not installed, or it may be dimmed or switched off as an energy-saving measure. Drivers therefore frequently experience travelling between lit and unlit sections of road, and this affects their visual adaptation, the process of adjusting to the quantity and quality of light that is mediated through changes in pupil size, neural adaptation and photochemical adaptation [8]. It is not currently known how such adaptation effects influence a driver's ability to detect hazards, and how any influence is mediated by variations in light characteristics such as luminance and spectrum.

Fog is a dense cloud of water droplets lying close to the surface of the ground, occurring when air temperature approaches its dew point. Fog reduces the visibility distance perceived by the driver through attenuation of the amount of light received at the eye. Fog also causes a scattering of light which may reduce the contrast and hence visibility of objects. Previous research has shown an association between fog or smoke and the severity and characteristics of road collisions ([9], [10]), and the distortion of distance cues by fog may also contribute to the increased collision rates during foggy conditions [11]. Little is currently known however about how road lighting influences the effect of fog on a driver's ability to detect a potential hazard.

We present results from three experiments that used 1/10th scale model apparatus to examine a driver's ability to detect a hazard ahead under different levels of road lighting luminance and spectrum, when transitioning from a lit to an unlit area and during foggy conditions.

METHOD

Three experiments were carried out using the same general apparatus, a sealed chamber viewed from one end through transparent acrylic, to simulate viewing a road scene through a windscreen, from the driver's point of view. The chamber was 5 m long, 2.5 m wide and 1.5 m high and simulated a road scene at 1/10th scale. The floor surface of the chamber showed three lanes to represent a major trunk road or motorway. Two scale model cars were placed in the two outer lanes at the far end of the chamber, at a simulated distance of 47 m. These cars were placed on a track hidden beneath the chamber floor that allowed them to move transversely. By default the cars made small, slow movements within their lane, but at specified times either car could make a faster movement into the centre lane, taking 6 s to reach the centre of the centre lane. In addition, a balsawood vane measuring 60 mm wide by 20 mm high was also hidden beneath the chamber floor at the same distance as the cars but in the centre lane. This could be raised to become visible, simulating an obstacle approximately the size of a car tyre lying flat on its side. At specified times the obstacle would become visible by rising to its height of 20 mm in 1 s, remaining at this height for 2 s, and returning below the chamber floor in 1 s.

The cars and the obstacle therefore presented two different types of detection task – participants were required to press a button on an artificial steering wheel in front of them when they noticed either car begin to move into the centre lane, or a foot pedal when they saw the obstacle appear. The proportion of correct detections were recorded, a correct detection defined as a response to a car lane change within 6 s of the first movement of the car or a response to the obstacle within 4 s of its first appearance. Reaction times to a detection were also recorded. Two car lane change events and two obstacle events occurred at pseudo-random intervals during each minute of a trial, but ensuring there was no overlap between separate events.

The chamber was lit from above by two LED arrays that could be rapidly switched to provide luminances of 0.1, 1.0 or 2.0 cd/m^2 at the target area, and two spectra with S/P ratios of 0.65 or 1.4. An LED array was also positioned at the participant end of the chamber facing towards the targets to provide the appearance of a headlight beam, although the illuminance provided by this was minimal (< 0.2 lux on the vertical surfaces of the car and obstacle targets).

Experiment 1 examined the effect of transitioning from a lit to an unlit area on performance of the two detection tasks. An initial 4-minute baseline period began each trial in which the overhead lights were switched on. After this 4-minute period the overhead lights were immediately switched off, leaving only the dimmed headlights on, and the trial continued for a further 4 minutes. Four light conditions were tested, these being 1.0 cd/m2 at 0.65 S/P and 0.1, 1.0 and 2.0 cd/m^2 at 1.4 S/P.

Experiment 2 examined the effect of fog on performance of the two detection tasks. The chamber incorporated a fog generator and extraction system that allowed a colourless aerosol of liquid droplets suspended in air to be injected into the chamber to provide the appearance of fog, at different levels of density. Three fog conditions were tested: No fog, Thin fog and Thick fog. The No fog condition was used a baseline against which to compare the other two fog conditions. The fog level was defined by the absorption coefficient calculated from the attenuation of light propagating through the chamber atmosphere [12]. The respective absorption coefficients for thin and thick fog were 0.005 and 0.04 m-1, these representing visibility distances of 600 m and 75 m respectively [13]. Four light conditions were tested under each of the three fog conditions, these being 0.1 and 1.0 cd/m^2 at both 0.65 and 1.45 S/P ratios. A trial lasted for four minutes under each light condition. The No fog condition was always presented first to ensure the chamber was completely free from fog, but the Thin and Thick fog conditions were counterbalanced between participants.

Both experiments used a repeated-measures design. Thirty participants were recruited for each experiment, with each participant being exposed to all conditions within that experiment. Young (18-30 years) and old (40-70 years) age groups were selected, with 15 young and 15 old in Experiment 1, and 16 young and 14 old in Experiment 2.

RESULTS

A. Experiment 1

Mean detection rates and reaction times for the car and obstacle are shown in Fig. 1. Detection rates for the car do not appear to change after the lights switch off but reaction times to detect the car lane change do increase. Detection rates and reaction times for the obstacle both become worse after the lights switch off. There do not appear to be any obvious differences between the four light conditions, with the possible exception of the Low S/P, 1.0 cd/m^2 and High S/P, 0.1 cd/m^2 conditions producing slightly better detection rates for the obstacle after lights switch off, compared with the other two light conditions. Four separate linear mixed-effects models were carried out for detection rates and reaction times on the car and obstacle targets. The light condition had no effect on detection rates and reaction times for the car. Light condition also had no effect on detection rates of the obstacle, but did have a significant effect on reaction times to the obstacle ($p = 0.02$). Post-hoc Tukey tests showed that the High S/P, 0.1 cd/m^2 condition produced significantly slower reaction times to the obstacle than the other three conditions. Switching off overhead lights produced significantly worse performance for both detection rates and reaction times to both car and obstacle targets ($p < 0.01$ in all cases).

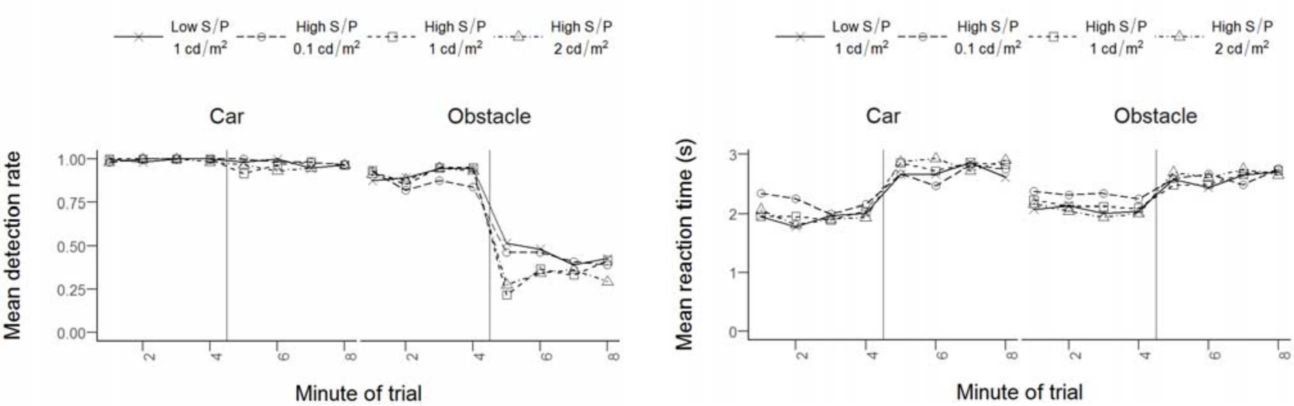

Figure 1. Mean detection rates (left) and reaction times (right) for car and obstacle by trial time, under four light conditions. Vertical line indicates when overhead lights were switched from on to off.

It is clear that detection performance generally reduced following the transition from overhead lights switched on to switched off. It also appears that following this transition performance remained constant, and there was little evidence of any change in performance as a result of visual adaptation. One explanation for this is that any adaptation effects would occur in less than a minute after the transition due to the rapid adaptation of the visual system to large changes in light levels [8]. This experiment was unable to assess such rapid adaptation effects as the first target that appeared after overhead lights were switched off could have taken up to 20 s after the switch, due to the pseudo-randomised scheduling of target appearances. Therefore a supplementary experiment was carried out (Experiment 1a) with five additional participants to assess how detection responses were affected in the first few seconds after overhead lights are switched off, and how this may have changed over the course of the next few minutes.

B. Experiment 1a

A repeated cycle of 60 s with overhead lights on followed by 30 s with lights off was presented to 60 consecutive times to five participants (aged < 30 years). Only the High S/P, 1.0 cd/m^2 light condition was used. Six target events occurred within each cycle at pseudo-random intervals, although one event was always scheduled within 3 s after the lights switched from on to off. Due to the consistency of this scheduled event, two of the six target events in each cycle were actually 'null' events, in which no target was presented. This allowed for the measurement of false responses due to anticipation rather than actual detection of a visible target. Each participant was therefore exposed to 240 real target events, equally split between the car lane change and the obstacle, and 120 null target events. Detection rates and reaction times to detection were calculated using the same criteria as used in Experiment 1. Only 4% of null events produced a response from the participant suggesting false responding was minimal. Fig. 2 shows mean detection rates for the target when it appeared in the first 3 seconds after lights were switched off, compared with the rest of the off period, and the period when lights were on. Mean reaction times are not shown due to the low number of correct detections in the initial 3 s post-switch period.

Detection rates for both car and obstacle are better when the overhead lights are on compared with off. There is also a possible trend for detection rates to be worse in the first 3 seconds after the lights have been switched off, compared with the rest of the off period. A paired-comparison t-test suggested detection rates in the first 3 s after lights were switched off were significantly worse than in the rest of the off period for the obstacle ($p = 0.01$) but not for the car ($p = 0.56$).

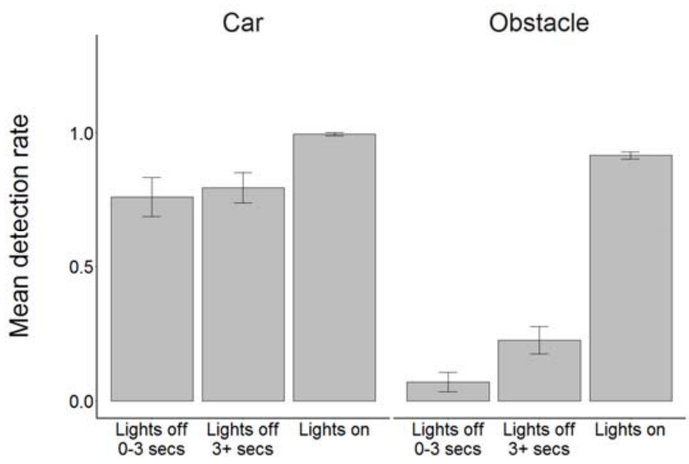

Figure 2. Mean detection rates for car and obstacle initiated during first 3 seconds after light switch and 3+ seconds after light switch, with overhead lights on or off. Error bars shown standard error of the mean. N = 5.

C. Experiment 2

Each participant experienced four light conditions under three different levels of fog, as defined by the absorption coefficient – None, Thin and Thick. Mean detection rates and reaction times under the four different light conditions and three fog conditions are shown in Fig. 3. The thick fog condition produces noticeably worse detection rates and reaction times compared with the other two fog conditions. Fog level also appears to have had a variable impact on detection performance depending on the lighting condition. Separate linear mixed-effects models were carried out for detection rates and reaction times on the car and obstacle targets. These showed that the lower luminance level produced significantly worse detection performance for both car and obstacle ($p < 0.01$ in all cases). Thick fog also produced significantly worse detection for both car and obstacle, compared with thin or no fog ($p < 0.01$ in all cases). There was also a significant interaction between fog and luminance levels, with an increase in luminance producing improved detection under thick fog conditions but not under thin or no fog conditions. The only effect the S/P ratio of the lighting had on detection was through an interaction with the fog level – the high S/P ratio helped improve detection performance under thick fog conditions, but made no difference to detection under other fog levels. This effect was only found for reaction times to the obstacle however, and not for detection rates, or reaction times to the car.

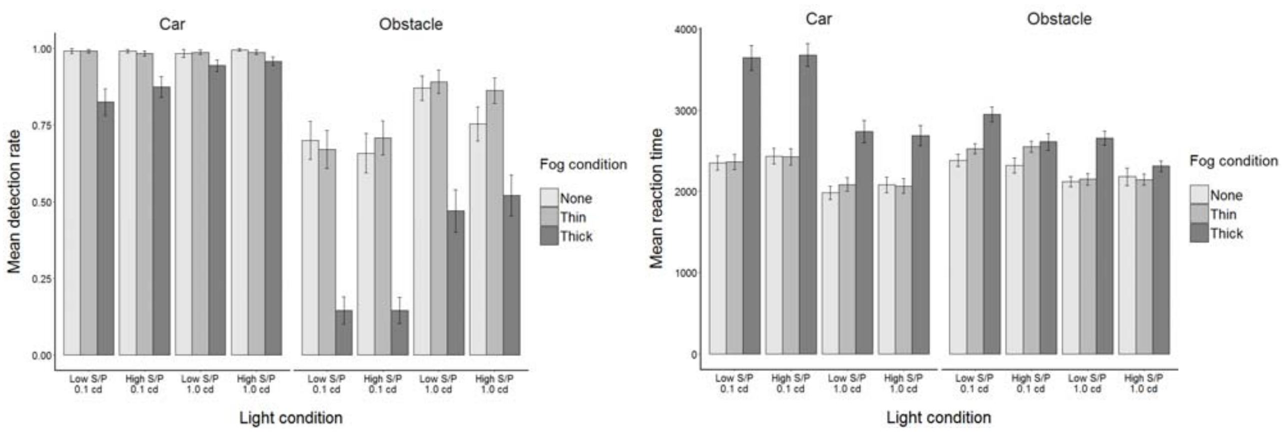

Figure 3. Mean detection rates (left) and reaction times (right) for car and obstacle targets, by light condition and fog level. Error bars shown standard error of the mean.

CONCLUSION

Three experiments were carried out to examine how lighting mediates the detection of potential hazards during two different situations that may impede hazard detection – the sudden transition from a lit to unlit area of road, and the presence of fog. Overhead lighting significantly improved the detection of a hazard, and the speed with which it is detected. For example, reaction times to detection of the obstacle became 517 ms slower when overhead lights were switched off. Such a delay in reaction would increase a vehicle's stopping distance by 16 m if travelling at 70 mph. Experiment 1 did not reveal any improvement over time after lights are switched off, but Experiment 1a did suggest the ability to detect a potential hazard is worst in the immediate 3 s after lights are switched off. The presence of thick fog can cause a significant reduction in the ability to detect a hazard, but increasing the luminance of overhead lighting from 0.1 to 1.0 cd/m^2 can improve this ability. Using light with a higher S/P ratio may also help under conditions of thick fog, although further work is required to confirm this.

ACKNOWLEDGEMENT
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Urban Environment Illumination Impact on Users' Priorities and Respond

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***Abstract*—A concept of the night city is not only material reality, but it is also a mental structure that results subjective perception. Human well-being is equalled important as architecture aesthetic, technological possibilities and environmental protection. A three domain scheme was created in order to determinate user profile on focused area. Users respond in accordance with psychological priority, sociological priority and aesthetic-functional priority. An empirical research was conducted, based on the descriptive and causal experimental method in order to explain consequences of illumination on human well-being. A sample of 200 respondents in Maribor city was taken. Analytical research work discovered that illumination strongly influenced environmental perception that should be adjusted with speed and mobility. Illumination forced city awareness along the most commonly used routes that are different between day and night. General satisfaction with city lighting is important as well. The study results are useful as important environmental analysis starting point in decision making process that leads to successful lighting strategy preparation.**

***Index Terms*— city, illumination impact, users' profile, response to human needs**

INTRODUCTION

Cities and urban areas are still the most interesting places to live in. Environmental subjugation necessary for modern living patterns is the reason for talking about public space development possibilities. This is a challenge because urban surfaces are always used by many users at the same time, by drivers, cyclists, pedestrians, and residents. Each group has their own spatial needs [1]. A starting point of the presented contribution is the awareness that a city is not a constant form. Urban development is guided by social progress and technological capabilities. City of tomorrow strikes a balance among social, environmental and economic needs. It is very important to plan the best possible spatial interventions. Human well-being is the highest priority.

Cities change in time and space. Artificial night light is important environmental factor. Night spatial circumstances are not only material reality, but they are also mental structures that result subjective perception. Visual perception dominates over other perception modes such as: hearing, smell, taste, and type. Eyesight provides the largest amount of information to explain what happens around us. We are supplied with a lot of information, e.g., distance, colors, shapes, textures, and contrasts. Vision gives us two thirds of all environmental information [2]. The environment should go along with it and create a good personal feeling. To ensure satisfied users, environmental circumstances should be adjusted. How to achieve it? We have to know how different stakeholders see, perceive, and experience their environment in everyday life. Technical criteria of light intensity can be measured, but the citizen good feeling cannot be measured in the same way. Assessing the level of convergence between planners and users can be helpful in building a consensus [3] - [5]. Urban development of night city is often characterized as being split on "technical" and "social" grounds [6]. The key to successful lighting design is allocation of light sources forwarded through different branches of decision-makers. To achieve interaction between urban environment and its users, it is necessary to understand how users perceive their surroundings [7].

There are perceptual differences between two interest groups: planners and users. Planners experience the environment differently than other social groups, but their decisions about light resource allocation have a great impact. This level has often been defined as the objective [8]. Planners operate in accordance with the principles of good practice. Their priorities are aesthetically functional, technological, economic, legal, and environmental. On the other hand, users' environmental perceptions are always subjective because they rely on individual responses. Their observation is dependent upon the individual's sex, age, time, experience, and culture. Their priorities are psychologically-, sociologically-, and aesthetically functional- conditioned [1].

The article focuses on users' priorities and respond regarding artificial night light of urban environment. It is supposed that good lighting arrangements are precondition for human well-being. Lighting the city must come from a man, who is equally important as architecture aesthetic and technological possibilities. Urban planning features, architectural sights and light effect on users must be treated equally. The article explains the possible evaluation of illumination impact on users' needs. The research results can be integrated into decision making process and planning practise.

DETERMINATION OF USERS' PRIORITIES IN NIGHT CITY

A boundary between light and dark is the most powerful contrast who defines relations between buildings and open space. Lighted elements are more visual. At night new relationship between elements is created. Visual value of the city is increased. Lighted surfaces have a great recognition potential and make recognizing spatial order and structural connections possible. Light has also an impact on individual impressions, ability of environment identification, orientation ability, sense of safety, and ability to recognize spatial segmentation. According to Canter [9] (p. 158) space concept is based on individual experience and designated by the composite conceptual system. We are informed about a place through "what behavior is associated with, or is anticipated to be housed in it, what physical parameters of the settings are, and the description, or conceptions, which people hold of their behavior in that physical environment" [9] (p. 159). Space defines a cognitive image of a specific location, like any human performance that includes physical and mental links between an observed location and its surrounding [9] (pp. 22–26).

Using information obtained by different authors, a three domain scheme was created using a method of inductive conclusion in order to determinate groups of users' priorities (figure 1). It is assumed that our respond based on priorities like psychological, sociological, and aesthetic functional. All of them are equitable and connected. We respond and act in accordance with them.

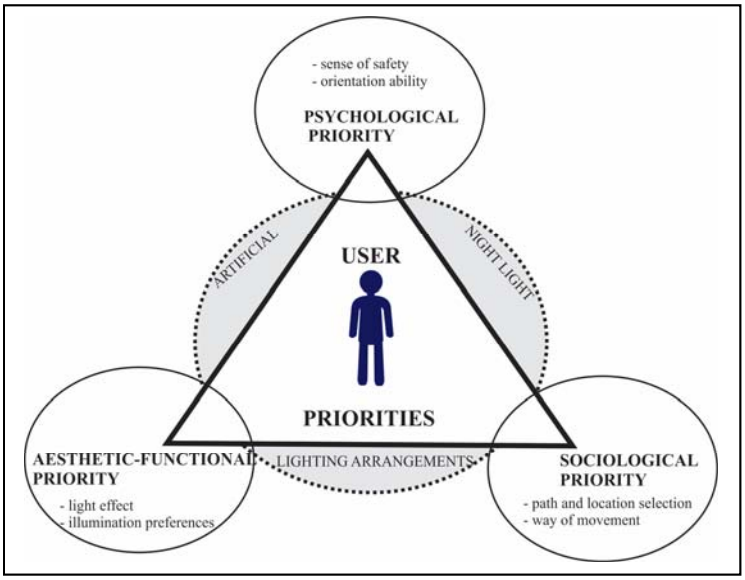

Figure 1: The three domain sheeme of users' priorities

A scheme represents the most important aspect that must be taken into account when planning and arranging city lighting like: sense of safety, orientation ability, path and location selection, way of movement, light effect and illumination preferences.

CASE STUDY MARIBOR CITY

The adequacy of the scheme was verified with the help of Maribor City case study. Maribor is the second largest Slovenian city with an important central regional role. A sample of 200 respondents was taken. Data obtained on the basis of a questionnaire were statistically processed and analyzed using SPSS Windows, Version 21. Methods of descriptive statistics (frequency and numerical analysis, the arithmetic mean of the difference between the mean, and standard deviation) and inferential statistics (*t*-test for dependent samples, and Pearson's correlation coefficient-r) were used.

A. Sociological Priority

The way of moving influences spatial perception and behavior, and vice versa, our spatial perception and behavior influence the way of moving. It can be concluded that priorities and respond are always connected. Many studies already deal with that topic. For example Susilo et al. [10] in UK study found that sustainable modes of travel are related to urban design features. City lighting is integral part of that. Secured bike storage, high connectivity of the neighborhoods, natural surveillance, high-quality of the public realm, and traffic-calming all proved significant. Mostafiz Shatu et al. [11] reported that availability of opportunity and services located within the transit-oriented development reduces car use by 5% and increases the use of active transport by 4%. It can be concluded that speed and mobility have the biggest impact on priorities and respond. They are very important lifestyle indicators. In presented case study respondents evaluate mode of movement frequency by day and by night. They use five-level evaluation scale (1 never used - 5 everyday used).

TABLE 1: DESCRIPTIVE MEASUREMENTS OF WAYS-OF-MOTION AND THE RESULTS OF THE T-TEST AND CORRELATION FOR DEPENDENT SAMPLES OF THE PAIRS DAY - NIGHT

Movement mode	**Day**		**Night**		**Difference**			
	$\overline{x}$	σ	$\overline{x}$	σ	$\overline{x}$	**t**	**2p**	**r**
On foot	4,40	0,918	3,52	1,156	0,875	11,513	0,000	0,482
By car	2,75	1,151	2,50	1,139	0,250	3,567	0,000	0,625
By motorcycle	1,15	0,515	1,09	0,378	0,055	2,892	0,004	0,863
By bycycle	1,94	1,272	1,52	0,951	0,420	7,626	0,000	0,722
By bus	2,19	1,224	1,70	1,027	0,485	7,213	0,000	0,665
By taxsi	1,36	0,618	1,77	0,956	-0,405	-7,027	0,000	0,535

$\overline{x}$– atithmetic mean, σ – standard deviation, t – value difference arithmetic test, 2p – bidirectional level of statistical significance, r – Person product-moment correlation coefficient.

The results confirm the assumption that the movement mode in day-time and night-time is different. Walking is the most common movement mode at both time sequences. In all cases, the results of the t-test show that the difference is statistically significant within the condition 2p <0,05. The r correlation results show that there is a moderate to high degree of correlation in the day and night movement mode. Of course, at this point, the question remains, if artificial night light effect is the one that effect movement mode. The answer is given below.

First it was assumed that there are differences in choice of day-time and night-time routes. On the five-level assessment scale, the respondents subjectively evaluated the level of route difference between day- and night-time. The results show that most of respondents estimate that they use different routes at day-time and night-time.

TABLE 2: THE NUMBER OF ANSWERS AND THE PERCENTAGE OF THE FREQUENCY OF THE ROUTE-USE DURING THE DAY-TIME AND NIGHT-TIME

The route-use during the day- and night-time	f	f %
It does not differ	42	21,0
It's a little different	83	41,5
It is moderately different	57	28,5
It's very different	15	7,5
It's totally different	3	1,5
SUM	**200**	**100,0**

f – Number of responses, f % – Percentage of responses

Second it was evaluated the extent to which lighting is the one that influences the choice of the route. We assumed that different degrees of illumination influence the use of urban space. Respondents evaluate through a five-level assessment scale the influence of light on their use of space. The results show that when choosing a route, lighting is very important factor.

TABLE 3: THE NUMBER OF ANSWERS AND THE PERCENTAGE OF THE IMPACT OF LIGHTING ON THE SELECTION OF THE ROUTE AT NIGHT

The lighting impact on route selection	**f**	**f %**
No impact	16	8,0
Small impact	21	10,5
Moderate impact	51	25,5
Big impact	74	37,0
Very big impact	38	19,0
SUM	**200**	**100,0**

f – Number of responses, f % – Percentage of responses

B. Psychological Priority

We notice both shape and color. Shape belongs to the object and it is objective, independent of the viewing angle. Color is determined by the length of light wave emitted by the object. It is not an absolute object property; it occurs only in the user's head. Both shape and color are perceived by the light. Light increases the visual value of the city. Well-lit surfaces have greater recognition potential and allow for recognizing spatial order and structural connections possible; thus strengthening spatial orientation.

Quality lighted environments have larger visual potential; they can be more attractive and, therefore, frequently used. However, not only is visual effect important; feeling safe is a priority for users. Pinter and Farington [12] report that lighting optimization increases feeling safe and decreases criminal activities by 15%, but how much light do we need to achieve a positive effect of good visibility and to recognize danger from far away? Additional light (between zero and 10 lux) increases our safety perception, as reported Boyce et al. [13]. According to their opinion, an acceptable illumination is 30 lux and over. Boyce et al. [13] concluded, if illumination is over 50 lux, additional light makes no sense. Feeling safe is not absolute priority. It is very important priorities among equivalent space factors as show the results below. Respondents rated the importance of space factors on the basis of a five-point rating scale (1 extremely irrelevant - 5 extremely relevant).

TABLE 4: DESCRIPTIVE STATISTICAL EVALUATION OF INDIVIDUAL SPACE FACTOR

Environmental factor	$\bar{x}$	σ
Well organized and maintained road network	4,36	0,722
Presence of greenery and large green areas in the city	4,51	0,702
Accessible sports surfaces	4,05	0,881
Public space as public life venue	3,87	0,986
Feeling safe	4,48	0,750
Illuminated surfaces	4,20	0,813
Beauty and attractiveness of environmental design	4,48	0,641

$\bar{x}$– atithmetic mean, σ – standard deviation

The results in table 4 show that respondents evaluated the importance of individual environmental factor in the city relatively high between 3,87 and 4,51. Factor Illuminated surfaces is not recognized as very important, although it has a significant impact on other factors. The respondents do not realize the importance of this factor and do not recognize the direct connection between security and lighting intensity.

C. Aesthetic- Functional Priority

Sometimes the lighted environment provides us with more information than we can accept. We select only those messages that are important and useful for us, but we accept only as much as we can process [14] (p. 22). The authors of [15] consider that every approach that reveals the image of an environment in people's minds in all its variety, contributes to our knowledge of human–environment interactions. Material and the texture have a great impact on light effect. Dark surfaces absorb much more light than light surfaces; smooth surfaces reflect more than structured. Straight, flat surfaces do not cast shadows, while strongly structured surfaces do. Interplay of light and shadow creates visually appealing components and is desirable, but too excessive a contrast is felt to be unsuitable [16]. According to Veitch [17] the most acceptable structures are vertical, constantly illuminated smooth surfaces. Colour contrasts are accepted as interesting, as well as spot lighting. Colorful elements catch the attention and are categorized as more noticeable.

Urban surfaces are always used by many users at the same time, by drivers, cyclists, pedestrians, and residents. Each group has their own spatial needs. The environment should go along with it and create a good personal feeling. To ensure good living conditions to all environmental perception should be adjusted. Problems occur when our visual system is overwhelmed by the amount of input. Therefore, it is necessary to reassure the facts that the reduction of the illumination is as important as the intensity. How important it is for the respondents to see the night sky in the city show the results in table 5. 98.5% of the respondents rated the view of the night sky as desired. The results show that the majority do not agree with the constant full brightness. Urban lighting should also be directed towards the areas of total light reduction.

TABLE 5:THE NUMBER OF ANSWERS AND THE PERCENTAGE OF EVALUATION OF THE IMPORTANCE OF SEEING THE NIGHT SKY IN THE CITY

Possibility of night sky vision	**f**	**f %**
Irrelevant	3	1,5
Little important	26	13,0
Important	81	40,5
Very important	59	29,5
Extremely important	31	15,5
SUM	**200**	**100,0**

f – Number of responses, f % – Percentage of responses

At the end, city lighting should be treated as a whole unit. Therefore, the general satisfaction rate city lighting is important. It is a subjective assessment of individuals taken on the basis of previous experience (table 6). Positive adjustment increases the level of spatial satisfaction.

TABLE 6:USERS' ILLUMINATION SATISFACTION OF MARIBOR CITY

Assessment of overall Maribor Illumination	**f**	**f %**
Too weak	6	3,0
Poor	55	27,5
Satisfactory	122	61,0
Strong	16	8,0
Excessive	1	0,5
SUM	**200**	**100,0**

f – Number of responses, f % – Percentage of responses

Most of the respondents expressed satisfaction with the city lighting. It was considered too weak and poor by 30,5% of respondents, while only 8,5% evaluated as strong and excessive. Such results prove that beyond regulations and standards, less light is sometimes even more.

CONCLUSION

Urban environments are basically controlled and designed by our measures. Improving environmental perception increases visibility, personal security, and enhances orientation. Basically, users and planners have different priorities. Planers work in consensus with functional demands, economic demands, legal framework, technical capabilities, and nature conservation demands. But lighting the city must also take user's point of view into account, not only aesthetics principles, technological possibilities and environmental protection demands. A user profile was set based on psychological priority, sociological priority and aesthetic-functional priority. Six the most important aspects were listed that should also be considered in environmental analysis. Application of user profile provides us useful results. Obtain knowledge can be used as an evaluation tool during a preliminary analysis implementation phase, followed by lighting strategy preparation. It helps to identify the current situation and to respond to users' demands within specific spatial circumstances.

When preparing lighting strategy, it must be clear set for what purposes it is done, who are focused users, and what are their priorities. Otherwise it is not possible to prepare lighting plan. Quality illuminated environments have larger visual potential; they are more attractive and therefore frequently used. Increased lighting intensity can't save spatial problems. We need to be careful not to exaggerate with any of the factors but within reasonable limits.

Luminaries are important design elements, but users do not focus on them. Other environmental factors are more internalized. The research results in case study Maribor city prove that the city lighting is not considered as priority. Desire to feel safe is much more pronounced. The connection between artificial night light and feel safe is not sensed. Of cause lighting optimization increase feeling safe, but there is still no need to exaggerate. Constant illuminated surfaces and areas with detected illumination contrasts are provided with the greatest sense of security [18]. Even low light in the middle of the dark surroundings attracts a lot of attention [18]. The relevance of retained illumination planning is also supported by the fact that the capability to see night sky is expressed as important. Movement mode significantly varies between day and night. Respondents estimate that their route choice varies according to day- and night-time. Movement mode and route choice are a reflection of the individual's lifestyle. Lighting design can only partially influence them in a way to be pointed only there, where we need it, and to be adjusted to particular movement mode on focused area.

Finalized it is work out that Maribor city is one of those cities with low general lighting intensity, but users considered it as satisfying. Nature conservation and economic factors are not discussed in this contribution, but as far as the user is concerned, no great changes are needed.

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Does Pedestrian Useful Visual Field Change At Night?

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***Abstract*— This paper reports an investigation into the shape and size of the useful visual field over which pedestrian visual gaze tends to fall during day and night and discusses the factors affecting useful visual field and the function of peripheral vision. A previous study by authors explored what people look at at night in the streets employing an eye tracking methodology. This study is secondary analysis of the data captured by the previous study. The study shows that street lighting affects and reduces useful visual field of pedestrians and provides guidelines to more effective distribution of light at night based on the optimum pedestrian useful field of view. Our finding emphasises the importance of illuminance on vertical surfaces and hence the for it to be considered when designing light for our streets.**

***Index Terms*—Pedestrian Lighting, Eye-tracking, Useful visual field, Road lighting**

INTRODUCTION

This paper reports the results of a study into the shape and size of the useful visual field over which pedestrian visual gaze tends to fall during day and night. The useful visual field in human vision corresponds to the surface around the point of fixation inside which information can be perceived and processed during a visual task[1]. The following discuss the factors affecting useful visual field and the function of peripheral vision.

A. Useful visual field (UVF):

UVF is the visual area from which information can be extracted without eye or head movements at a brief glance[2]. The size of the useful visual field is not fixed and is generally smaller than the visual field. It can be affected by several factors including peripheral target conspicuity [3]. The size of the useful visual field is critical for the analysis of the environment and depends on the quantity and quality of visual information[4]. The UVF decreases when the quantity of relevant information to be processed in visual field is large[1]. Central and peripheral task complexity, and priority of the central task or the peripheral task can reduce the useful visual field[5-14]. Increased cognitive work load leads to changes in visual scanning patterns and tunnel vision[10]. A tunnel vision phenomenon refers to a situation where the increasing load of the foveal task significantly deteriorates performance on the peripheral task[15]. Its size decreases when the amount of information in the visual field is large[4]. In the case of pedestrians, it is likely when the road scene is complex with numerous vehicles, pedestrians, cyclists, trees and obstacles. Any deterioration of the useful visual field has major consequences for many everyday activities[6].

B. Peripheral Vision and UVF:

Peripheral vision comprises most of the visual field and the collaboration of central and peripheral vision plays an important role in the total performance of human vision[15]. Central vision includes fovea, parafovea and perifovea compromising 18º 20' visual angle (Image 1)[16]. After a potentially informative or visually salient object is located by the peripheral region, the following saccade will be directed to this object for more detailed examination by foveal vision. This is a general principle of visual search and scanning behavior.[17]

The central field of vision has the function of recognition and is more concerned with tasks such as the resolution of fine detail, reading, color perception, or object motion. The peripheral vision plays a dominant role in spatial orientation in the visual system[18]. While reduction of illumination reduces contrast sensitivity and recognition tasks such as reading are

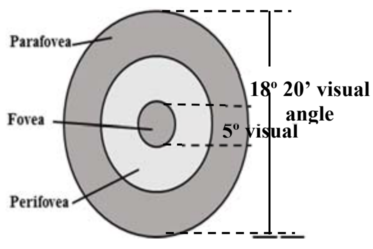

Image 1: Schematic diagram of the macula lutea of the retina, showing perifovea, parafovea, fovea, and clinical macula

impossible under low illumination levels, spatial orientation can be carried out without difficulty under low lighting level[18]. Central field recognition and peripheral field/spatial orientation are also different in the fact that people are typically aware of recognition tasks while spatial orientation is carried out reflexively or with minimal awareness. It can be easily observed in the ability of most individuals to read while walking[18].

Gaze behavior analysis has been used to investigate UVF[3, 19] by examining where car drivers look by capturing the majority of the drivers' eye movements[20]. A previous study by authors explored what people look at at night in the streets employing an eye tracking methodology. That study concluded that not only visual tasks but also reassurance can affect gaze behavior of pedestrians [21, 22]. In their study they showed that when pedestrians are more reassured they spend more time looking at the pavement and when they are less reassured they spend less time on the pavement and more time collecting information from their surroundings. This study is secondary analysis of the data captured by the previous study[20]. In the experiment participants were asked to walk along a residential street following a schematic map to find their way while their eye movements were captured using an eye tracker.

METHOD:

The eye tracking data was collected from two groups of participants walking in a residential area of London during day and night. Pedestrians' eye movements were recorded using a head-mounted eye tracking system. This apparatus has two cameras, one recording the field of view and one following the eye movements of pedestrians. Before each trial the eye tracking system was calibrated by instructing fixation on five distinct points arranged within the visual field (for a fully detailed methodology detail please see [21]). To extract the fixation locations ten still images from every second of video were extracted. The co-ordinates of the point of fixation and the point at eye height on the centre of the footpath, and the angle of tilt of the notional horizon were measured (Image 2). This was a complex task as the video images were not taken in a fixed frame of reference as the subjects turned and tilted their heads as they walked along. A total of 44,528 images were analysed.

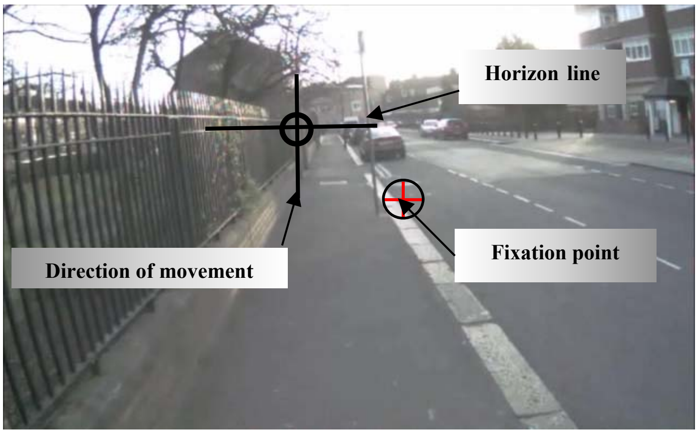

Image 2: The co-ordinates of the point of fixation and the point at eye height on the centre of the footpath, and the angle of tilt of the notional horizon were measure

RESULTS:

From the measured data the angular position of the gaze direction with respect to the axis of travel along the street was measured. The visual field was divided into squares that were 1° by 1° visual angle and it was counted how many times the subjects looked in that direction and thus the percentage of time that subjects spent looking in a particular direction was measured. Figure 1 represents the gaze distribution during day and night.

Comparing the two sets of results, it is clear that during the night pedestrians tend to focus more on what is directly ahead and there is a significant drop in looking to the sides close to the horizon.

Figure 2 shows the distribution of gaze beyond 10º visual angle during day and night. Independent t-test shows gaze distribution significantly drops beyond 10º visual angle at night compare to day time, $t(7781)= 4.031$, $p=0.0001$.

This results suggest that there is information available in the periphery during the day that is not accessible at night. The data has been explored to better understand the nature of the objects/areas fixated during the day in the periphery (beyond 10º visual angle). The results show that the number of fixations is significantly higher on vertical surfaces (73.79%) compared to horizontal surfaces (26.21%). It should be borne in mind that there was an asymmetry in availability of horizontal surfaces on either side of the direction of movement (see Image 3). The right side of the direction of movement had more availability of horizontal surfaces compared to the left hand side. Comparing the number of fixations on horizontal surfaces on the left hand side and right hand side of the direction of movement

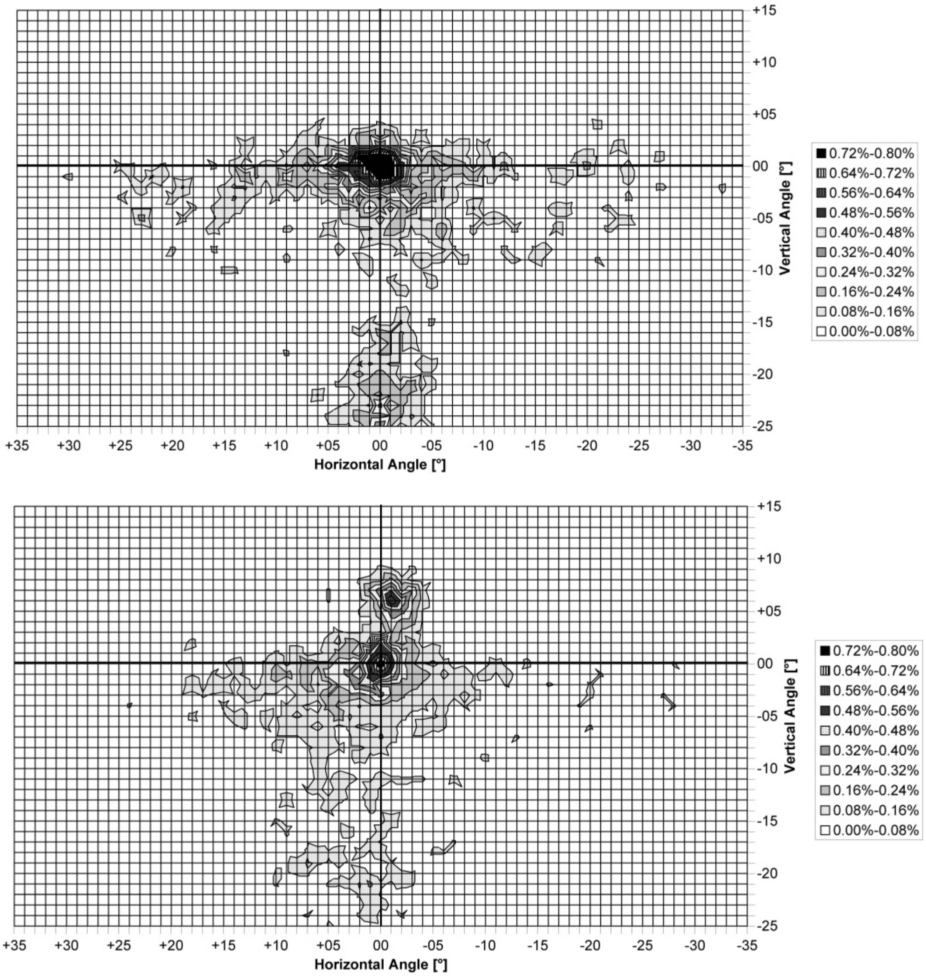

Figure 1: Above: Gaze distribution during day time. Below: Gaze distribution at night time.

shows a significant increase in the number of fixations on horizontal surfaces when there is more availability, p<0.01 (Table 1). As it is known, central vision includes fovea, para fovea, peri fovea and macula which comprises 18º 20' visual angle (Image 1). Therefore, the area beyond 10º visual angle is directly related to peripheral vision of the subjects.

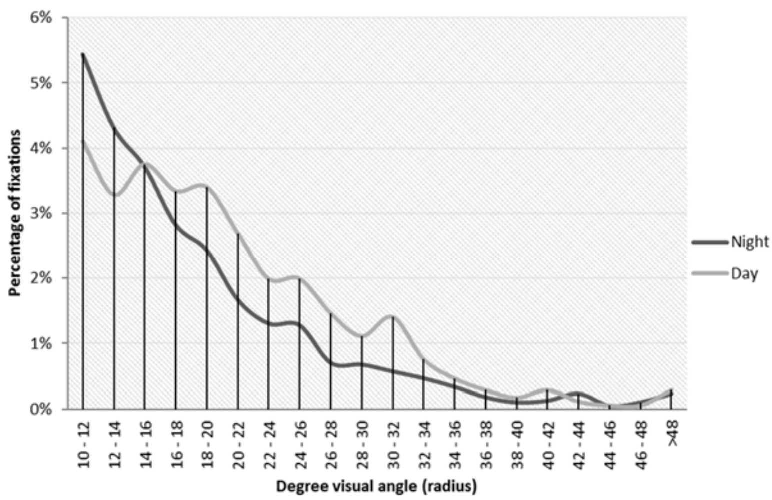

Figure 2: Comparing distribution of gazes between successive fixations beyond 10º visual angle at day and night

Additionally, a study on the objects fixated in the periphery has been carried out. However, the results do not suggest any preference to particular objects. Fixated objects vary from random objects presented in the environment to critical objects such as moving cars and bicycles.

Fixations on	Horizontal surfaces (%)	Vertical surfaces (%)
Right hand side	31.94	68.06
Left hand side	20.83	79.17

Table 1: Percentage of fixations on vertical and horizontal surfaces on both sides of the direction of movement (day time)

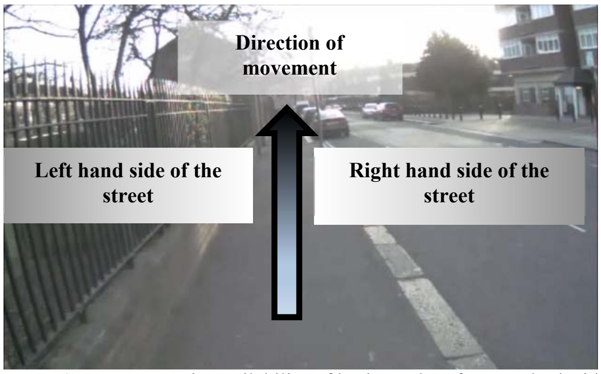

Image 3: Asymmetry in availability of horizontal surfaces on both sides of the direction of movement

DISCUSSION:

The study compared pedestrian UVF during day and night. The results show that the size of UVF has decreased to central vision at night and as a result tunnel vision phenomenon[15] has occurred. Based on the discussed literature three explanations can be proposed on the loss of peripheral information at night:

- Visual saliency of objects reduces at night, so objects do not stand out and capture visual attention and consequently no gaze direction to the peripheral area (reduced UVF due to lower conspicuity of peripheral objects[3]).
- Lower illumination level at night increases the cognitive work load compare to day time and can cause tunnel vision phenomenon (increased cognitive work load leads to changes in visual scanning patterns[10]).
- A combination of both factors.

Whatever the actual explanation it is clear that the UVF at night is smaller than during the day and it would be sensible to assume that daytime conditions represent an optimum lighting condition. It may also be assumed that any change to street lighting to improve the situation should consider providing more light at the point of fixation and more light to vertical targets in the periphery. Figure 3 shows the areas for consideration, each square represents 1° visual angle.

This study of UVF also provides the basis for studying the adaptation level of pedestrians at night as the average luminance of the UVF will be a significant factor in determining the adaptation luminance. The data also suggests that it is mainly vertical surfaces have been attended in the periphery. This is the case for both left and right sides of the street even when the field of view on one side of the road is largely made up of horizontal surfaces. It may be argued that this loss of peripheral vision will affect navigation when walking. Wayfinding also seems to be affected by lighting, it is suggested that subjects tend to select different routes at night. This seems to be mostly due to changes in the perception of space and of known landmarks[23].

It is known that pedestrians' perception of space, fear of crime and wayfinding behaviour change at night mainly due to the lighting conditions in streets[23, 24]. This study aims to better understand the potential information that is lost at night compared to day time which can result in changes of perception of space, reassurance and wayfinding as well as estimating the field of view for assessing adaptation luminance.

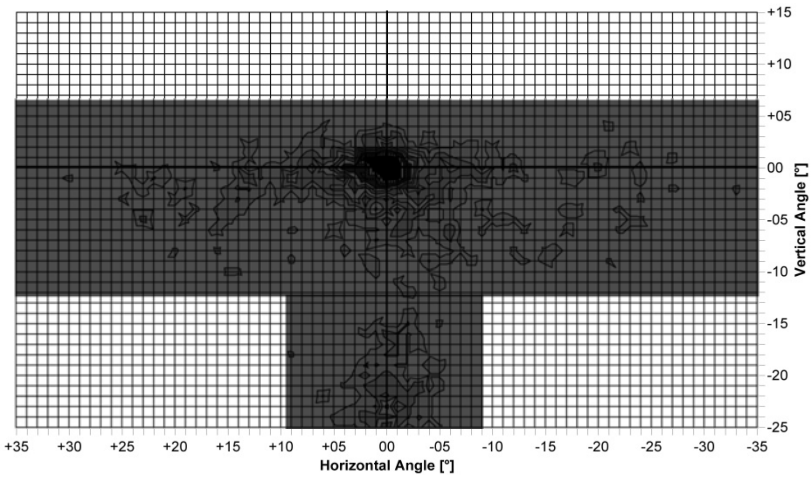

Figure 3: Above: Suggested area of attention for street lighting, each square represents 1° visual angle.

CONCLUSION:

The study shows that street lighting affects and reduces useful visual field of pedestrians. Our finding emphasises the importance of illuminance on vertical surfaces and hence the for it to be considered when designing light for our streets. The need for vertical illuminance on streets is starting to be recognised in lighting standards. For example the recent edition of EN 13021-2 [25] has included the option to require vertical illuminance where the road lighting is being provided to meet the needs of pedestrians and cyclists. Table 2 gives the requirements for the standard. However, the standard only suggests the application of vertical requirements when facial recognition is necessary, the findings of this study would suggest that there would be benefits from using the vertical requirements even when facial recognition was not necessary.

Class	**Horizontal illuminance**		**Additional requirement if facial recognition is necessary**	
	Ē in lxa [minimum maintained]	***Emin in lx [maintained]***	***Minimum vertical illuminance Ev,min in lx***	***Minimum semicylindrical illuminance Esc,min in lx***
P1	15.0	3.00	5.0	5.0
P2	10.0	2.00	3.0	2.0
P3	7.50	1.50	2.5	1.5
P4	5.00	1.00	1.5	1.0
P5	3.00	0.60	1.0	0.6
P6	2.00	0.40	0.6	0.2
P7	Performance not determined	Performance not determined		
a To provide for uniformity, the actual value of the maintained average illuminance shall not exceed 1.5 times the minimum Ē value indicated for the class.				

Table 2. Lighting classes for residential roads

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Does Lighting Affect Pedestrian Flows? a Pilot Study in Lund, Market Harborough and Dublin.

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***Abstract*—A study records pedestrian footfalls in Lund, Dublin and Market Harborough during the day and after dark, either side of the Autumn 2016 clock change, using the change of end of civil twilight time to measure the effect of different lighting levels at the same clock time on footfall rates. Examination of total footfalls on weekdays and at weekends found significant decreases in counts after the clock change, on 5/6 sites on weekdays and half the sites at weekends. Further analysis found that the percentage decrease in the counts in the test period (same time/day of the week, light one week, dark the next) was more than in the control period (same time/day of the week, light both weeks), in 79% of counting sessions. The findings demonstrate higher reduction in footfalls on weekdays in mixed use areas, such as the sites selected in Dublin, and on Sundays in non-central locations.**

***Index Terms*--Accessibility, footfalls, lighting, routes, streets.**

I. INTRODUCTION

Well connected, accessible environments encourage usage, which in turn improves the social and physical health of people in cities [1] [2]. Lighting contributes to the accessibility of streets because it helps pedestrians see their surroundings and other people which informs decision making including routes choices. Route choices are informed by environmental conditions including lighting. City wide street lighting changes tend to be implemented without consideration of the impact on street users. For example, upgrades to LED street lighting luminaires change the night time appearance of many cities due to changes in the distribution and spectrum of light. Lighting control systems which are easy to embed in LED luminaires, permit unprecedented flexibility and have potential to reduce energy consumption at a large scale. Local Authorities must decide when to dim street lighting, without compromising comfort and accessibility.

Whether street lighting changes compromise pedestrian comfort and street accessibility is difficult to prove when pedestrians tread the same familiar daily routes. External lighting may influence route choices [3], [4], as could other physical characteristics such as space configuration, for example how narrow a street is or how many escape routes are visible [5], [6]. Focusing on the details of optimum electric lighting conditions could be premature if familiarity with an environment reassures pedestrians to the extent that other parameters do not matter. Therefore, the aim of this study is to establish whether a change in large scale ambient lighting conditions influences pedestrian flows measured by footfalls. The clock change provides an opportunity to do this, as the same clock time offers daylight and after dark conditions in subsequent weeks. Footfall counts are a simple, quantitative measure of how many pedestrians are using a street. If an overall effect is found, then further research into the effect of electric lighting conditions on pedestrian behaviour after dark, is relevant.

II. METHOD

A. Procedure

Pedestrian movement flow is recorded by counting pedestrians passing through notional “gates” at locations in Lund, Market Harborough and Dublin during five minute intervals. The surveys were completed either side of the clock change in Autumn 2016, so that different lighting conditions at the same time of day could be compared. Footfall sites are sampled on the basis of relative illumination conditions and whether they provide direct or indirect routes to a destination. Two sets of footfalls are compared; (1) Changes in count rates for all footfall data before and after the clock change and (2) changes in count rates before and after civil twilight on specific days. The collection dates and site characteristics are provided in Table 1.

TABEL1 FOOTFALL DATA COLLECTION INFORMATION

City	***Route***	***Abbreviation***	***Route info.***	***Building type on route***	***Minimum illuminance** [a]*	***Maximum illuminance** [a]*	***Pre-Clock Change Dates 2016***	***Approximate time street lighting switched on***	***Post-Clock Change Dates 2016***	***Approximate time street lighting switched on***
Dublin	Kilmainham Rd	D-KL	Indirect & lighter	Housing blocks and shops.	11 lux	25 lux	25/10 26/10 29/10 23/10	18.10hrs 18.10hrs 18.10hrs 18.10hrs	1/11 2/11 12/11 13/11	16.55hrs 16.55hrs 16.40hrs 16.20hrs
	Kilmainham Rd	D-KD	Direct & darker		2 lux	5 lux				
Lund	Monument Park (left)	LL	Lighter	None, green area in residential area.	2 lux	7.8 lux	25/10 26/10 29/10 23/10	18:06 18:04 17:57 18:10	1/11 2/11 12/11 13/11	16:51 16:49 16:32 16:30
	Monument Park (right)	LD	Darker		No lighting.					
Market Harborough	High Street	MH-HS	Indirect & lighter	Mainly shops.	8.7 lux	41.8 lux	23/10 24/10 26/10 29/10	18:15 18:10 17.55hrs 17.30hrs	6/11 7/11 2/11 19/11	16.30hrs 16.20hrs 16:45hrs 16.15hrs
	Adam and Eve Street	MH-AES	Direct & darker		4.2 lux	35 lux				

a. Horizontal Iilluminance at gate

B. *Sites*

Footfall data collection sites were selected in pairs in each city, based on local knowledge of common routes and shortcuts. Each pair is comprised of a lighter longer route and a darker shorter route, except Lund where parallel paths are the same length (270m). Illuminance levels are recorded in Table 1. A visual appraisal of relative lighting conditions was supported by photometric measurements along the routes. Figure 1 shows the gate locations and possible routes pedestrians were walking when they were identified as a count through the gate. In Dublin the two routes provided options for walking between the train station and a residential area. The ratio of one route length to the other was 1.3 (Gate 1 route: 1640m, Gate 2 route 1290m). The Market Harborough site also captured pedestrian flows between a train station and a residential area, however in this case both sites were in the town centre, High Street is a main thoroughfare and Adam and Eve Street, a pedestrianized shortcut. Assuming the same start and end points, the ratio of the longer route (168 meters) to the shorter one (108 meters) was 1.6. In Lund, one path was lit the other was not, in a green area in a residential district. Street lighting switch on times are listed in Table 1.

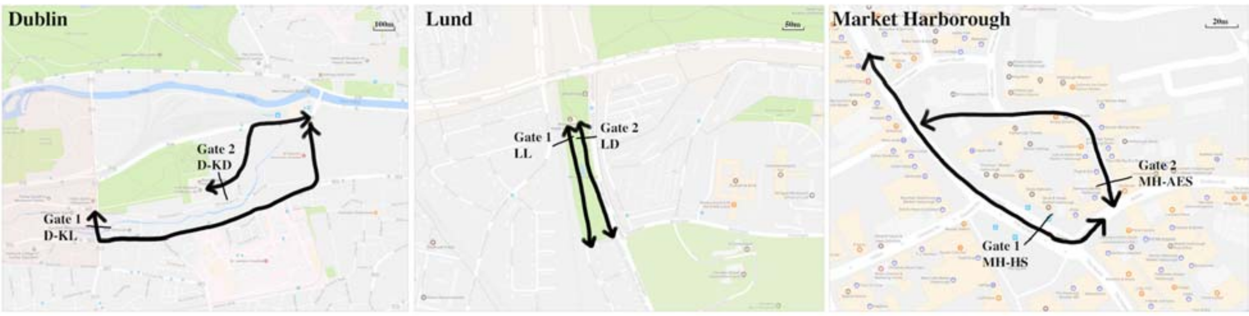

Figure 1. Routes selected for gate locations in Dublin, Lund and Market Harborough. Map data ©2017 Google.

C. *Statistical Analysis of footfall data*

The count rate (i.e. the total number of pedestrian taking a route per unit time) for a particular survey period (typically 3:30pm-6:30pm) were compared before and after the clock change on the same day of the week, for example, Tuesday before and Tuesday after the clock change. The statistical significance in the count rate ratios recorded before and after the clock change were determined by calculating 95% confidence intervals. A comparison was made between the overall footfall rate before and after the clock change. Then count rates for different time periods were compared. The time period of particular interest is the period of time where it was light before the clock change and dark afterwards defined as t2. This is the time after the civil twilight on the survey date after the clock change. The time period where it was light both before and after the clock change was used for control purposes (t1). Figure 2 shows how these time periods are divided.

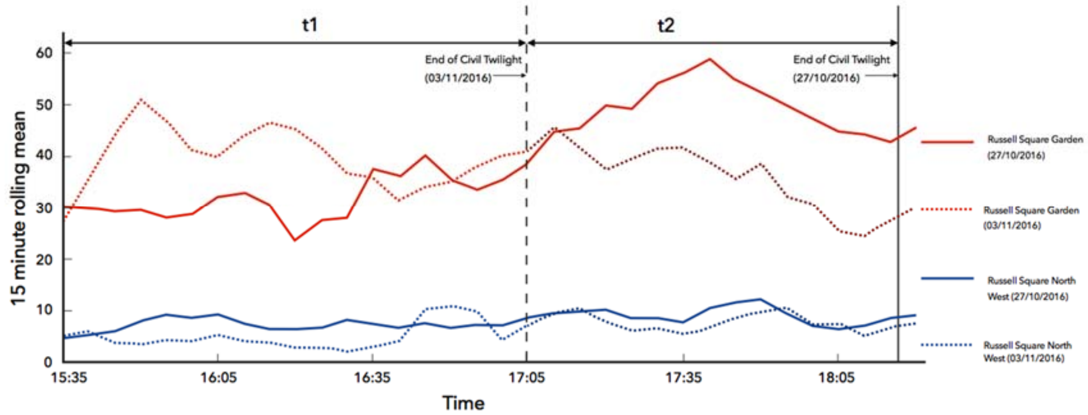

Figure 2. Example of t1 and t2 time split on a pre pilot study site in London.

III. Results

A. Count rates

Figure 3 shows the mean counts per 5-minute interval measured in the afternoon/evening (3:30-6:30pm) for all of the routes reported in this paper. Table 2 shows the number of occurrences in which there were statistical changes in the rates of footfall after the clock change. Rate ratio plots are also shown which includes the 95% confidence interval on these values. This enables us to determine if the rate change is statistically significant. Results are shown for weekdays and weekends for both pre- and post-clock change. The results indicate that, in general, there was a decrease in pedestrian footfall counts after the clock change. On weekdays, 5 of the 6 sites recorded statistically significant reductions (at the 95% confidence level) in the number of pedestrians passing through the gate. The exception was High Street, the busy thoroughfare in Market Harborough. On weekends, reductions in footfall count rates after the clock change were also observed. All the relatively darker route options (Gate 2 at each site) saw statistically significant reductions in footfall counts.

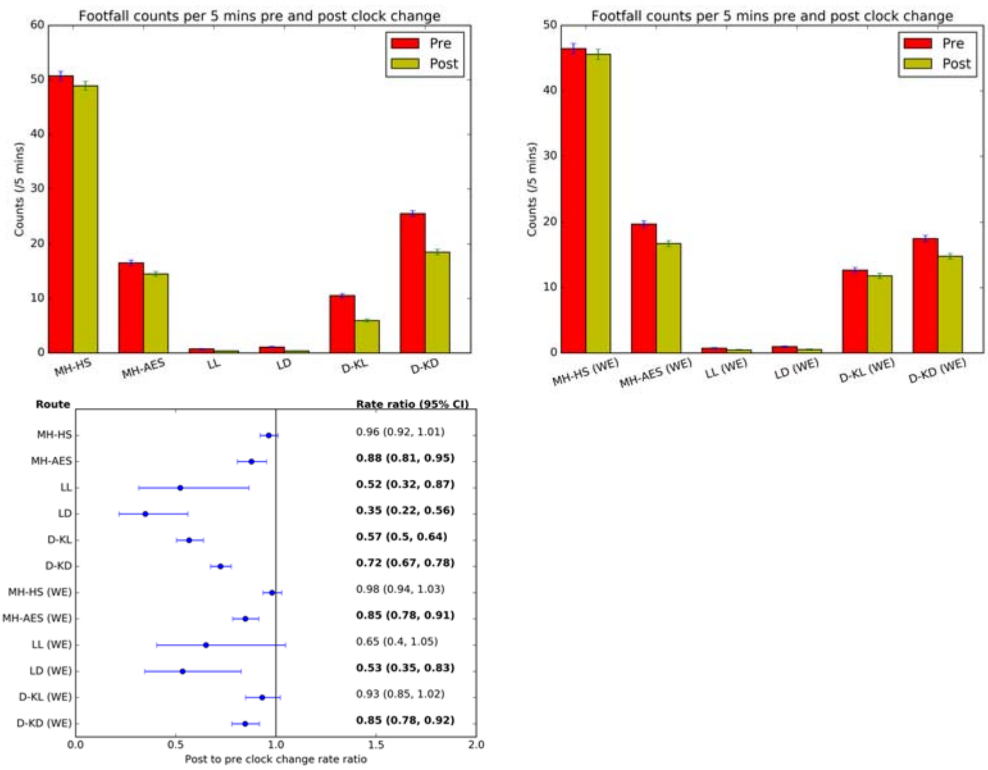

Figure 3. Bar charts showing the mean counts per 5 minutes across all locations pre and post clock change on weekdays (top left) and weekends (top right). Error bars represent the statistical (1σ) error on the count rate. The bottom plot show the ratios of pre- to post- footfall rates for all routes with 95% confidence interval error bars shown.

B. Count rates before and after civil twilight on specific days

This section looks at the count rates for different routes on particular matched days. The time periods, t1 and t2, have been defined in section IIC. Figure 4 plots rate ratios of post to pre clock change in footfalls in t1 and t2 for 24 days across six sites. Sites showing a difference in change rate ratio between t1 and t2, indicate a change in pedestrian behaviour expressed in footfalls, possibly due to lighting conditions. The results indicate that there were statistically significant reductions in footfall count rates after the clock change for 23/48 time periods including both t1 and t2. Data are summarised in Table 2 which reveals that on weekdays there are slightly more statistically significant reductions in footfall counts observed after the clock change in t1 (8/12) compared to t2 (7/12). At weekends, this behaviour changes with fewer footfall reductions in t1 (2/12) compared to t2 (6/12). On closer examination of t1 and t2 at each site, on 18/24 days the post to pre clock change rate ratio is lower in t2 compared to t1, indicating a trend for higher footfall reductions in t2 compared to t1, even if reductions in both t1 and t2 were significant.

TABLE II ROUTES WITH RATE CHANGE AFTER THE CLOCK CHANGE

Number of routes with statistically significant (at 95% confidence interval) rate change after the clock change		
Time period of counts	***Decrease***	***increase***
All weekday	5/6	1/6 (MH-HS)
All weekend	3/6 (All Gate 2)	3/6 (All Gate 1)
Weekday t1	8/12	3/12
Weekday t2	7/12	5/12
Weekend t1	2/12	9/12
Weekend t2	6/12	6/12

Market Harborough had the highest footfalls of the three locations, with mean counts per five minutes ranging from 6 to 112 pedestrians. High Street was the busiest street in this study (Figure 2). Comparisons of post to pre clock change rate ratios in t1 and t2 (Figure 4) shows no effect of lighting conditions at the two sites in Market Harborough on weekdays or weekends, because significant change rate ratios in t2, are almost always matched by significant changes in t1. On Wednesdays (26/10), t1 shows more decrease than t2 at both sites. The Market Harborough routes were centrally located thoroughfares, the darker street was pedestrianized with cafes and small shops. New LED street lighting was installed on Adam and Eve Street before data collection on the 19.11.17., which may have influenced the results. A shop launch on Adam and Eve Street on 2.11.16. between 17-20hrs explains the anomaly in the change rates in t2 MH-AES (26/10 02/11). The inconclusive findings in Market Harborough imply that activities in busy urban environments continue regardless of the lighting conditions on the streets selected for study.

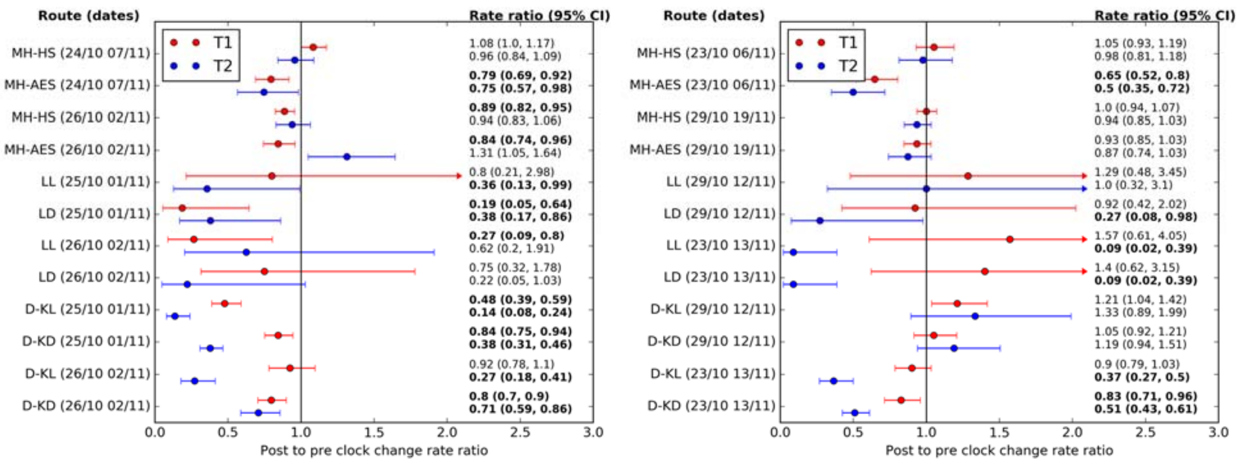

Figure 4. Rate ratios of post to pre footfall during time intervals t1 and t2 for the routes on weekdays (left) and weekends (right). The 95% confidence intervals are indicated. Bold denotes significant decrease results.

The error bars for Lund are long because the counts were low, at mean counts per five minutes of less than two pedestrians. On weekdays, the findings are inconsistent. On Tuesday (25/10/2011), the lighter side of the path shows no change in t1 and a significant reduction in t2. This could indicate the effect of lighting conditions, however on the dark side of the path there was a significant reduction in both t1 and t2, indicating that less people use this side of the path after the clock change regardless of the lighting condition. Wednesdays however, showed no significant change rate except for for t1 on the lighter side of the path. Therefore on week days the effect of lighting conditions on pedestrian flows is inconclusive. Behaviour at the weekend appears different, as on three out of four counting sessions there was no significant change in t1 however in t2 there were significantly less pedestrians. If it is assumed that weekend journeys are more likely to be optional, as less people work at the weekend, then this suggests that the lighting conditions have more of an effect on optional journeys in areas of low pedestrian flows. Optional use of the external environment is more likely to be recreational and recreational use of the environment, particularly green spaces, may influence health and well-being [1].

In Dublin, the change rate is consistently higher in t2 compared to t1, with the exception of Saturdays. Figure 3 shows that the error bars do not overlap for most counting sessions. This implies that the post to pre clock change ratio expressing more of a reduction in pedestrian footfalls in t2 compared to t1, is significant. External lighting conditions could partially explain this behaviour change as could other site characteristics such as the stretches of impermeable wall found on both routes in Dublin. The illumination conditions recorded were slightly lower than the sites in Market Harborough (Table 1).

To summarise, pedestrian behaviour is both location and site specific, and pedestrian route taking decisions can not be isolated from their physical and social context. The study found that there is no effect of the change from light to dark ambient conditions on pedestrian behaviour in centrally located busy areas of Market Harborough, entirely pedestrianised or with wide pavements and where minimum horizontal illuminance is no less than 4 lux. At the other extreme, on quiet paths with few people, external lighting conditions seemed to influence only weekend journeys, perhaps recreational in nature. Mixed use urban areas such as those in Dublin, with a combination of residential blocks and shops along the routes and pedestrian flows of less than a mean of 30 per 5 minutes were the only areas where weekday pedestrian flow patterns could have been affected by ambient lighting conditions.

IV. CONCLUSION

Overall there are less people walking outside after the clock change, regardless of the lighting condition. This could imply that the fact the days are shorter deters people from going out, even before sunset. This study demonstrates that the relationship between lighting conditions and pedestrian behaviour is not easy to predict, however the following would be worth further investigation:

- Minimum acceptability in busy areas. As pedestrian may be reassured by hustle and bustle, explore how lighting load can be reduced in these areas, without compromising comfort and accessibility.
- Whether green spaces in quiet residential areas would be used more, if they were lit. Or whether the effect of shorter days, and the fact that people seem less willing to out after dark, would render this as energy wastage.
- The influence of spatial characteristics and land usage, for example the change in perception of mixed use areas after dark and the effect of long walls and wide roads on pedestrians' perceptions. The presence of other people in the environment, may matter to reassurance than illumination conditions alone, which means that lighting environments which reveal people may be important.
- To answer the question which forms the title of this paper, external lighting conditions seem to affect pedestrian flows in some places and at some times in the weeks before and after the clock change on the selected sites between 15:30-18:30hrs. Further work should compare dark conditions before and after the clock change to each other, as it may be that later on, when in most areas there are less pedestrians overall, change rates are more variable. This paper reported a pilot study. Further work can take these findings to design studies to explore specific conditions in which lighting conditions can improve accessibility and comfort. This can be used to inform Local authority decisions on when dimming is acceptable and how to light environments efficiently without compromising on comfort.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the contributions of Dr Ruth Kelly who identified sites in Market Harborough and completed the data collection with Mr Rony Thomas. Professor Thorbjörn Laike identified sites and organised the data collection in Lund, as did Mr Antonello Durante in Dublin. Mr Peter Raynham was instrumental in establishing a network of collaborators at the start of the study. This work would not have been possible without their valued contribution.

The findings reported here are part of wider study. Contributers to the wider study are Dr Diana Del-Negro (Lisbon), Dr Andreas Krensel and Mr Behzad Samani (Berlin) and Mr Michael Lyons (Peterborough). Full findings will be reported in due course. This work was funded by EPSRC grant 75552: Do external lighting conditions affect pedestrian movement? An epidemiological study. UCL Future Leaders in Engineering and Physical Sciences: Pump-priming and feasibility studies.

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Office Lighting Hierarchies – Lit Surfaces Contributing to Visual Appearance

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***Abstract*—This work investigates the effect of different parameters used in lighting design on the visual appearance of a typical cell office space. The experiment with 68 participants was conducted in a laboratory space where lighting parameters could be changed independently. Results showed a different impact of different surfaces on visual appearance ratings. While walls and ceiling had a large effect size, workplane illuminance in areas surrounding the desktop in comparison showed smaller effect sizes and far less pronounced results. The luminance of the desktop showed an interaction effect with vertical luminances but had no significant effect of its own. The results of this work can help to better understand how lighting on different surfaces in a space affects the visual quality of the space.**

Index Terms--Lighting Hierarchies, Lighting Quality, Office Lighting, Visual Appearance

Motivation & Research Question

Current standards and recommendations for office lighting design mainly aim at glare-avoidance and work plane-based horizontal illuminance levels. Changing office landscapes in combination with flexible working schemes have extended the focus here lately to additional functions such as support for health, wellbeing and aesthetic appearance.

Research has shown that many additional lighting parameters have an effect on the visual appearance of a space. This work investigates the research question how lighting on different surfaces within a typical cell office space contributes to the way the space is perceived by its occupants. Surfaces considered in this work are walls, ceiling, desktop and the workplane surrounding the task area.

Research Design

The research took place in the custom made cell office lighting simulator at TU Berlin as introduced in [1]. The laboratory's design enabled an adjustment of independent variables in a way that changes in one variable (e.g. increased wall luminance) did not affect all other independent variables (e.g. surrounding area illuminance) due to different possibilities of local adjustment.

The experiment was conducted as a 2 x 3 x 4 repeated measures design with two levels of desktop luminance, three levels of surrounding area illuminance and 4 levels of walls and ceiling luminance (cf. table I).

TABLE I. Independent Variables Presented in this Experiment

	Variable		
	Desktop Luminance $L_{Desktop}$	***Surrounding Area Illuminance E_{Sur}***	***Walls and Ceiling Luminance $L_{walls/ceiling}$***
Range	60cd/m^2, 95cd/m^2	100lx, 200lx, 300lx	11cd/m^2, 30cd/m^2, 50cd/m^2, 75cd/m^2

Dependent measure was the 'room appearance judgement' questionnaire introduced by Veitch and colleagues [2], (cf. table II). A subsequent principal component analysis suggested a two factor structure matching the components found in [2].

TABLE II. DEPENDENT MEASURES

Items		
negative	***positive***	***factor***
unattractive	attractive	visual Attractiveness
ugly	beautiful	
unpleasant	pleasant	
dislike	like	
cheerful	sombre	
vague	distinct	visual Lightness
dim	bright	
gloomy	radiant	

68 participants (55% female, 45% male, age 21-47 years) successfully finished the experimental session.
Each session started with two randomized anchor scenes to determine the range of variables presented throughout the experiment. All lighting scenes were then presented in randomized order, responses to the questionnaire were recorded electronically.

RESULTS

Statistical evaluation of responses showed significant effects of walls and ceiling luminance on visual appearance with large effect sizes. Brighter walls and ceiling resulted in significantly higher ratings for both factors. Pre-planned comparisons (repeated contrasts) revealed that effect sizes were largest for changes from 11cd/m^2 to 30 cd/m^2.

Changes in illuminance around the task area also showed a significant effect. However, contrast analysis revealed that differences were only present for certain illuminance levels. Also, only the visual lightness component showed significant effects, ratings of visual attractiveness were not affected by changes in surrounding area illuminance. Effect sizes were considerably smaller than for the effect of walls and ceiling illuminance.

The effect of the luminance of the desktop was non-significant, while the interaction between desktop luminance and walls and ceiling luminance was significant with medium effect sizes.

DISCUSSION

The results of this experiment showed the expected results concerning the luminance of walls and ceiling. Higher vertical luminances resulted in a brighter and more attractive space.
Curve estimation models correlating results with photometric parameters showed high coefficients of determination (R^2=.84 for visual lightness, R^2=.84 for visual attractiveness) when human responses were calculated as a power function of the average luminance in a 40° horizontal band as proposed by Loe, Mansfield, and Rowlands [3].

Further analysis showed an average luminance of about 35-40 cd/m^2 as the tipping point where responses changed from negative appraisal to positive for the components considered in the survey. This is in good accordance with other research on the matter [3]–[5], where a luminance in the same range was found to be the point where appraisal changed from dark to bright and from unattractive to attractive.

The effect of surrounding area illuminance was statistically significant. However, the effects were smaller than for vertical illuminances. Further investigation revealed that while changes in the perception of visual lightness were statistically significant with small to medium effect sizes, visual attractiveness stayed unaffected by changes in illuminance around the task area.

Interestingly, while the average luminance in a 40° horizontal band was found to be a crucial factor for visual appearance ratings, the same was not true for the luminance of the desktop. Although making up about 10%-15% of the 40° band, changes in average luminance caused by changes in desktop luminance did not lead to significant changes in visual lightness or visual attractiveness ratings.
Ratings of visual lightness and visual attractiveness were significantly higher for the brighter desktop when walls and ceiling were relatively dark. The effect was reversed for brighter room surfaces where the darker desktop was rated as lighter and more attractive when walls and ceiling luminances were in the high end of the range presented here.

All results show that a perception based model for the visual appearance of an office space has to consider more than just a horizontal illuminance approach. While certainly crucial for task performance, there are other factors to consider when designing light and attractive spaces. Lighting design should include vertical luminances as well as the varying impact of different room surfaces. While walls and ceiling play an important role in lightness and attractiveness responses, other surface luminances (e.g. the desktop) seem to interact with other surfaces while not showing significant changes on their own.
Thus, a careful application this hierarchy of surfaces can be used to design high quality luminous environments in an energy efficient way.

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Digital Lighting: a Macro-Economic View

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***Abstract*—Light has always been an important contributing factor to the quality of life and productivity of human kind. Lighting has always had significant part in the economy, roughly 1.7 per cent of GDP. In 2013, 17-19% of electricity was used to generate light.**

LEDs, smart lighting and associated digital technologies promise increasing performance and efficiency on micro applications level. If we simply sum-up those savings, it concludes in proportional decrease in global need of electrical energy used for generating lighting.

However, the historical tendencies suggest a different trend. In the last three centuries, the decreasing cost of ownership of light resulted in increasing demand of it.

In this paper, first I overview recent macro-level studies of historical and contemporary consumption pattern and extrapolations of past behaviour into the future.

The second part of the paper will collect technology and socio-economic trends which can influence the projection originated in historical. Technology trends include technics improving quality and timing of lighting applications, as well as potential value added services associated to lighting applications. Socio-economic trends will cover projected population, urbanization trends, changes in the way of use of offices, workplaces, residential buildings, and public places. Increasing number of regulations, standards and guidelines are also intended to influence the pattern and amount of light used globally.

***Index Terms*-- Energy Efficiency, Global Economy Trends, Use of Light, Regulations**

INTRODUCTION

When technology evolves so rapidly as it does in lighting industry nowadays, the importance of forecast has never been more important. Traditions of 100+ years can sink in a short year, thousands of skills need to be converted within months and vital business decisions must be taken in days. That is why so important to understand the nature of the forecasts, the facts (and assumptions) behind them and limitations of their use. Due to the limited volume of a conference paper, this evaluation cannot be comprehensive, but may give a kick-off and keep thinking of it day by day.

HISTORICAL AND CONTEMPORARY CONSUMPTION PATTERN OF LIGHT

A. Historical Patterns

Technologies for more-efficient production of light evolved spectacularly during the last three centuries. However, consumption of light follow it proportionally. This evolution is illustrated in Figure 1, which shows a 5-order-of-magnitude increase in the consumption of artificial light over the past three centuries in the UK[1].

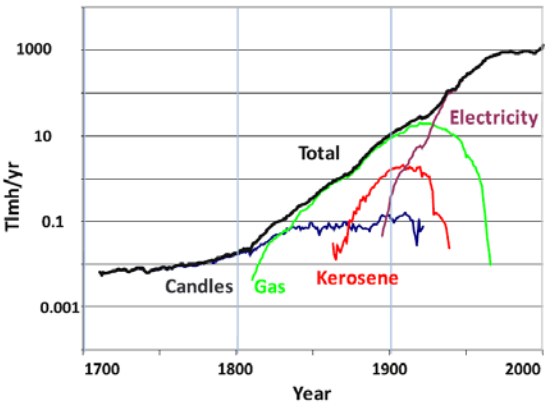

Figure 1. Three centuries of light consumption in the UK, adapted by Tsao [2] from Fouquet and Pearson [1]. The left axis has the units Tlm h/yr (teralumen-hours per year). The colored lines represent consumption of light produced by technologies powered by different sources; the black line represents total consumption of light produced by all technologies.

A recent comprehensive study [2] of historical and contemporary consumption of light found that empirical data, drawn from a wide range of sources were consistent with a per-capita consumption of light that is proportional to the ratio between per-capita gross domestic product and cost of light:

$$\varphi = \beta \cdot \frac{\text{gdp}}{\text{CoL}}. \tag{1}$$

ϕ is per-capita consumption of light, in Mlmh/(pers-yr) (megalumen-hours per person-year);
gdp is gross domestic product per capita, in \$/(pers-yr) (dollars per personyear);
CoL is the ownership cost of light in \$/Mlmh (dollars per megalumen-hour);
β = 0.0072 is a fixed constant

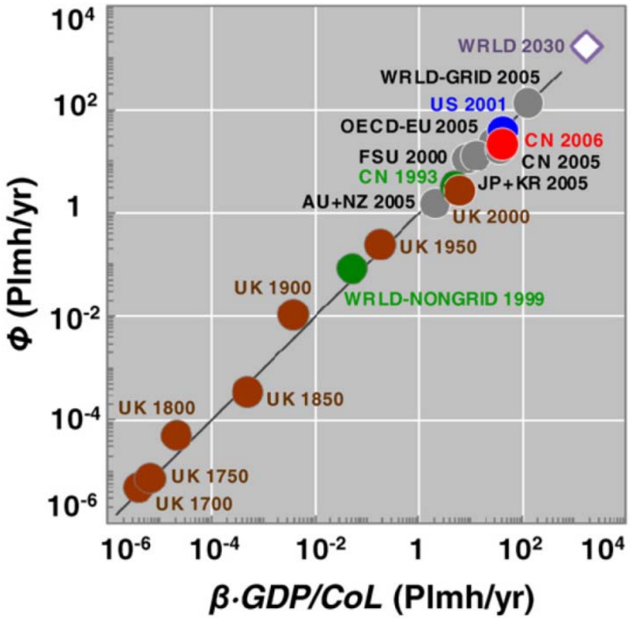

Figure 2. The consumption of light plotted against β · GDP/CoL, [2] Both in units of petalumen-hours per year. The relationship is the same as that of equation (1), except total rather than per-capita units are used (i.e. the left and right sides of those equations have been multiplied by population, N. The filled circles are data points that illustrate the relationships represented by equation (1).
The nation abbreviations are US = United States; CN = China; UK = United Kingdom; FSU = Former Soviet Union; OECD-EU = Organization for Economic Cooperation and Development Europe = Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, UK, Ireland, Greece, Portugal, Spain, Hungary, Poland, Czech Republic, Slovak Republic, Turkey, Iceland, Luxembourg; JP + KR = Japan + South Korea; AU + NZ = Australia + New Zealand; WRLD = World; WRLD-NONGRID = World not on grid electricity; WRLD-GRID = World on grid electricity. The diamonds represent the consumptions of light and energy projected for the world in 2030, assuming the evolution and market penetration of SSL, and a business-as-usual cost of energy.

B. Governmental Forecasts

The DOE report of *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications* [3] estimates the energy savings of LED white-light sources over a period of 2013 to 2030. With declining costs and improving performance, LED products have been seeing increased adoption for general illumination applications. This is a positive development in terms of energy consumption, as LEDs use significantly less electricity per lumen produced than most traditional lighting technologies. LED lighting is projected to achieve a market share of 84% of lumen-hour sales in the general illumination market by 2030, reducing lighting energy consumption in that year alone by 40%, see Figure 3.

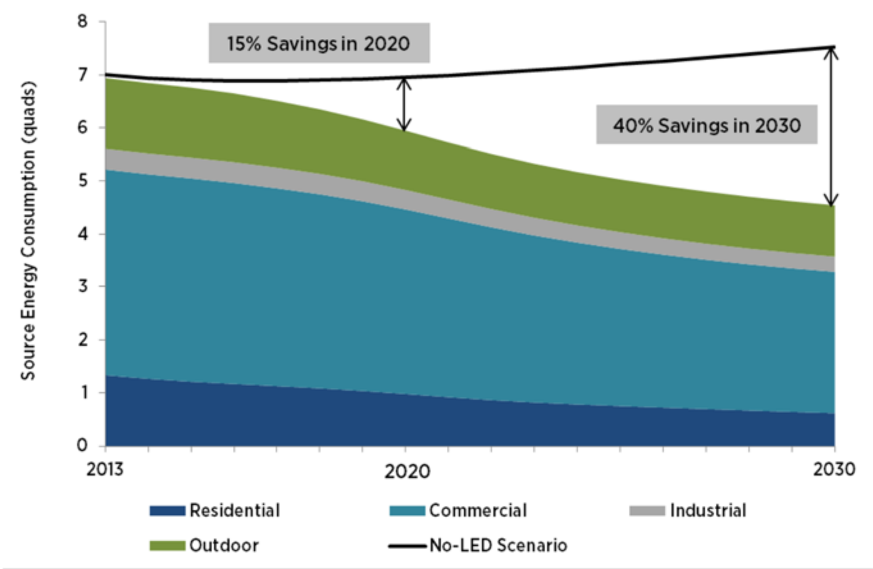

Figure 3. Total U.S. Lighting Energy Consumption Forecast, 2013 to 2030, assuming 84% LED penetration based on in lumen-hours. One quad is approximately equal to 293 TWh (terawatt-hours).

However, this report assumed constant lumen demand per square foot of floor space in each sector, projections also suggest that residential floor space will increase by an average of 1.31% per annum, and the commercial sector floor space will increase by an average of 1.00% per annum. Similar forecasts are available for other economical regions like EU, India. The common conclusions of those forecast are that significant energy-saving is expected by penetration of LED technology on applications level and those savings are just summed-up for sectors considered. This is seemingly in contradiction with the projection of Tsao at all [2] made for a global perspective.

REASONS FOR GAP IN FORECASTS

A. Increased Consumption of Light

All those governmental projections, however, share a common assumption: that consumption of light is insensitive to the cost of light, the increased efficiency in lighting technology and decreased cost. This will lead to a decrease in the consumption of energy rather than an increase in the consumption of light. This assumption has not been proved, even there are clear sign for the opposite tendencies.

1) Road lighting

In running streetlighting reconstruction to LED, it is common to change traditional luminaires to LED ones with a significant energy saving of 50% as an average, supposing that luminous flux of the luminiares unchanged. However, lighting levels defined by road lighting standards are not always respected by old installations. The new installations should pass rigorous approval process, including lighting levels. A short survey on recent 5 Hungarian road lighting reconstruction shows, that new installation requires 10% more luminous flux on application level to be able to meet current lighting requirements. The same survey also showed that surveys before street lighting reconstruction also discover sections of the streets where new lighting points are needed. This is justified by either the lack of uniformity or just simply by new pattern of road usage, where there had not been lighting before. As an average the number of lighting points is 10% more compared to pre-reconstruction level. The two effects above usually inflate the saving by 20%.

2) Resindential lighting

Although the primary demand for light is to illuminate our environment for visual acuity, there are many other features of light that are important to the consumer.

One of those features is real-time control of wavelengths and intensities. It is possible to tailor the spectral match to those (retinal and non-retinal) components of the human photoreceptor system responsible for circadian, and seasonal regulations. According to our current knowledge, the lighting levels for some of the non-retinal responses (like curing sesonal depression by light) are much higher than levels for visual acuity. That is definitely will increase demand for light both in intensity and duration.

Another potential feature is real-time control of the placement of light by either shaping the array or changing the intensity of light sources in different locations. Traditionally, a residential room had two positions of light sources: One in the middle of the ceiling for general lighting of the space and another for task lighting (undercabinet lighting in the kitchen or reading light in bedrooms). Due to the compactness, easy installation and decreasing cost of the new SSL sources, the number of lighting points are already increased significantly and we cannot see the end of this trend.

g. *Lights for Signalling and Data Transfer*

i. Companies are working to unleash the ultimate living experience through a suite of connected products designed to make our life simpler and help us do more. A contemporary LED table lamp that embeds voice service directly inside, allowing users to use a table lampt to order dinner, listen to the latest headlines, preheat your oven or give a host of other voice commands. This is still a table lamp. Where the 24/7 consumption is counted for? Lighting? Communication? Entertainment?

ii. LI-FI: Various researchers and companies are betting light waves from LED lamps and overheads can also stream data and connect people to the internet 100 times faster than current technologies. Li-Fi technology, which uses a much more abundant slice of the wireless spectrum, is also more energy-efficient than Wi-Fi. Light waves can't pass through walls like radio waves do, but that also makes the networks more secure. The world's largest technical association, IEEE, plans to have a draft standards for Li-Fi ready by end of 2017.[4] Companies are eager to commercialize the technology. Where the 24/7 consumption of LI-FI is counted for? Lighting? Communication?

h. *World Urbanization Trends and Lighting*

Globally, more people live in urban areas than in rural areas, with 54 per cent of the world's population residing in urban areas in 2014. In 1950, 30 per cent of the world's population was urban, and by 2050, 66 per cent of the world's population is projected to be urban.[5] The significantly more extensive use of light by urban population compared to rural one is dominant. There are several efforts are underway at various institutions to produce globally comparable estimates of the urban population with uniform criteria to define urban areas based on satellite imagery of night-time lights. Another study from Mellander at all [6] suggests that night-time light may be a better proxy for the degree of urbanization. Despite of the urbanization trends, and their clear correlation to increased amount of light produced, this effect is not considered by most of the governmental forecasts for lighting needs.

i. *Human Centric Lighting*

There are plenty research activities proving the benefits of human-centric lighting. When research yields these results, it stands to reason that majority of (wealthy) houses, schools, hospitals, offices, factories and other building owners will be outfitted with Human Centric Lighting. Tangible and intangible benefits in productivity, health and wellbeing would far outweigh the additional costs, energy efficiency and energy consumption concern.[7] It will work as a drug and it will cost as a drug. The important conclusion regarding this paper is that lighting refurbishment will break out of the vicious cycle of energy efficiency and energy saving and will end up increased spending on lighting both in CAPEX and OPEX.

SUMMARY

The list of conflicting trends is far from completeness. However, the already listed trends clearly proved that forecasts of energy consumption used for generating light made on micro application level, cannot be simply scaled up proportionally to macro-economic levels. Lighting has several additional layers and influential factors as social life, economic growth, improvement in productivity, influence on health. Emotions are also difficult to predict. Human factor has been always played a significant role in choice of level, pattern, colour quality and time of lighting.

I hope, this paper helped the readers with opening their perspective and gave a balanced view about the future of light and lighting industry.

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Decision Schemes for Lighting Controls-How to Apply the CIE TR 222

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***Abstract*— In early 2017 CIE has published the technical report 222: Decision Scheme for Lighting Controls in Non-Residential Buildings and stated: "This report offers guidelines in order to balance lighting quality, user comfort and energy efficiency in lighting controls solutions for lighting in non-residential buildings (i.e. for commercial, institutional and industrial buildings). It provides a decision scheme with a focus on the user requirements (visual comfort, performance, personal control) to determine the most applicable control solution, including the consequences for possible savings. In this, it assumes that there are no technological or financial hurdles. The decision scheme identifies 16 possible control strategies, for both daylight and electric lighting, and provides guidance for which strategy would be most effective in each of the 12 cases defined by space usage and occupancy."**

***Index Terms*—Energy_efficiency Lighting_controls Lighting_quality User_Acceptance**

IDENTIFICATION OF LIGHTING CONTROL STRATEGIES

The technical report on decision schemes for lighting controls was worked out by numerous experts. It starts with the identification of control strategies. The driving factor is very often energy efficiency. But by using controls also a higher lighting quality can be expected. A critical factor is the user acceptance. The use does not only cover the design but also the installation and the operation of the lighting and its controls. To say in short: if the user does not understand the system, and lighting is doing unexpected things the user might feel uncomfortable or disturbed.

We identified the following reasons for using lighting controls:

- Make use of potential energy savings
  (e.g. occupancy sensing, daylight harvesting, time scheduling, demand response).
- Improve user satisfaction, mood and performance
  (e.g. personal control, daylight glare control, user demand control, algorithmic stimulation lighting).
- Support building appearance, ambience and company image
  (e.g. scene setting).
- Increase safety
  (e.g. when the lighting control system offers emergency lighting, or the lighting prevents feelings of danger or uncertainty, for example through occupancy sensing).

The control strategies were investigated. A large number of references were surveyed. The major applications are non-residential indoor facilities like offices, warehouses, hotels, educational buildings, retail facilities, hospitals and public assemblies.

The very essential content of the report is table 6 which identifies the strategies for lighting controls with regard to the potential influence on energy efficiency, lighting quality and user acceptance.

In another table of the report the impact of lighting controls is explained. The impact on energy efficiency, lighting quality and user acceptance might by low, medium or high or there might be none impact. It is essential to provide a common understanding of these items.

TABLE 1: – 16 IDENTIFIED STRATEGIES FOR LIGHTING CONTROLS BY CIE TR 222 (TABLE 6)

Strategies of lighting controls	**Explanation**	**Potential positive influence on energy efficiency**	**Potential positive influence on lighting quality**	**Potential positive influence on user acceptance**
1 - Personal (switching, dimming, manually on / off)	Most simple control, using switch or dimmer; conscious user expected	Medium Working light simply often forgotten	High Offering personal autonomy	High Offering personal autonomy
2 - Daylight harvesting (switching, auto off, auto on)	Switching at a limiting value, measured by a daylight sensor	Low, except in spaces with high daylight provision No dimming savings up to limiting value	Small Lighting levels are fulfilling requirements	None Sudden switching is disturbing. User cannot adjust the system.
3 - Daylight harvesting (switching, auto off, manually on)	Switching off when daylight reaches the limiting value, measured by a sensor, switching on by the user	Medium Saving when user switches on late	Small Low lighting levels might be accepted for a longer time period which might affect visual fatigue and performance. Personal control allows for adjustment of the lighting.	Small Sudden switching off is disturbing, but personal control over the light. User has to switch on the light.
4 - Daylight harvesting (dimming, auto off / on),	Dimming to combine daylight and artificial light to a predefined lighting level measured by a sensor	High Adding only artificial light to keep the limiting value	Small Lighting levels are fulfilling requirements	Small Constant lighting level is not the expectation of most users. User cannot adjust the system.
5 - Daylight harvesting (dimming, auto off, manually on)	Dimming down according to daylight availability measured by a sensor, dimming up by the user	Very High Savings when user dims up late	Small Low lighting levels might be accepted too long, personal control	Small-High Automatic saving, offering personal control over the light. User interaction is necessary, but not always desired.
6 - Occupancy sensing (presence detection: auto off / on)	Lighting on or off when a person enters or leaves the field of a sensor	Low - High Only light when the space is occupied. Low savings in applications with high occupancy (e.g. multiple occupants, specific job functions)	Small No influence	Small No awareness of the user if properly installed and delay times are chosen appropriately
7 - Occupancy sensing (absence detection: auto off, manually on)	Lighting off when person is leaving, but switching on by the user	Very High Only light when the space is occupied, the user will not always switch light on when entering the room	Small No influence	Small - high User might appreciate personal choice, but user interaction is necessary, and not always desired
8 - Constant light control	Output of luminaire is automatically kept on a constant level	Medium Initial lumens dimmed to a maintained level	Small Lighting levels are fulfilling requirements	Small Not visible to the user
9 - Tuning	Over-specified lighting installations are dimmed down to reduce energy consumption while still provide required lighting levels with reduced energy consumption	High Over installed installation dimmed to a maintained level	Small No influence, lighting levels are fulfilling requirements	Small Not visible to the user
10 - Load shedding, or demand response	Automatic reduction of energy demand by an external signal	Low Saving when needed, on single days, to last for a few hours at most. Overall energy savings are low, but immediate reductions in peak demand can be critically useful to electrical system stability and cost	None Temporarily lighting falls below necessary levels	Small General acceptance for externally induced need for electricity savings, user acknowledges savings
11 - Time scheduling	Time setting of predefined scenes or time based on and off	High General switch off saves unneeded or forgotten lighting	Small No influence	Small User acknowledges savings
12 - Task demand control (manual)	Lighting (including blinds) adjusted to the actual task or demand by the user	Medium First priority for task and environment	High Different demands in lighting available	High Most acceptance as immediate personal control

Strategies of lighting controls	**Explanation**	**Potential positive influence on energy efficiency**	**Potential positive influence on lighting quality**	**Potential positive influence on user acceptance**
13 - Algorithmic Lighting	Automatic changing of lighting (e.g. level or colour temperature) according to predefined rules	Medium When energy optimization is a target	High Fits to different purposes as well as health issues. Current knowledge supports improved fit of lighting to immediate needs. With increased understanding, it has the potential to support occupant health and well-being as well.	High Motivation and positively influencing people
14 - Scene setting	Setting of predefined static or dynamic lighting scenarios, to create different atmospheres	None	High Fits to different purposes as well as health issues	High Motivation and positively influencing people
15 - Daylight glare control (manual)	Control of incoming daylight by adjusting blinds manually by the user	None No optimization, reduced daylight usage when user adjusts glare control late	High Reduces disturbances by brightness of daylight	High Direct personal control appreciated
16 - Daylight glare control (automatic)	Automatic control of blinds to reduce glare and heat, sensor necessary	Medium Usually fit to optimize lighting and thermal comfort	High Controls disturbances by brightness of daylight	Small - high Appreciated by user when manual control to override is available

APPLICATION OF THE CONTROL STRATEGIES

The single lighting control strategies were evaluated for the use in different applications. F.e., there is a different influence of strategy 6 or 7 "occupancy sensing" in open plan offices and in corridors. Daylight availability and rate of occupancy have an influence. The impact on EE (energy efficiency), LQ (lighting quality) and UA (user acceptance) vary between "none" and "very high".

Occupancy sensing in a daylit open-plan office with high occupancy has no influence (table 9 in TR 222) while in a non-daylit corridor with low occupancy it has an high impact on energy efficiency (table 15 in TR 222).

The extensive evaluation was carried out for twelve applications (in tables 7 to 18 in TR 222).

Table 7 – Lighting controls evaluation for owned, small rooms for one to two people

Cellular office, hospital bed sitting room, small workshop, consulting room

	Strategy of control		Daylit						Non-Daylit					
			High occupancy			Low occupancy			High occupancy			Low occupancy		
			EE	LQ	UA	EE	LQ	UA	EE	LQ	UA	EE	LQ	UA
Owned: small rooms for one to two people	1 - Personal	switching, dimming , manual	M	H	H	M	H	H	M	H	H	M	H	H
	2 - Daylight harvesting	switching, auto off, auto on	L	S	None	L	S	None	-	-	-	-	-	-
	3 - Daylight harvesting	switching, auto off, manual on	M	S	S	M	S	S	-	-	-	-	-	-
	4 - Daylight harvesting	dimming, auto off, auto on	H	S	S	H	S	S	-	-	-	-	-	-
	5 - Daylight harvesting	dimming, auto off, manual on	VH	S	S-H	VH	S	S-H	-	-	-	-	-	-
	6 - Occupancy sensing	auto off, auto on	-	-	-	L-M	S	S	-	-	-	L-H	S	S
	7 - Occupancy sensing	auto off, manual on	-	-	-	VH	S	S-H	-	-	-	VH	S	S-H
	8 - Constant light	automatic dimming	M	S	S	M	S	S	M	S	S	M	S	S
	9 - Tuning	automatic dimming	H	S	S	H	S	S	H	S	S	H	S	S
	10 - Load shedding	automatic dimming	L	None	S	L	None	S	L	None	S	L	None	S
	11 - Time	automatic switching, dimming	H	S	S	H	S	S	H	S	S	H	S	S
	12 - Task demand	manual dimming	M	H	H	M	H	H	M	H	H	M	H	H
	13 - Algorithmic lighting	automatic dimming, switching	M	H	H	M	H	H	H	H	H	H	H	H
	14 - Scene setting	automatic dimming, switching	None	H	H	None	H	H	None	H	H	None	H	H
	15 - Daylight glare	manual	None	H	H	None	H	H	-	-	-	-	-	-
	16 - Daylight glare	automatic	M	H	S-H	M	H	S-H	-	-	-	-	-	-

Note: Potential positive influence: L – low, S – small, M – medium, H – high, VH – very high, ■ = not applicable
Strategy: EE – Energy efficiency, LQ – Lighting quality, UA – User acceptance

Figure 1 – Screen shot of one of the tables in TR 222

When looking into the tables a decision maker will identify for which situation in which application a lighting control has an high or even a very high impact. It shows also where the impact might be rather depreciable. The higher the impact the more suitable the control strategy is. The tables provide a good navigation for the decision for lighting controls.

ACKNOWLEDGEMENT

The author expresses grateful thanks to all the active members of the technical committee TC 3.49 in CIE. Very special thanks go to Martine Knoop from the Technical University of Berlin who acted as the secretary of the committee and to Peter Zwick, Technical Manager of CIE, for their tremendous support in providing this report.

We hope that the report will be widely used and help many decision makers to find the appropriate lighting control.

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Indoor Lighting Design with Included non-Image Forming Effects

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Abstract— **Effects of different concepts of internal environments design in terms of materials and colours have been compared in this study. Image forming effects modelled in Dialux have been upgraded to estimations in terms of non-image forming effects based on our measurements, calculations and previous research. We usually design lighting systems based on the requirements for specific illumination of the working surfaces, for example in Dialux. However, such modelling does not take into account non image forming effects of lighting nor does it consider light reflected from coloured surfaces in the inner rooms. Different setups of inner rooms were taken into account and the magnitude of design impact was evaluated. Furthermore, comparisons with daylight were also made. The study broadens the knowledge about the influences of spectral power distribution of light sources with the spectral distribution of light reaching observers photoreceptors.**

Index Terms-- **action spectra of human photoreceptors; built environment; non-image forming effects; reflected light; spectral power distribution.**

INTRODUCTION

Modelling of lighting conditions with programs such as Dialux or Relux has become widely accepted and is highly efficient in terms of evaluating illuminated surfaces of interest in the inner and outer scenery in advance, before actually installing lamps for real. Apart from detailed lamp parameters, street and building design including rooms' settings, materials of the surfaces including their reflectance, transparency, colour properties in terms of RGB parameters etc. can also be included in the model. However, as previous studies mentioned, an interdisciplinary research is needed for human-responsive daylighting design to fully embrace its complexity and dynamics [1]. Observers perceive light when it reaches photoreceptors and those are not only image forming rods and cones but also non-image forming (NIF) some of the ganglion cells that are intrinsically photoreceptive (intrinsically photosensitive Retinal Ganglion Cells, ipRGC) [2]. Since illuminated surfaces in the above mentioned programs can only be described in lx or cd/m2, image forming average daylight vision function $V(\lambda)$ is "locked" into all results. To evaluate NIF effects, spectral power distributions (SPD) of light reaching illuminated surfaces of interest should be weighted by the "melatonin" function.

Daylight modelling is addressed in studies from many different angles. Meteorologists for example address it in terms of spectral analysis such as hourly solar radiation analysis [2], that includes studies of the sky conditions (clear, overcast etc.). Many past studies were focused particularly on evaluating energy levels of skylight and sunlight [4] to aid in simulation of energy balance in the building for example. Such data is very relevant in the field of building physics, for example when shaded hours of transparent building parts are evaluated to access heat gains and losses [5]. However, it is very hard to find detailed data on fluctuations of visible part of the SPD daylight hourly, daily, seasonal etc. Nevertheless, this are the most important input data for all models predicting lighting conditions and expected needs if for example transparent façade is applied. Some past research showed promising modelling approaches [6], but image forming effects are still in the centre of such models.

In our past studies we have calculated the SPD of light reaching retina as a product of the SPD of the light source and the spectral transmittance and/or reflectance of materials that are positioned between the light source and the retina of the observer's eye [7]. Wall surfaces painted in different colours are probably the most common material of the built environment. The spectral composition of light reflected from these surfaces can change considerably which influences also the image- and non-image forming effects significantly. The largest contribution is made by the first reflection/transmission, so that multiple optical events occurring inside a room could be neglected. It was obtained that the influence of wall paints on NIF effects are similar for warm and cold white lights.

Based on past studies, we've calculated different cases, where $V(\lambda)$ function has been extracted from the proposed results and based on this, NIF effects were evaluated by the same software to predict some causes of different inner surrounding setups. We were focused only on daylight penetrating transparent parts of the façade as a light source.

Different transparent façade systems were taken into account as well as shading types and sharing level (%) of shaded areas (position of the shading system). In this study, the effects daylight is evaluated in terms of illuminance levels and NIF effects on six workplace positions in a room. The influences of the colour of walls were also modelled. This way our former study made on white light sources is extended on daylight [8].

EXPERIMENTAL

Reflectance of the materials in the inner ambient has been measured with spectrophotometer Lambda 950 (Perkin Elmer). PerkinElmer's UV WinLab™ software has been used to process the data. The spectral reflectance was measured from 380 nm to 780 nm with 1 nm resolution. Later calculations were simplified to 5 nm step.

Modelling was done in Dialux, some preliminary modelling was also achieved in Relux (where glass transmittance of façade can be any number). We have assumed that programs used for lighting design take into account different spectral transmittance and/or reflectance of building materials such as wall paints. We are not sure however, whether spectral properties of different daylight are considered.

The photobiological effects of light were evaluated by the proportion of light responsible for the image forming effect - ($S(\lambda)=S_D(\lambda)\cdot V(\lambda)\cdot R(\lambda)$) and NIF effect ($S(\lambda)=S_D(\lambda)\cdot M(\lambda)\cdot R(\lambda)$) where $S_D(\lambda)$ are daylight phases D65(λ) or D27(λ) and R(λ) is the spectral reflectance of the wall. The SPDs of the daylights and the two action spectra, V(λ) and M(λ) are shown in Fig. 1.

Illuminance levels were calculated on two 80 cm high working tables, one in the middle of the room (T1) and another one next to the window (T2), considering three places for each table (Figure 2). The influence of five wall colours was considered - white, blue, purple, green and orange (Figure 3).

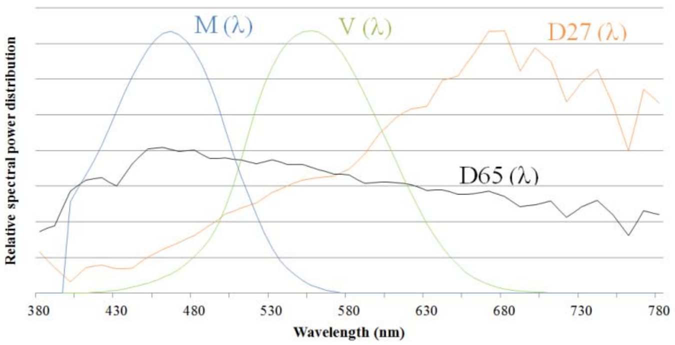

Figure 31: Spectral power distributions of daylights D27 and D65 considered in this study and action spectra of image (V) and non-image (M) forming effects.

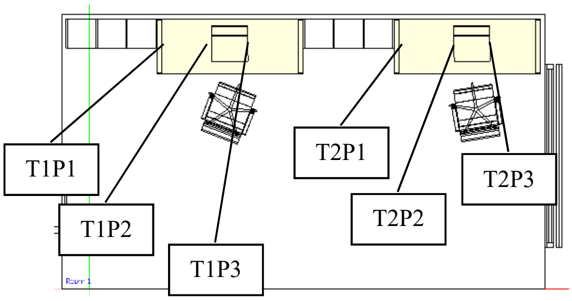

Figure 32: Modelled and simulated situation in the Dialux environment, diagram represent positions where illuminance level has been assessed (T-table, P-position), all values were taken into account on the table (80 cm high).

Figure 33: Wall paints modelled in Dialux environment.

RESULTS

The reflectance spectra of walls painted by different colours are shown in Figure 34. These spectra were used in equation 1 and the results were calculated in Relux (**Napaka! Vira sklicevanja ni bilo mogoče najti.**). The illuminance levels of working planes on six positions (see Figures 2 and 3) in a room with five different colours of walls were calculated in Relux program. The results are given in Table 1 and Figure 5.

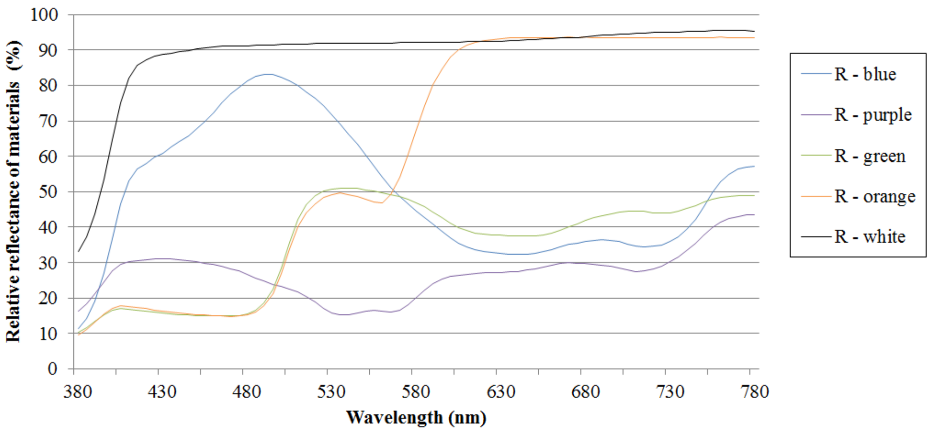

Figure 34: Measured relative reflectance of wall paints used in further calculations

TABLE 3: Illuminance levels (lx) of working planes on tables 1 and 2 at 3 positions (T2P3 is located by the window) when walls of different colours in front of the table are assumed (white, blue, purple, green and orange)

	T1P1	T1P2	T1P3	T2P1	T2P2	T2P3
White Wall	60 lx	65 lx	73 lx	247 lx	308 lx	203 lx
Blue Wall	45 lx	48 lx	58 lx	192 lx	241 lx	152 lx
Purple Wall	40 lx	42 lx	53 lx	175 lx	221 lx	136 lx
Green Wall	55 lx	59 lx	67 lx	227 lx	284 lx	185 lx
Orange Wall	49 lx	52 lx	61 lx	206 lx	258 lx	165 lx

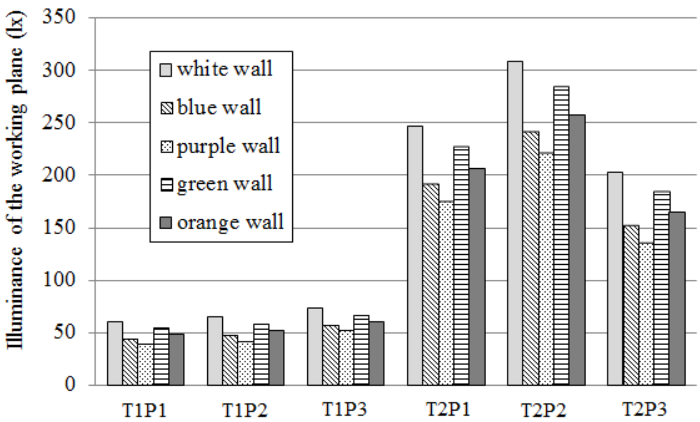

Figure 35: Illuminance of the working planes (lx), desk in the middle of the room (T1P1-T1P3) and desk by the window (T2P1-T2P3). The calculations were made for 5 wall colours.

Considerably higher illuminance was obtained on the Table 2, which is next to the window, the highest in the middle position (T2P2). The colour of the wall influences the illuminance levels in all studied positions. The highest illuminance is when the wall is white and the lowest if it is purple.

Relative image forming and non-image forming effects caused by daylight at 6.500 K has been calculated based on the cumulative value modelled by Dialux and SPD of daylight phases D65 and D27, spectral reflectance of wall taken into account (see Figure 36). The same was done for the morning and evening hours with different spectral distribution of light then during the day (see Figure 37).

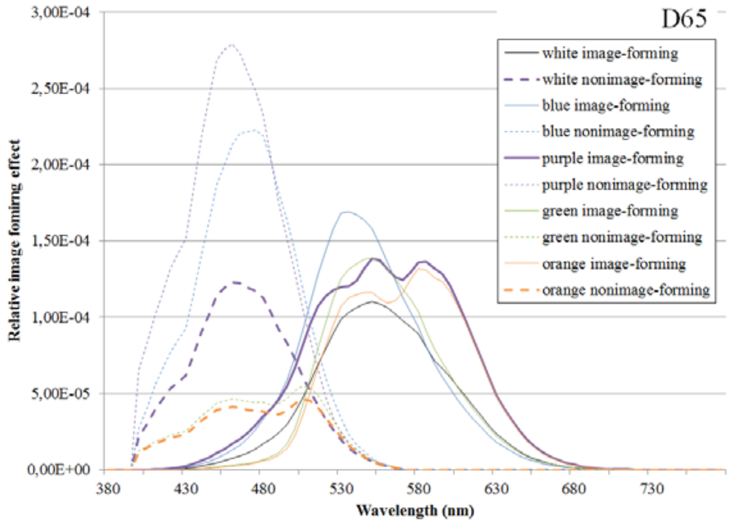

Figure 36: Relative image forming effects caused by daylight at 6.500 K (D65), light reflected from walls painted with different colours (continues lines represent image forming effect confirmed by simulations in Dialux, non-continues lines represent non-image forming effect calculated relative to the image forming effects).

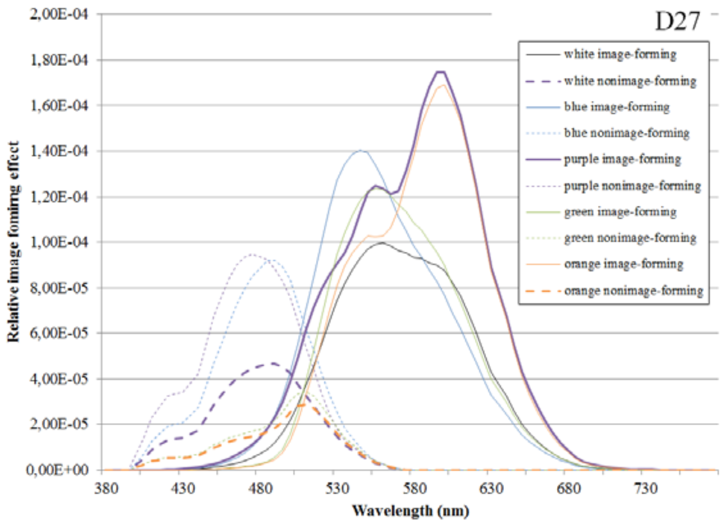

Figure 37: Relative image forming effects caused by daylight at 2.700 K (D27), light reflected from walls painted with different colours (continues lines represent image forming effect confirmed by simulations in Dialux, non-continues lines represent non-image forming effect calculated relative to the image forming effects).

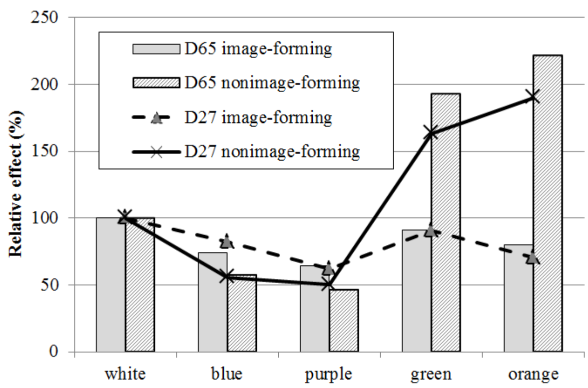

Figure 38: Relative effects comparison for D65 and D27 in terms of wall colour dependence on image and non-image forming effects

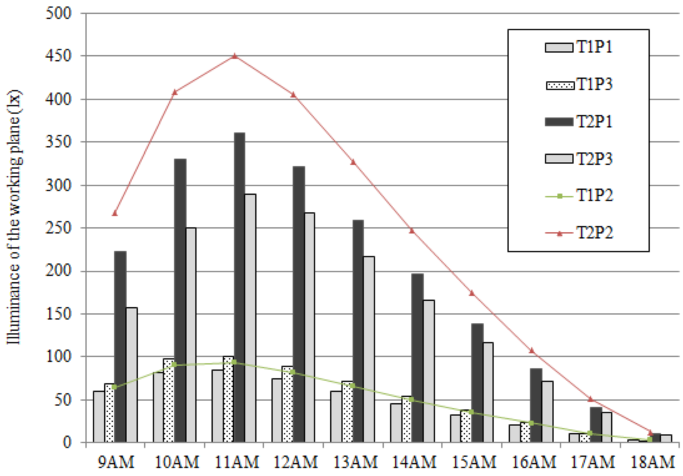

Figure 39: Hour-in-the-day dependant model of the illuminance levels

CONCLUSIONS

As concluded in previous studies, human interaction with built environment including daylighting effects is complex. Not only image-forming effects are relevant, thus we have presented a simple method, where non-image forming effects are taken into account as well. It is important to point out here that doses related to melatonin effects are still not standardized due to the complexity of human responses [9]. We use simplifications and relative amounts to conduct these calculations.

From our study, one can conclude, that image as well as non-image forming effects of our light photoreception is greatly dependent on the spectral properties of materials surrounding us as well as light sources SPDs. The amount of light diminishes with the distance from window, except on the position T2P3, where it is partly obstructed by the corner of the window. Thus, let us analyse the case with the biggest differences, which is T2P2. In the case of white wall, we receive 308 lx at the working plane (21th of March at 13 AM, 50 % shaded glazing with LT 0,68), but only 78 % of this value if the wall is blue, 56 % of this value if the wall is purple, 52 % of this value if the wall is green and 43 % of this value if the wall is orange. In the non-image part of the results, we have concluded that only relative estimations can be made, since the dose is not confirmed yet. Results again revealed, that image forming system in lx cannot reveal the non-image effects. This is similar to our previous conclusions that CCT might not the correct parameter to describe the non-image forming effects of light [8]. For example, while blue wall lit by D65 only cause 57 % of the non-image forming effect compared to white wall, green wall cause 193 % of the white wall value. However, image forming effects are 74 % for the blue wall and 91 % for the green one (see Figure 38).

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Environmental Effects of Wall Colours in Offices and User Preferences

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***Abstract*— In offices, the aim is to make employees feel comfortable and to maximize productivity by creation of physical environment. The physical environment which is created by the combination of lighting, wall colour, furniture and objects forms spatial identity and effects users.**

In this study, a survey was conducted to determine the effects of wall colours on the user and the preferences of users for office wall colour. Within the scope of this study, different wall colours were created for the same office. Each office with different wall colour was displayed on the television screen to the subjects and the questionnaires were conducted. The data obtained from the study shows that there are differences in space evaluation and subjects have different degrees of appreciation for different wall colours of the same space. Accordingly, this study will guide the designers in selecting the wall colour considering the user's different features such as age and gender.

***Index Terms*—Office, Preference, Space Assessment, Wall Colou**

INTRODUCTION

Space size, shape, lighting, office equipment and environmental colour schemes in offices constitute a part in the interior design criteria. For this reason, environmental colour schemes are an important issue to consider when designing interior architectural arrangements for offices. The important elements that bring out the environmental colours in spaces are the colours of the ceiling, the floor and most importantly the wall [1]-[2]. Considering ceilings with white applications commonly and floors entering less into the visual field, it is important to determine how colours of the office wall change scheme of the space and how the user's is influenced. For this purpose, in this paper, a study has been conducted on how the colours used in the working environment affect the emotional status (mood) and preferences of the users.

METHOD

The study was carried out by designing an office space of 4.00m x 7.00m x 3.00m (Figure 1) in different wall colours by using DIALux 4.13 Lighting program, then displaying the visualized office pictures on the digital screen to the subjects. In the designed office space, 8 luminaires with 1x41 W LED34S/840 PSU were used. The light distribution of luminaires are shown in Figure 1. The colour temperature and colour rendering index of lamps are 4000 K and 85, respectively. An illuminance of 400 lx was obtained in the working plane.

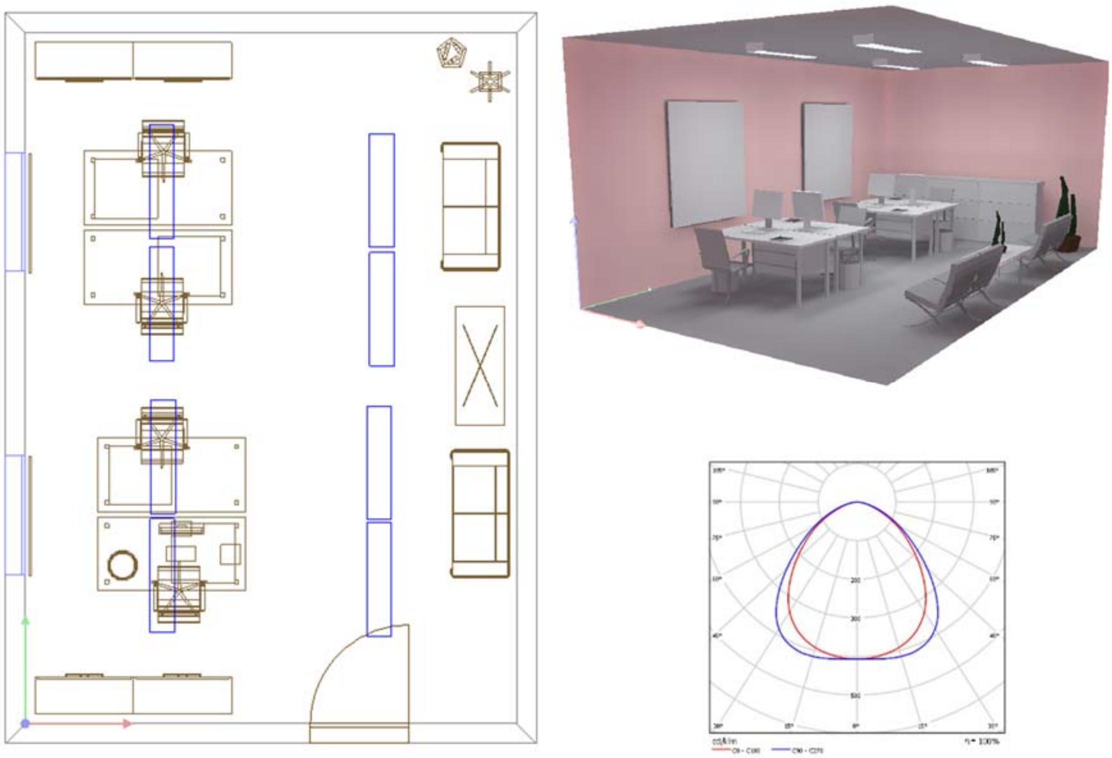


Figure 1. Plan, perspective of the office and light distribution of luminaires used in the office

Equipment, ceilings and floors in the office were chosen from gray (neutral) colours, and 6 different office colour schemes were obtained using 6 different colours on office walls (Table I, Figure 2). Five of the office colours are chromatic colours (red, yellow, green, blue and purple) and followed by 20 different steps each other according to the Munsell Colour System, the other wall colour is monochromatic (grey) [3]-[4]. All chromatic colours were selected as "8" value, “4” saturation and gray colour with saturation “0” was selected as “8” value. The Munsell Colour System Notations of the wall colours are shown in Table I, and the office visuals used in the study are shown in Figure 2. Each office visual was shown on the Panasonic TX-P50VT50E FHD 3D Plasma LED display with dimensions of 110.7 x 62 x 7 cm and subjects were asked to make an assessment of the space (office) colour. Wall colour evaluation questionnaire was given to the subjects for assessment and colour preference. The first part of the questionnaire consisted of seven-point Semantic Differential Scale about the perception how the subjects found office for the specified office wall colour. The subjects then evaluated the importance of each 12 bipolar adjective pairs on a (-3)-(+3) scale. These bipolar adjectives are meaningful/meaningless, big/small, inefficient/efficient, nice/ugly, dynamic/stable, pleasant/unpleasant, bad/good, unlikeable/likeable, bored/relaxed, cold/warm, unproductive/productive, pleasurable/unpleasurable [5]. In the second part, there are 5 levels of Likert Scale showing office wall colour appreciation ratings. Subjects rated the degree of office colour appreciation on the Likert Scale.

TABLE I. MUNSELL COLOUR SYSTEM NOTATIONS FOR OFFICE WALLS

COLOUR	Hue	Value/Saturation	Sample of Wall Colour
RED	5R (5)	8/4	
YELLOW	5Y (25)	8/4	
GREEN	5G (45)	8/4	
BLUE	5B (65)	8/4	
PURPLE	5P (85)	8/4	
GREY	N	8/0	



a) Red (5R-8/4) b) Yellow (5Y-8/4) c) Green (5G-8/4)



d) Blue (5B-8/4) e) Purple (5P-8/4) f) Grey (N-8/0)

Figure 2. Selected colours for the office walls

The experimental study was implemented in the Lighting Laboratory of Department of Architecture in Yıldız Technical University and it took approximately 20 minutes for each subject. A total of 30 subjects aged from 18 to 65 years, 16 women and 14 men were recruited in the study. Before the survey, the colour vision deficiencies of subjects were tested using an Ishihara Colour Vision Test [6] and colour vision deficiency was not detected in any of the subjects.

Figure 3. Photos from the experimental study

FINDINGS

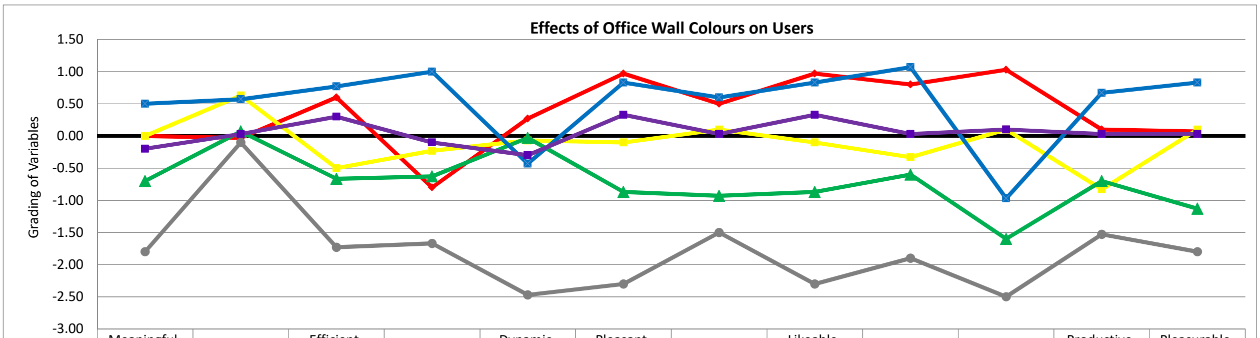
The results obtained from the study were evaluated separately on the basis of the Semantic Differentiation Scale, which evaluates how the office wall colour is found with adjectival equivalents, and the Likert Scale, which directly grades the office wall colour.

A. Findings of Semantical Differential Scale

The results of Semantic Differential Scale with 12 adjective pairs are shown in the graph in Figure 4. The results from the Semantic Differential Scale show that,

- the 5B-8/4 blue wall colour has been evaluated positively by the adjectives that are meaningful, big, efficient, nice, pleasant, good, likeable, relaxed, productive and pleasurable in spite of being stable and cold.
- the 5R-8/4 red wall colour was found favorable by many users such as efficient, dynamic, pleasant, good, likeable, relaxed and warm.

- the 5Y-8/4 yellow and 5P 8/4 purple coloured office responds in all adjective pairs with a neutral response close to the "0" line.
- the N-8/0 gray office does not provide positive feedback for any adjective pairs by the users and the gray wall is located in the negative area of the semantic differential scale graph,
- the 5G-8/4 green office also shows that the users are responding negatively to all adjective pairs, but not as much as the gray office.



	Meaningful-Meaningless	Big-Small	Efficient-Inefficient	Nice-Ugly	Dynamic-Stable	Pleasant-Unpleasant	Good-Bad	Likeable-Unlikeable	Relaxed-Bored	Warm-Cold	Productive-Unproductive	Pleasurable-Unpleasurable
RED	0.00	-0.03	0.60	-0.80	0.27	0.97	0.50	0.97	0.80	1.03	0.10	0.07
YELLOW	0.00	0.63	-0.50	-0.23	-0.07	-0.10	0.10	-0.10	-0.33	0.10	-0.83	0.10
GREEN	-0.70	0.07	-0.67	-0.63	-0.03	-0.87	-0.93	-0.87	-0.60	-1.60	-0.70	-1.13
BLUE	0.50	0.57	0.77	1.00	-0.43	0.83	0.60	0.83	1.07	-0.97	0.67	0.83
PURPLE	-0.20	0.03	0.30	-0.10	-0.30	0.33	0.03	0.33	0.03	0.10	0.03	0.03
GREY	-1.80	-0.10	-1.73	-1.67	-2.47	-2.30	-1.50	-2.30	-1.90	-2.50	-1.53	-1.80

Figure 4. The graphics of Semantic Differential Scale

B. Findings of Likert Scale

Subjects denoted their wall colour appreciation rating by 5 level of Likert Scale. “5” is the best and “1” is the worst. Assessments showed that,

- although the office wall colour preferences with no noticeable difference between three different age groups, 41-50 age group preferred blue and yellow office more than the other age groups,
- apart from the blue office, there was no difference in preferences ratings between women and men in terms of preferences ratings. The blue office was more appreciated by men compared to women (Table II, Figure 5).

TABLE II. FINDINGS OF STUDY RELATED TO AGE AND GENDER OF SUBJECTS

PREFERENCE	AGE			GENDER		GENERAL
	20-30	31-40	41-50	WOMEN	MEN	
BLUE	3,35	3,20	4,00	3.06	3.71	3,37
PURPLE	3,29	2,50	3,00	2.94	3.07	3,00
RED	2,82	3,20	3,33	3.13	2.86	3,00
YELLOW	2,76	2,60	3,67	2.69	2.93	2,80
GREEN	2,24	2,00	2,33	2.13	2.21	2,17
GREY	1,94	1,50	2,00	1.50	2.14	1,80

According to the Likert Scale results, the most popular colour for the office wall colour was blue, as seen in the Table II (3,37 of 5) and Figure 5. The most favoured blue wall colour was followed by the purple and red wall colours while the least preferred (liked) colour was the gray wall colour in the six wall colours. The results of previous studies show that users prefer blue colours more [7]-[11].

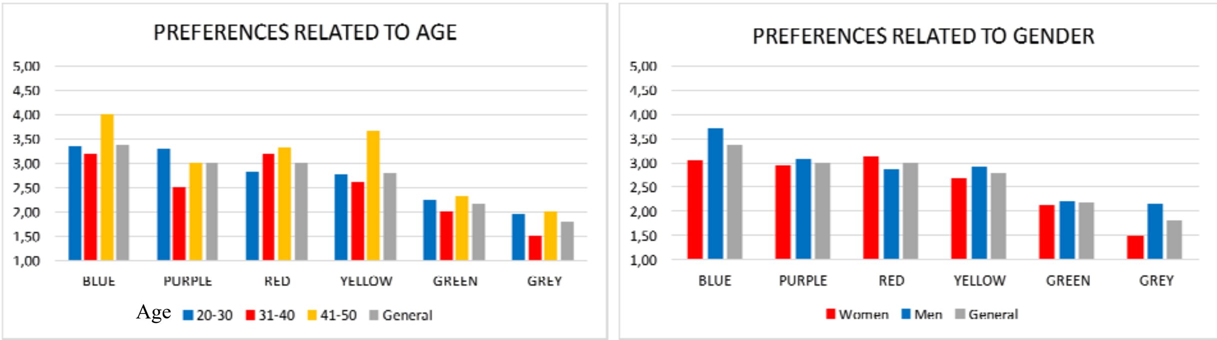


Figure 8. The graphics of preferences of subjects related to age and gender

CONCLUSION

This study is aiming to investigate the evaluations of environmental colour and preferences in offices. It was carried out by using 6 different colours in the walls of an office via DIALux 4.13 Lighting program and visualizing to the subjects. The subjects assessed separately each visualized office with different wall colour and evaluations were conducted by the questionnaires based on the Semantic Differentiation Scale and Likert Scale. The results of the study can be summarized in the following two sections in this respect.

The results of 12 adjective pairs and seven-point Semantic Differentiation Scales in the first section shows that the red and the blue colours are described by the users as "positive" for the adjective pairs. The yellow and purple office was found neutral on the graphic by users in all adjective pairs. And the subjects scored gray colour most negatively and that the green coloured wall was scored negatively on all adjective pairs following gray wall colour scores.

The Likert Scale was implemented in a format that targets the users' direct preference and it was scored with this rating method. The results of this scale show that the blue wall coloured office is most preferred by the users. Subjects preferred a gray office the least.

The working environments where employees spend a long period of their time is important in order to increase the efficiency of the environmental effect. Accordingly, this study will guide the designers in selecting the wall colour of a working environment, considering the users' different features such as age and gender. Various studies to be done in a similar or real environment using different colours will be useful for investigating the effect of increasing the working quality of the users.

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The Effect of Short Exposure to Coloured Light on Thermal Perception: a Study Using Virtual Reality

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***Abstract*— This study investigates the effect of short exposure to coloured light on thermal perception. To give the impression of natural daylight passing through coloured filters, but avoiding the drawbacks of conducting an experiment with daylight, continuously changing due to daily and seasonal variations, and to weather conditions, we investigate the use of Virtual Reality as a means to control the visual conditions, creating a hybrid environment with thermal and visual stimuli from the real and virtual world, respectively. Two temperature levels (24 °C and 29 °C) are controlled in a climate chamber, while three visual conditions (orange, blue and neutral colour filters) are displayed in the Virtual Reality headset. Results of a between-subjects experiment show that the coloured light led to different thermal evaluations. In particular, under orange light conditions at 24 °C, subjects felt warmer, less comfortable and judged the thermal environment as less acceptable than under the other colours at the same temperature.**

***Index Terms*— daylight, hue-heat-hypothesis, temperature-colour interaction, virtual reality.**

INTRODUCTION

The evaluation of indoor comfort requires a thorough understanding of how people perceive and respond to the indoor environmental factors, namely air quality, acoustic ambience, visual and thermal conditions. In the last decades studies have focused on the effects of their interactions on comfort perception [1]–[9], given that the human sensory system is not modular but integrates and responds to different environmental factors occurring simultaneously [10]. The hue-heat-hypothesis, in particular, focuses on the influence of visual parameters on thermal perception, asserting that colour toward the red end of the spectrum are perceived warmer than colour toward the blue end of the spectrum [11]. Positive outcomes from experiments investigating this hypothesis can lead to application in building design and operation for energy saving purposes [9]. To this aim, it is necessary to conduct further experiments to investigate conditions that are similar to real world settings. A recent literature review on the topic by the authors highlighted the necessity to investigate the effect of coloured daylight on thermal perception [12]. Experiments that use daylight as one of their independent variables face the challenge of a variable that is difficult to control due to daily and seasonal variations, and change in weather conditions [13]. To address this problem, we investigate the use of virtual reality as a means to control the visual conditions independently of the external ones, creating a hybrid environment with stimuli from both the real and virtual world. The immersion and interaction of people with a virtual environment have been shown to be factors of importance [14]-[15], suggesting the use of immersive virtual reality as an empirical research tool. The virtual reality environment developed and used in this study has been recently tested by the authors as an independent visual stimulus and shown to be an adequate surrogate for real environments in daylight perception studies [16]. Similarly, benchmarking studies on user performance in virtual reality show similar user behavior in the real and virtual environment [17].

HYPOTHESIS

We hypothesize that short exposure to coloured light in immersive virtual reality will affect people's thermal perception. In particular, our hypothesis asserts that people experiencing an orange light condition would feel warmer and less comfortable than people experiencing a "neutral" or blue light condition.

METHODOLOGY

The methodology followed in this study consists of the combination of stimuli in the real and virtual environment, with the aim to investigate the effect of coloured daylight conditions on thermal perception. In order to increase the realism of the virtual scenes, we decided to use projected photographs rather than simulation. These images were taken in the test room where the experiment took place, with three different coloured filters applied on the glazing of the north façade. Using 180° HDR photographs, these conditions were then reproduced into immersive virtual reality scenes. Through this procedure, all participants saw one of three visual stimuli projected in the virtual reality headset, corresponding to the neutral, orange and blue coloured condition. By combining the participants' visual immersion in the virtual reality projection and bodily immersion in the thermal conditions of the climate chamber, we can ensure their exposure to controlled colour and temperature stimuli.

A. *Experimental Design*

A completely randomized full factorial design was selected, for a total of 6 combinations, testing two levels of temperature (24 °C and 29 °C), and three levels of colour (neutral, blue and orange) displayed in the immersive virtual reality. As the experiment was conducted in the summer, the two temperature ranges correspond to commonly found conditions in non-air-conditioned office-rooms in mid-Europe, and to thermal conditions considered as being outside of the comfort range based on the SIA [18] norm. As a between-subjects design was used, each participant experiences just one combination of temperature and colour. The sample size for each colour condition was 21 subjects, distributed in the temperature groups as shown in Table 1 below. The measurements of operative temperature during the experimental sessions show that the average value fell within a range of ± 0.5 °C among the three colour exposures at both 24 °C and 29 °C temperature levels (Table 2). Relative humidity was kept between 45-55% and air velocity below the threshold of 0.1 m/s. Temperature-colour combinations were counterbalanced to ensure that testing occurred equally often in the morning and afternoon.

TABLE I. SAMPLE SIZE PER COLOUR-TEMPERATURE COMBINATION

	24 °C level [-]	29 °C level [-]
Blue	12	9
Neutral	12	9
Orange	12	9

TABLE II. MEAN MEASURED OPERATIVE TEMPERATURE

	24 °C level [-]	29 °C level [-]
Blue	23.6	29.2
Neutral	24.0	29.3
Orange	23.8	29.1

The thermal perception of the participants was recorded through their responses to a verbal questionnaire while they were experiencing the immersive virtual scene. The verbal questionnaire was supported by a visual reference of each item scale in the virtual reality environment. The dependent variables are divided into two main categories: (i) subjective thermal perception and (ii) objective thermal perception. Four questions fall into the first category (i.e., thermal sensation, comfort, preference and judgement) and one into the last one (i.e., temperature estimation). For a summary of the dependent and independent variables used in the study see Table 3.

TABLE III. OVERVIEW: INDEPENDENT AND DEPENDENT VARIABLES

Independent Variables	
Temperature	Low temperature range (24°C) or high temperature range (28°C)
Colour	Neutral, blue, or orange
Dependent Variables	
Thermal Sensation	At this precise moment, how are you feeling? Scale (1:7): Cold - Cool – Slightly cool – Neither cool nor warm - Slightly warm - Warm - Hot
Thermal Comfort	Do you find this condition: Scale (1:5): Very comfortable – Comfortable – Slightly Uncomfortable – Uncomfortable – Very Uncomfortable
Thermal Preference	How would you prefer to feel now? Scale (1:7): Much cooler – Cooler – Slightly cooler – No change – Slightly warmer – Warmer – Much Warmer
Thermal Judgement	How do judge the thermal environment on a scale from 0 to 100, where 0 is unacceptable and 100 is acceptable? Scale (1:100): Unacceptable - Acceptable
Temperature Estimation	Could you please estimate the room temperature in °C?

j.

B. *Participants*

Participants were contacted via email with a pre-selection questionnaire, used to select the candidates that fulfilled eligibility criteria regarding normal BMI, age under 35, and no color vision deficiency. Once selected, subjects could choose a timeslot for their experimental session. The sessions were set to allow the balancing between genders, timing of the session (morning or afternoon), temperature condition, and colour exposure. Of the sixty-three participants tested, thirty-one were men and thirty-two were women. Gender balance was respected across temperatures with eighteen men and women in the 24 °C level and thirteen men and fourteen women in the 29 °C level. Following a single-blind procedure, subjects were told they were participating in a study investigating the effect of different scenes displayed in the immersive virtual reality on physiological responses. Physiological responses were also recorded, but their analysis is not reported in this paper. Subjects were told that their responses to the verbal questionnaire would be compared with their physiological measurements. To this end, they were asked to give evaluations that reflected their perception in the exact moment when the questions were asked.

C.Experimental Set-up and Equipment

i. Visual stimuli in the virtual environment

To generate the virtual scenes, the experimental room was set up to create four different visual conditions that were recorded and reproduced in the virtual reality: one with artificial light and curtains closed, and three with daylight passing through the coloured filters, corresponding to neutral, blue, and orange colour, illustrated in Fig. 1. The scenes were photographed using a 180° fisheye lens from the viewpoint of a participant seated in the middle of the room, resulting to High Dynamic Range (HDR) image per condition, each calibrated using two luminance reference measurements in the corresponding real environment. The HDR images were tone mapped using the local adaptation of the Reinhard02 photographic tone mapping algorithm [19], transformed into BMP files using *ra_bmp* with a gamma correction of 2.0, and applied as cubemap projection with the procedure developed in [16] to create 180° immersive scenes that can be projected onto Oculus Rift CV1. In the resulting virtual reality environment, the user of the headset can freely explore the space by moving their head and looking around. Although the user was immersed in a 360° visual environment, half of the scene was black and half of the scene was visible, corresponding to the 180° fisheye photograph of the real environment (Fig. 1, d). The equipment for the visual stimuli consisted of the Oculus Rift CV1 virtual reality headset, with field of view of 110° and resolution of 1080×1200 pixels per eye. The maximum luminance of the display, measured at the lens, was 80 cd/m$_2$, due to current technical limitations.

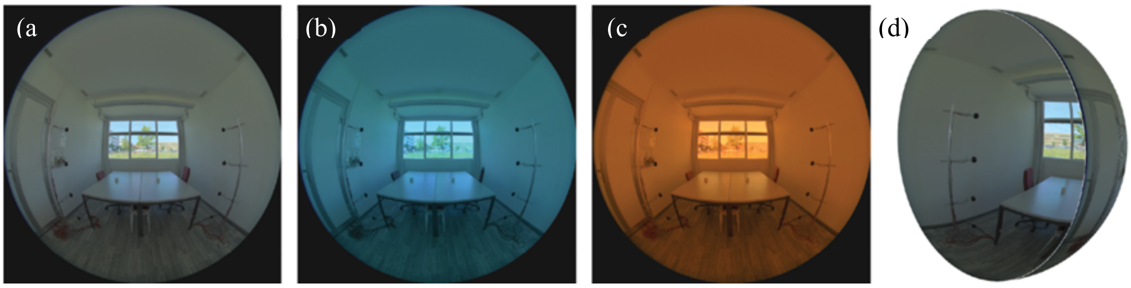

Figure 40. Tone mapped fisheye photographs of the neutral (a), blue (b) and orange (c) colour conditions, and illustration of the 180° scene (d).

ii. Thermal Stimuli in the real environment

The experiments were conducted in the "DEMONA" test room, a climate chamber facility on the EPFL campus. The test room is designed to control and keep within ranges the principal indoor environmental factors responsible for thermal comfort: temperature, humidity and air velocity. In order to keep the visual conditions constant for all participants before their wearing the virtual reality headset, only artificial light was used, and daylight was prevented to enter the test room with white solar blackout curtains positioned on the north and south facing windows. The room was equipped with sensors that measure with a sampling period of one minute the air and globe temperature, the relative humidity, the CO_2 content, and the air velocity. Temperature measurements were recorded on both the left and right side of the participant seated in the middle of the room (Fig. 7).

D.Experimental Protocol

Each experimental session lasted approximately 30 minutes and followed the same protocol, shown in Table 4. All participants were asked to conform to a similar clothing level. Once inside the test room, the participant received a short explanation of the study and was asked to read an information sheet and sign a consent form. After this step, they filled a questionnaire on their background information. The participant was then shown how to wear the VR headset and adjust its fit in a training scene, and was instructed to limit their head movements within the boundaries of the visible 180° scene. For the remainder of the session, the participant was immersed in the virtual reality environment. The first scene they were exposed to is the test room with artificial light and closed curtains, followed by the scene of the coloured environment, where only one colour condition was shown to each participant. Few additional questions not related to thermal perception were asked to allow for colour adaptation. The participant was exposed to the temperature in the test room for an average of 20 minutes before the thermal perception questionnaire.

TABLE IV. STAGES IN THE EXPERIMENTAL PROTOCOL

1. Introduction	*2. Consent*	*3. Questionnaire*	*4. VR Scene*	*5. VR Scene*	*6. VR Scene*	*7. Questionnaire*
Short Explanation	Information Sheet and Consent Form	Background information	Training scene	Control scene (curtains)	Colored light scene (neutral, blue, orange)	Thermal perception

RESULTS

In the following sub-sections we analyse the effects of colour on the subjective and objective evaluation of thermal perception. The analysis consists of box-plots and statistical results referring to a two-way between subjects Analysis of Variance (ANOVA) are reported to evaluate the main effects of colour and temperature and their interaction on the different thermal perception evaluations, for a significance level α of 0.05. Post-hoc Tuckey$_a$ (Honestly Significant Difference) tests are conducted for each thermal evaluation to carry out all possible pairwise comparisons across the three levels of the factor "colour" (neutral, blue and orange), using a significance level α of 0.05.

A. Effect of colour on subjective thermal perception

Figures 2-5 show the subjective responses related to the thermal sensation, thermal comfort, thermal preference and thermal judgement, respectively. The left hand side of each figure indicates the results for the 24 °C level, while the right hand side for the 29 °C level. Within each temperature level, the single boxes illustrate the thermal responses for each colour. The figures demonstrate that the short exposure to coloured light in the immersive virtual reality led to different thermal perception evaluations. The fact that we observe different responses confirms that the immersive virtual reality can be used to evaluate thermal-visual interactions, even with a short exposure time. The results of a two-way ANOVA on the effects of colour and temperature exposure on thermal perception show that the main effect of colour is significant on the evaluations of thermal sensation ($F = 4.7$, $p = 0.012$), thermal comfort ($F = 5.9$, $p = 0.004$), and thermal judgement ($F = 6.1$, $p = 0.003$). Thermal preference demonstrates a less strong result ($F = 3.2$, $p = 0.047$), which can still be considered significant for a significance level α of 0.05. The main effect of temperature is always significant (with $p < 0.01$), while the interactions between colour and temperature are significant only for the thermal comfort evaluation ($F = 3.9$, $p = 0.025$). This can be explained by the fact that the blue light is considered comfortable at 24 °C, in line with the evaluation of the neutral condition, and slightly uncomfortable under 29 °C, in line with the evaluation of the orange colour condition, as can be seen in Fig. 4. The post-hoc Tuckey$_a$ (HSD) tests showed that with $\alpha = 0.05$, there was a statistically significant difference only between the means of the evaluations in orange and neutral light conditions ($p = 0.012$ for thermal sensation, $p = 0.003$ for thermal comfort, and $p = 0.002$ for thermal judgement). Figure 2 shows a greater effect of colour within the 24 °C level, considered slightly warm by the majority of the people. In this thermal level, people exposed to the orange condition felt warmer and less comfortable, and considered the thermal environment less acceptable than under the neutral and blue conditions.

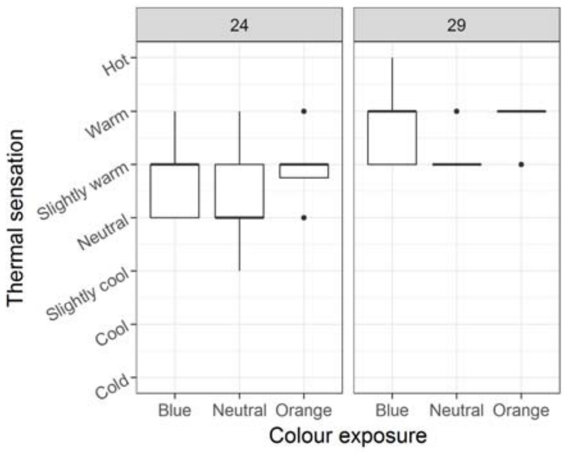

Figure 2. Thermal sensation evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

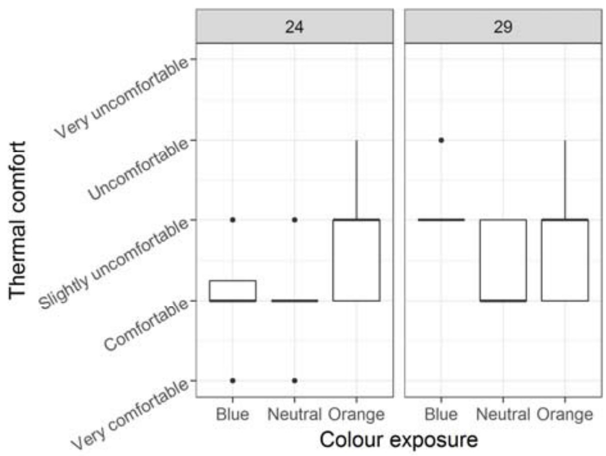

Figure 3. Thermal comfort evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

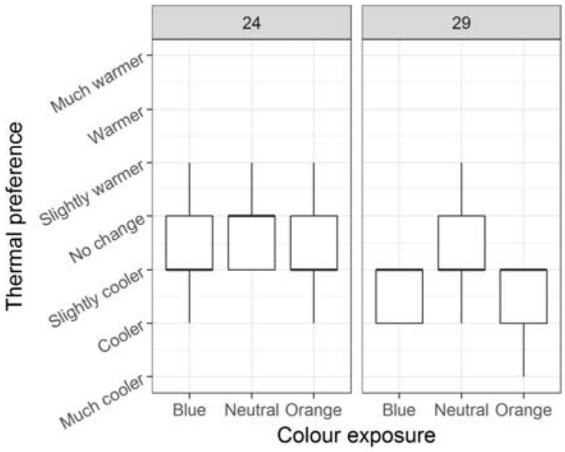

Figure 4. Thermal preference evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

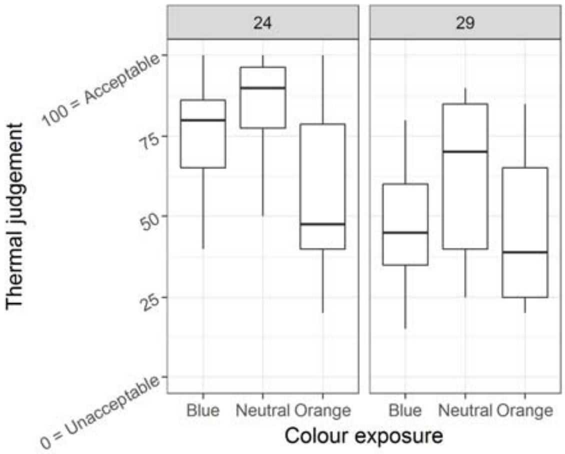

Figure 5. Thermal judgement evaluation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

B. Effect of Colour on Objective Thermal Perception (Temperature Estimation)

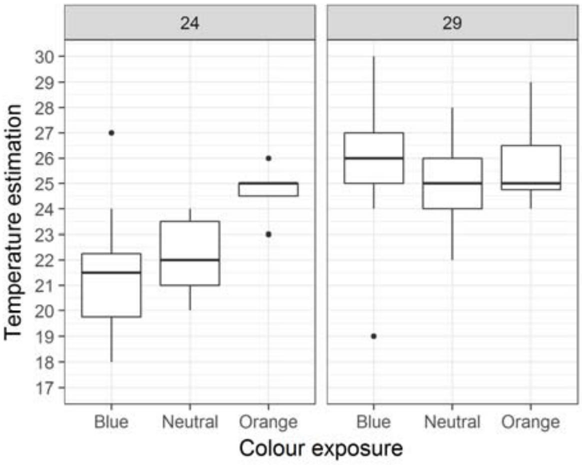

Figure 6. Temperature estimation of subjects exposed to the three colours for the two temperature levels (24 °C, left, 29 °C, right).

Figure 7. Photograph of a participant using the virtual reality headset and experiencing an immersive scene in the test room.

The same conclusions can be drawn for the objective thermal perception, where subjects were asked to estimate the room temperature. A two-way ANOVA revealed that the main effect of colour is significant ($F = 4.4$, $p = 0.016$) as well as the main effect of temperature ($F = 18.09$, $p = 0.000$), while there are not significant interactions ($F = 0.58$, $p = 0.56$). A post-hoc $Tuckey_a$ test shows statistically significant difference for $\alpha = 0.05$ only between the means of the evaluations in the orange and neutral light conditions ($p = 0.014$). The effect of exposure to orange light is much clearer in the 24 °C level (Fig. 6), where temperature under orange exposure is estimated as 3 and 4 °C higher than in the other two colour conditions. Under 29 °C, temperature estimation is similar across colour conditions.

CONCLUSION

We found that short exposure to light displayed in virtual reality led to different evaluations of thermal perception, showing that this immersive technology can be used to test visual and thermal interactions. Most significant differences can be found between neutral and orange light exposures. We can conclude that under slightly uncomfortable thermal conditions (slightly warm in this case, as the experiment was conducted in the summer), a short exposure to coloured light can affect thermal evaluations of people even under the same thermal conditions. People feel warmer, more uncomfortable and consider the thermal environment less acceptable when exposed to orange light compared to blue or neutral light conditions. Similarly, when investigating objective thermal perception through temperature estimation, exposure to orange light led to higher estimated temperature compared to the other two visual conditions. However, the post-hoc Tuckey test revealed no significant differences between the blue light and the other two conditions for any of the studied evaluations of thermal perception. The experimental design, testing two levels of temperature, allowed the investigation of interactions between colour and thermal conditions. Findings show that the effect of colour on thermal perception is greater at 24 °C (still considered slightly warm), indicating that the effects of thermal stimuli at 29 °C predominate over the colour stimuli on the evaluation of thermal perception. Based on these findings and considering the between-subjects design of this study, we foresee a second series of experiments to increase the sample size and reduce the variability within subjects.

Although the use of virtual reality in this study greatly increased the control over the visual stimuli, one of the main challenges that emerge is the reproduction of colour on the headset display. The selection of tone-mapping operators can greatly affect the colour rendering of the scene, which can in turn directly impact the effect of exposure to colour. The limited luminance of the virtual reality display is another factor of importance, which should be investigated to test the reproducibility of the findings in real environments. Future studies are encouraged to compare subject thermal perception across combinations of thermal and visual conditions in real and virtual environments, and further our understanding of the capabilities and limitations of immersive virtual reality in experimental studies.

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The Evaluation of Measurement Uncertainty of LED Luminaire for Industrial Applications

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***Abstract*— The European standard EN 13032-4 *Measurement and Presentation of Photometric Data – Part 4: LED Lamps, Modules and Luminaires* for the photometric characterization of LED sources and luminaires requires the evaluation of the measurement uncertainty for each measured photometric and colorimetric quantity.**

For industrial photometric laboratories, this approach increases flexibility in the selection of instruments and in the definition of measurement procedures, but requires the development of *ad hoc* methodologies for the evaluation of measurement uncertainty, necessary to obtain accreditation from National Accreditation Bodies.

In order to not increase measurement costs or time, simplified approaches could be developed but conventional approximation shall be considered at normative level to guarantee an accurate and consistent evaluation of the measurement uncertainty and comparable evaluation between laboratories.

The paper considers mainly the measurement of Solid State Lamp (SSL) and luminaires and describes how measurement models can be simplified following conventional rules that have been proposed for the development of an Italian National Technical Specification.

***Index Terms*-- Measurement uncertainty, Photometry, Standard.**

INTRODUCTION

The European standard EN 13032-4 [1] for the photometric characterization of LED sources and luminaires requires the evaluation of the measurement uncertainty for every measured photometric and colorimetric quantity.

Reliable and accurate photometric and colorimetric data are the basis for designing efficient and reliable luminaires and lighting systems. For this reason EN 13032-4 [1] specifies *standard test conditions* for the laboratory and the device under test (DUT) and gives *specific requirements* for test equipment. The standard proposes a tolerance interval for these conditions and requirements, but it permits deviations outside the tolerance intervals if the related measures are corrected for the influence of the deviation and the measurement uncertainty adequately evaluated. This is a quite new approach because in this way the standard does not specify a maximum acceptable measurement uncertainty level, but every laboratory can operates according to the real expectation of its market, optimising costs and times of measurement and laboratory initial investments.

In part 1 of the same standard [2] (now under revision) the evaluation of measurement uncertainty is formally not required but a great number of detailed quantitative specifications on the metrological characteristic of instruments and on the operating, environmental and geometrical conditions are given. These requirements were evaluated starting from an undeclared, but realistic, measurement uncertainty level. They consider the main sources of measurement uncertainty and measurement errors but they are strongly correlated to the characteristic of the measured light source types.

Part 1 of the EN 13032 standard [2] has been developed more than 10 years ago. At that time, the measurement uncertainty concept was well known in the technical and scientific context, but its evaluation was practically an unknown task in many industrial and testing-house laboratories. The JCGM guides [3][4] and the CIE technical report [5] are now powerful documents but their application is still considered very difficult for every day work, especially if considering industrial photometric measurements.

This reason mainly justify the approach adopted by the technical group that developed part 1 of the CEN standard [2], but this approach has several drawbacks:

- The influence of the laboratory measurement procedure is completely underestimated. A good measurement procedure can overcome some lack in the metrological characteristic of the used instruments, while increasing the number of influence parameters that are measured permits to quantify and to apply correction factors. On the other hand, an inadequate measurement procedure can increase the contribution, in the uncertainty budget, even of an instrument with very good performances.

- Requirements for instruments and laboratories are based on the prevalent light sources and luminaires technologies on the market when the standard has been developed: new light source types or power supply devices may require different specifications, additional precautions or even a “softer” approach. A detailed new standard or addendum to the existing ones shall be published when new technologies appear on the market. This is the case of LED sources, for which two aligned standards have been published by CIE [5] and CEN [1] and should be the situation for OLED luminaires in the next future. They have peculiarities (dimensions, possible presence of fluorescence due to incident light, chromatic non-uniformities of the luminous surface, etc.) that should be characterized and can influence the measurements uncertainty of the photometric and colorimetric quantities. In these situations, parts of the laboratory instrumentation could become obsolete and the idea to accept or to permit a greater measurement uncertainty for those sources could be a reasonable solution.

- Requirements should consider the more stringent conditions for a given class of products or sources. This was reasonable in the past when a small number of lamp and ballast types or categories was present in the market. Nowadays, with the same device name (i.e. LED drivers) many products are available with a great dispersion of technical characteristics, with the consequence that it is possible to find luminaires with the luminous flux very stables considering the voltage variations of the power line but that can significantly change with small variations of the power line impedance [7]. This situation could become an unnecessary cost for the industrial laboratory (both in instrumentations and in measurement time) if the lab measures a well defined set of light sources or luminaires.

- The uncertainty value that could be obtained following the entire set of standard requirements is not given in the standard and cannot be declared explicitly in test reports, as accreditation bodies requires [8]. The accredited laboratory shall evaluate its uncertainty following only its experience, scientific bibliography and guides, often considered too complex for industrial laboratories. The result is that often the measurement uncertainty is not given in the test report, the measured values are given with an unrealistic too high number of significant digits or the customer requiring the text report has no information about the algorithm followed to obtain the measurement uncertainty value or about its reliability.

- Industrial laboratories use commercial measurement systems and commercial software. This solution has the advantage that instruments and measurement procedures implemented by software follow standard requirements. The laboratory has not the necessity to validate the software (acquisition, elaboration and text report editing) because the validation process is done or supposed to be done by the measurement system manufacture. The disadvantage is that generally the measurement software does not evaluate the measurement uncertainty and the metrological characteristics of the used instruments are not known with the necessary accuracy and completeness. Without these peculiar data and those arising from the type of measured device it is difficult to develop a scientific and sound measurement model and correctly evaluate the measurement uncertainty.

In addition, if at a first reading the standard structure seems to be the same, the approach of EN 13032-4 [1] is completely different. In this standard, the evaluation of measurement uncertainty is the key point: all requirements and decisions in developing a measurement procedure shall consider a measurement uncertainty level that is now a peculiarity of the laboratory. Standard requirements can be considered as way to simplify the measurement model and its management, not a shortcut to substitute its development. The laboratory measurement procedure, the selection of instruments and the environmental constrain shall be defined considering both the requirements of the standards and the uncertainty level goal of the laboratory. The use of correction factors, with known uncertainty, and/or peculiar procedures can compensate for some discrepancies to standard requirements without lose the possibility to write in the test report that measurements complies with standard.

This approach has two main advantages for the industrial or testing house laboratories:

- The measurement cost can be correlated to the required measurement uncertainty level. Measurement can be done for different aims: data to be published in catalogue, verification of production tolerances, pass/not pass testing, verification of performance respect to EU directives [9], verification of design expectations, research for new design solutions, studies for evaluating performances at different working conditions.

- The selection of instruments, the laboratory layout, the definition of the steps in the measurement procedure can be done according to the main aims of the laboratory or to the type of product that will be measured.

This approach has advantages for customers too:

- The accredited laboratory can be selected according to the best compromise between measurement cost and measurement uncertainty, considering the aim of the measurement.

- Results can be easily compared considering the influence of the measurement uncertainty [10].

- In problematic cases the selection of a laboratory with a better accuracy can resolve any dispute between manufactures and customers.

THE DEVELOPMENT OF A MEASUREMENT MODEL

For the photometric laboratory, the approach adopted in EN 13032-4 [1] increases flexibility in the selection of instruments and in the definition of the measurement procedure, but requires the development of a methodology for the measurement uncertainty evaluation (measurement model), useful to obtain accreditation from National Accreditation Bodies or in applications where the measurement uncertainty has an impact in lighting installation design for its strong relationship with the manufacture tolerances of devices and luminaires.

In developing a measurement model [3], [4] the following technical rules and compromises should be considered:

- The model shall be simplified as much as possible (i.e. it shall give a realistic evaluation of the uncertainty value, preferably with a small overestimation, with the lower reasonable number of parameters).
- The parameters involved shall give a real contribution to the uncertainty level (e.g. all parameters that have a contribution lower that 1/10 of the main ones should not be considered). When a parameter is considered in the model, not only the cost (time) necessary to measure it, but also the cost of its management (i.e. the calibration of the instrument necessary for its measurement) shall be considered.
- For a laboratory that would like to be accredited and to avoid discussions during the accreditation procedures, it is a good rule that its procedure for the measurement uncertainty evaluation mentions all the influence quantities that can affect the measurement results, giving quantitative, experimental or bibliographic justification of their level of relevance.
- Many parameters with small contribution can be gathered together in a single parameter.
- If possible, correction factor or correction coefficients should be considered to reduce the influence of same parameters in the measured values and in their measurement uncertainty, but it is an unproductive work to spend time and resources for correcting parameters that have a very small influence in the measurement results and uncertainty. Moreover, it is important to notice that the same correction factor can be irrelevant for a type of lamp and very important for another one (e.g. the spectral responsivity of the photometric detector).
- The real cost in evaluating the measurement uncertainty is not in the mathematical complexity of the measurement model, but in the way the single parameter values are obtained and justified.
- If the laboratory uses a commercial measurement system, sometime the manufacture of the system does the planned maintenance of the system considering also the calibration of reference sources or detectors. Generally, the calibration is carried out using traceable reference standards and measurement conditions very similar to those adopted by the lab (i.e. same type of instruments). In this case, the measurement uncertainty in the calibration certificate is greater than the typical value given by a national metrology institute, but the measurement model can be simplified because the influence of some parameters is already considered in the calibration uncertainty.
- Generally, in photometry a wide-used measurement model has the following form:

$$M_{\mathrm{m}} = (M_{\mathrm{r}} - C_1 - \dots C_c - \dots - C_C) K_1 \dots K_k \dots K_K \quad (1)$$

where:

M_{m} is the measured quantity;

M_{r} is the instrument reading of the measured quantity;

C_c is the c-th influence or input quantity (subtractive parameter in the following) with the same measurement units of M_{r};

K_k is the k-th influence or input quantity (multiplicative parameter in the following) with its own measurement units (1 if K_k is a factor).

Subtractive parameters can have a peculiar value (e.g. the dark current of the luminance meter that reads M_{r}) or they are null if only their uncertainty shall be considered. Multiplicative parameters can have a peculiar value (e.g. the calibration coefficient of that luminance meter) or their value is 1 if only their uncertainty shall be considered. For simplicity in the following, subtractive and multiplicative parameters with a peculiar value are called *correction parameters*.

When the measurement model is defined, there are two different approaches [9] to calculate the measurement uncertainty:

- the GUM uncertainty framework [3], i.e. an analytical approach that gives exact results if the measurement function is linear in the input quantities and their probability distributions are Gaussian. The analytical approach often works sufficiently well for practical purposes also if these conditions are not hold. This approach is relatively complex because requires the evaluation of sensitivity coefficients for each parameter of the measurement model and of the correlation coefficients for correlated input quantities. However can be managed with simple spreadsheet programs and gives a clear understanding of the parameters that have the greater importance in the uncertainty budget. This information is extremely useful when the obtained uncertainty level is not satisfactory and a strategy for improvement shall be defined.

- The Monte Carlo method [11] establishes numerically the measurement uncertainty by making random draws from the probability distribution of the measurement model parameters. Its numerical accuracy can be mathematically controlled. This approach is simpler to implement, the acquisition software can be easily modified for its evaluation or the uncertainty value can also be obtained with same spreadsheet programs.

SEMPLIFICATION RULES AND CONVENTIONS

The influence quantities considers in the measurement model depends on the:

- Characteristics of the laboratory, like the metrological characteristics of the used instruments, the calibration method and interval, the measurement procedure (e.g. the number of measurements, the stabilization time, etc.), the environmental and geometric conditions. These parameters can be considered constant for a given type of luminous source or luminaire.
- Characteristics of the DUT, like its short-term stability, its repeatability between different switch on and off, its mechamical limits in the accuracy of its alignment in the correct measurement position.

Unfortunately for industries and testing facilities it is usually difficult to consider both aspects, as the JCGM guide [3] instead requires.

In the Italian National Technical Specification for the evaluation of measurement uncertainty in photometry, to solve this problem two conventions have been proposed and are going to be evaluated by several Italian laboratories:

- specify the uncertainty considering classes of lamps or luminaires, the metrological characteristics of the laboratory instrumentations and the influence of the measurement procedure;
- not introducing in the uncertainty budget some parameters that are strongly correlated to the light source characteristics but instead specify in the testing report the measurement conditions that influences these parameters.

Following these conventions three measurement uncertainty specifications can be considered.

- **Complete specification**: the light source is measured several times to evaluate its repeatability (type A uncertainty). This means a statistically significant number of measurements and complete switch on/off cycles (alignment of the DUT in the measurement position, switch on, stabilization, measurement, switch off, cooling, safety removal). Values of the most relevant correction parameters that depend mainly on the light source characteristics are measured. Values of less relevant correction parameters, but light source dependent, can be obtained, using *average* data that the laboratory knows from similar light sources. These parameters shall be highlighted in the test report. The uncertainty contribution of influence quantities can be obtained using *average* data the laboratory knows from similar light sources (type B uncertainty).
- **Average specification**: the light source is measured only one time. Its repeatability is obtained using *average* data the laboratory knows for similar light sources or from the light source manufacture (type B uncertainty). This value of repeatability shall be given in the test report. Values of correction parameters that depend mainly on the light source characteristics can be measured or obtained, using *average* data the laboratory knows from similar light sources. These last parameters shall be highlighted in the test report. The uncertainty contribution of influence quantities can be obtained using *average* data the laboratory has from similar light sources (type B uncertainty).
- **Partial specification**: the light source is measured only one time. Its repeatability and some influence quantities are not considered in the uncertainty budget. These parameters shall be highlighted in the test report as not considered in the uncertainty budget. For the other influence quantities (those considered in the uncertainty budget) the same rules adopted for *average specification* are followed.

Some consequences of these conventions are:

- In the test report, it is clearly highlighted how the measurement uncertainty is evaluated.
- The number of measurement is reduced to the minimum necessary for the given applications. For example, manufactures can know very well the repeatability of their sources and can consider this aspect independently from the measurement results.
- Testing laboratories can evaluate their measurement uncertainty considering type of light sources, range of luminous flux values, rated or typical spectral distribution of the emitted light with given tolerances, etc.

- Testing laboratories can create their own database of values for the influence quantities and correction factors. In creating this knowledge, they can use measurements carried out for personnel training, during laboratory intercomparison, duplicate measurements for testing laboratory repeatability, etc.
- In measurement where the alignment of the light source is very important (e.g. the luminous intensity distribution) the measurement uncertainty can be express as a single value in percent of the luminous intensity, instead of different absolute values for every direction.

EXAMPLES

A. Influence of the dark current

The dark current is a typical example of a subtractive correction parameter that is not dependent from the light source type, but is determined by the characteristic of the light detector and its photocurrent amplifier. It can be measured periodically and for every detector range. In spectral measurement it can vary randomly wavelength by wavelength but its mean value is practically independent from the wavelength [12].

B. Luminous Intensity Distribution

In this case the measurement uncertainty is strongly dependent on the accuracy of the alignment of the light source in the goniophotometer and on the luminous intensity distribution itself, not only on the goniophotometer angular accuracy and repeatability. Sometimes the alignment is not possible with adequate accuracy for lack of reference points in the luminaire body. The problem is solved giving the measurement uncertainty following the rules of the *partial specification* previously described.

C. Stray Light

Stray light depends on the luminous intensity distribution of the DUT and the reflectance properties of the laboratory environment. Its measurement with the same DUT requires a new measure, but considering that in good laboratory it is a small fraction of the DUT luminous flux, it influence can be corrected considering this fraction and the uncertainty can take into account its variability with the measurement directions.

D. Influence of the Bandwidthin Spectral Measurements

In spectral measurements when the measurement uncertainty is greater than 3 %, generally bandwidth (if ≤ 5 nm) and spectral deconvolution are not the main sources of uncertainty, also when SSLs are considered [12].

CONCLUSIONS

In developing a measurement model, several mathematical simplifications can be done and the influence of several parameters can be obtained considering information from the laboratory historical database. Some simplification can influence the interpretation of the measurement uncertainty; therefore Standard should give clear conventional rules to avoid misunderstanding or wrong interpretations of results. A proposal of three measurement uncertainty specifications has been presented and discussed in the Italian standardisation group working on a Technical Specification concerning the measurement uncertainty in photometry.

These specifications consider the characteristic of light sources. For example, several SSLs have short-term stability and reproducibility better than the measurement uncertainty a typical industrial laboratory can declare without considering their influence [12]. On the other hand, if integrating spheres are used, errors can become very high with directional lamps or luminaires. In this case more measurements are required with the light source in different positions.

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Photometric and Colorimetric Testingof Colour-Tunable LED Lighting Products

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***Abstract*—Today a variety of colour-tunable LED lighting products are brought to market. Colour-tunable LED lighting comprises dim-to-warm (DTW) products, which reduce in correlated colour temperature (CCT) when dimmed, white-tunable (WT) products, which can be adjusted over a range of CCTs, and full-colour-tunable products. The new capabilities that come with these products engender new demands regarding test methods, in order to be able to compare and to evaluate the alternatives in a proper fashion. The key question that is addressed in this study, is which and how photometric and colorimetric properties of colour-tunable LED lighting should be reported. For this, radiometric and photometric characteristics of 7 DTW and 4 WT products are determined and analysed, covering the range of dim and CCT settings specified by the manufacturers. Results reveal significant differences in product characteristics which cannot be specified with measurements at just one test point.**

***Index Terms*—Colour-tunable LED lighting, colorimetric testing, photometric testing, product specification**

INTRODUCTION

Human Centric Lighting has become one of the key research areas within lighting over the past years. Putting health and wellbeing first, investigating the potential benefits of varying the light level and correlated colour temperature (CCT) over time in relation with a human being's 24 hour internal clock, the so-called circadian rhythm, has especially gained attention. Manufacturers of LED products respond to this trend by offering today a variety of so-called colour-tunable LED lighting products of which the spectral power distribution can be adapted. Colour-tunable LED lighting can be subdivided into three categories; dim-to-warm (DTW) products, which reduce in CCT when dimmed, white-tunable (WT) products, which can be adjusted and theoretically dimmed over a range of CCTs, and full-colour-tunable products, which can be adjusted to create white as well as coloured light.

The new capabilities and performance variables that come with this type of products engender new demands and requirements regarding test methods, since an appropriate specification of the LED products is necessary in order to be able to compare and to evaluate the alternatives on the market in a proper fashion. Indeed, with a change in the spectral power distribution, the photometric and colorimetric properties of the product are also adapted. Therefore, the key question that is addressed in this study, is which and how photometric and colorimetric properties of colour-tunable LED lighting products should be reported in relation to the product settings. More specifically, the amount of testing required to fully characterize DTW and WT products is investigated.

A series of 7 DTW and 4 WT products, produced by different lighting manufacturers, has been selected for use in the study. A near-field goniophotometer as well as an integrating sphere setup are used to determine the key properties of all products at several testing points, according to the specifications defined in IES LM-79-08 [1] and CIE S 025/E:2015 [2], and covering the range of dim (luminous flux) and CCT settings as specified by the manufacturers. For each setting, the features that are reported include the photometric quantities of total luminous flux and luminous efficacy, colour characteristics such as CCT, colour rendering index (CRI) and spectrum, and the electrical properties of power, voltage, current and power factor.

DEVICES UNDER TEST

In order to define the focus of the study, full-colour-tunable LED lighting products were excluded from consideration. Indeed, control of full-colour-tunable products is typically much more complex than for DTW or WT products, requiring for some type of digital interface if it is to be user-controlled and not preprogrammed [3]. Lighting manufacturers were requested to participate in the study by providing one or more of their products. In return, all measurement results obtained on their product(s) were made available to each manufacturer after completion of the study. A total of 7 DTW and 4 WT products were received form the following lighting manufacturers; da'LUX, Feilo Sylvania, iGuzinni illuminazione, Megaman, LEDVANCE, Philips Lighting, Radium, and Trilux.

A. *Dim-to-Warm products*

DTW products included in the study consist of 4 DTW lamps and 3 DTW lighting fixtures, product categories which will further be denoted as DTW-L and DTW-F, respectively. An overview of the specifications (total luminous flux, input power, luminous efficacy, covered CCT range, and minimum CRI) of all 7 DTW products, as specified by the manufacturers, is presented in Table I.

B. *White-Tunable Products*

WT products included 4 lighting fixtures, further denoted as WT-F. The products can further be divided into 2 groups; directional vs. non-directional fixtures. Typically, the directional fixtures with smaller apertures result in lower efficacies, although the type of white-tuning could also be a contributing factor. No WT lamps were found to be available on the market. An overview of the product specifications as provided by the manufacturers is again presented in Table I.

TABLE I. PRODUCT SPECIFICATIONS OF THE DEVICES UNDER TEST AS STATED BY THE MANUFACTURERS.

Product ID	Total Luminous Flux (lm)	Input Power (W)	Luminous Efficacy (lm/W)	CCT Range (K)	CRI
DTW-L-1	470	7	67	1800 – 2700	80
DTW-L-2	806	10	81	2000 – 2700	80
DTW-L-3	470	6	78	2200 – 2700	80
DTW-L-4	470	6.5	72	2000 – 2700	80
DTW-F-1	980	13.5	73	1800 – 2700	> 90
DTW-F-2	52 - 590	7.5	79	2000 – 2800	80
DTW-F-3	650	10	65	1800 – 2700	90
WT-F-1 (directional)	1074	23	47	2100 – 4300	90
WT-F-2 (directional)	780	28	28	2700 – 6500	89 – 96
WT-F-3 (directional)	901	17	53	2700 – 6500	> 80
WT-F-4 (non-directional)	4100	35	117	2700 – 6500	> 80

TEST PROTOCOL

Measurement specifications defined in IES LM-79-08 and CIE S 025/E:2015 were used as a starting point to determine the product characteristics of all devices under test at a specific testing point. Within CALiPER Report 23 (‘Photometric Testing of White-Tunable LED Luminaires’) [3], United States Department of Energy (U.S. DoE) defined a number of guidelines regarding the number of testing points for colour-tunable products. The report states that for DTW and WT products, colorimetric and photometric specifications should be provided for the minimum, mid-range, and maximum CCT settings. For products with more than 3 LED primaries, the number of testing points along the “white” range should be increased to 5 or 7 settings.

In this study, 4 testing points were put forward for DTW products, defined as a function of the dim value: 100 % (full luminous flux output), 60 %, 40 %, and a final testing point at stable minimum output. An additional testing point at 80 % of the full output could be considered. If the results showed that the selection of measurement points was insufficient, this extra measurement point was taken into account.

With regard to the WT products, the focus of the study lies on the performances over the colour (CCT) range. For each luminaire, 5 measurements were therefore put forward, at CCTs evenly distributed over the theoretically specified CCT range. Yet, for this product category it is also possible to dim the luminous flux at a fixed CCT. Quantifying the performance of the WT products when dimmed at a constant CCT was however not addressed.

All measurements were performed by use of a near-field goniophotometer and an integrating sphere (diameter 2 m), available at the Light & Lighting Laboratory research group of KU Leuven [4]. Electrical characteristics were measured with a calibrated power analyser (Yokogawa WT3000).

TEST RESULTS

Before addressing the measurement results, it is important to notice that the purpose of this study was not to evaluate the suitability of the devices under test. All products were selected with the intent of capturing the current state of the market, representing a broad range of performance characteristics. For each product line, only one test sample was evaluated. For these reasons, the respective results should not be generalized to the entire product line or taken as a verdict on the product line.

For all products, the measured range (minimum and maximum) of photometric quantities of total luminous flux, luminous efficacy and luminous efficacy of radiation, and the range of the electrical quantities of input power and power factor, are depicted in Table II. In a similar way, colorimetric characteristics of covered CCT and CRI are presented in Table III. Photometric quantity values that are more than 10 % below the values stated by the manufacturers are indicated in bold and in red. For the range of CCT, a deviation of more than 100 K from the stated range is regarded as not being in accordance with the specifications. Likewise, the non-conforming values are indicated in bold and in red.

TABLE II. MEASURED PHOTOMETRIC AND ELECTRICAL PROPERTIES OF THE DEVICES UNDER TEST.

Product ID	Total Luminous Flux (lm)	Input Power (W)	Luminous Efficacy (lm/W)	Luminous Efficacy of Radiation (lm/W_{rad})	Power Factor
DTW-L-1	187 – 486	3.15 – 7.34	**59** – 75	313 - 322	**0.34** – 0.65
DTW-L-2	7.6 – 872	0.48 – 10.1	**16.0** – 87	253 – 323	0.30 – 0.93
DTW-L-3	17.0 – 478	1.27 – 6.02	**13.4** - 79	278 – 325	0.24 – 0.84
DTW-L-4	22.9 – 463	1.09 – 7.46	**20.2** – **62**	250 – 324	0.17 – 0.86
DTW-F-1	26.1 – **692**	1.79 – 16.0	**14.6** – **43**	230 – 269	0.19 - 0.73
DTW-F-2	22.8 – 535	1.87 – 16.0	**12.2** – **34**	245 – 274	0.20 - 0.74
DTW-F-3	10.3 – 693	1.59 – 12.3	**2.6** – **56**	246 – 276	0.39 - 0.94
WT-F-1 (directional)	**842** – 1033	19.1 – 20.7	44 – 50	335 – 358	0.95 - 0.95
WT-F-2 (directional)	**592** – 712	21.6 – 25.5	27 – 33	327 – 349	0.90 - 0.93
WT-F-3 (directional)	**793** – 951	15.2 – 16.0	52 – 63	266 – 276	0.91 - 0.92
WT-F-4 (non-directional)	4132 – 4409	37.4 – 40.0	105 – 117	307 – 333	0.89 - 0.92

TABLE III. MEASURED COLORIMETRIC PROPERTIES OF THE DEVICES UNDER TEST.

Product ID	Covered CCT Range (K)	D_{uv}	Covered CRI range
DTW-L-1	**2638** – 2809	(-0.0032) – (-0.0021)	82 – 83
DTW-L-2	2014 – 2794	(-0.0018) – (-0.0001)	81 – 85
DTW-L-3	2229 – 2731	(-0.0025) – (-0.0012)	80 – 84
DTW-L-4	1975 – 2735	(-0.0017) – (-0.0001)	81 – 85
DTW-F-1	**1923** – 2802	(-0.0022) – 0.0001	95 – 97
DTW-F-2	1820 – **2644**	(-0.0022) – 0.0012	89 – 94
DTW-F-3	1811 – **2592**	(-0.0009) – 0.0019	89 – 94
WT-F-1 (directional)	2122 – 4284	(-0.0045) – 0.0023	**83** - 91 (90)
WT-F-2 (directional)	2432 - **5248**	(-0.0040) – (-0.0010)	87 - 92 (89 - 96)
WT-F-3 (directional)	**2833** - 6554	(-0.0077) – (-0.0024)	93 – 97
WT-F-4 (non-directional)	**3047** - 6955	(-0.0024) – (-0.0040)	81 – 84

k.

A. DTW Lamps

With the exception of the luminous efficacy of DTW-L-4, all reported measurement values at full output (100%) correspond to the values stated by the manufacturers, and are reasonably high. When dimmed at stable minimum output, the luminous efficacy of the products decreases drastically. The only exception is DTW-L-1, for which the luminous efficacy decreases by only 21 % (from 75 lm/W to 59 lm/W). Yet, even for this lamp, the luminous efficacy at stable minimum output is below the theoretical value calculated from the stated total luminous flux and input power.

Together with the luminous efficacy, also the CCT decreases with dimming. On the exception of DTW-L-1, for which the CCT range only covers 171 K (2638 K to 2809 K) instead of the stated range of 900 K (1800 K to 2700 K), all measured CCT ranges correspond to the values reported by the manufacturers. In each case, the CRI is above the stated threshold value of 80.

Important to notice from Table II is that, when dimmed, the power factor also decreases drastically. Yet, in general the reported values meet the threshold values for the lamp power factor for lamps with integrated control gear as defined in EU Regulation No 1194/2012 [5]. The only exception is again DTW-L-1, for which the power factor at 40 % dimming and at stable minimum output numbers 0.39 and 0.34, respectively, the threshold value in both cases being 0.4.

Before measurements are taken, solid state lighting products should be operated long enough to reach stabilization and thermal equilibrium. IES LM-79-08 defines stability to be reached when the variation (maximum minus minimum) of at least 3 readings of the light output and electrical power over a period of 30 minutes, taken 15 minutes apart, is less than 0.5 % [1]. It was expected that, when first measuring at full output, the stabilisation time would decrease as a function of dimming. Surprisingly, this was not the case. For products DTW-L-1 and DTW-L-4, even after 2 hours the stability criterion was not met for measurement at 40 % output and at stable minimum output. Nevertheless, even if the stability criterion was not met after 2 hours, measurements were started.

B. DTW Lighting Fixtures

While for the DTW lamps all reported measurement values at full output (100%) were in agreement with the values stated by the manufacturers, the results of the DTW lighting fixtures (luminaires) seem to correspond to a lesser extent to the theoretical data. For none of the 3 products the theoretical luminous efficacy is reached. While the stated luminous efficacies of the DTW lamps and fixtures are of the same order of magnitude, in practice, the values of the DTW fixtures are significantly lower, with values ranging from 34 lm/W to 56 lm/W. For DTW-F-1, the lower value can be attributed to the deficient luminous flux of 692 lm, instead of the stated 980 lm/W. For DTW-F-2, on the contrary, the low luminous efficacy is principally caused by the input power of 16 W, which is much higher than the stated 7.5 W. Luminous efficacy of radiation values corroborate the lower efficacy of the fixtures in comparison to the lamps, with values fluctuating around 275 lm/W_{rad} vs. 325 lm/W_{rad}, respectively. Similar as with the DTW lamps, the luminous efficacy of the DTW fixtures significantly decreases when dimmed at stable minimum output.

For none of the 3 DTW fixtures the CCT range over dimming corresponds to the stated values. While for DTW-F-1 and DTW-F-2 the range is shifted upwards and downwards with about 100 K, respectively, the specified range for DTW-F-3 is not achieved. Similar as to the DTW lamps, the CRI is always in agreement with the stated threshold values.

In analogy to the DTW lamps, the power factor significantly decreases with dimming, but values meet the threshold values as defined in EU Regulation No 1194/2012 at the various dim settings, except for DTW-F-1, for which the power factor at 40% dimming numbers 0.42, while the threshold value numbers 0.5.

Finally, for each fixture and setting, the stability before measurement was reached in a period between 30 min and 1 hour.

C. WT Products

While for the DTW products the total luminous flux and CCT obviously decreased with dimming, for WT products the stated total luminous flux should theoretically be maintained throughout the range of CCTs (since product manufacturers indicated just one value for the total luminous flux). As can be seen from Table II, this is not the case for the directional WT products WT-F-1 to WT-F-3. For the non-directional WT luminaire WT-F-4, on the contrary, the total luminous flux is maintained across all CCT settings, and moreover the output is much higher than for the directional WT counterparts. Taking into account the previously stated tolerances, the luminous efficacy of all 4 products is always within specifications. As expected, the luminous efficacy of WT-F-4 (non-directional luminaire) is much higher than the luminous efficacy of the directional WT products, with values exceeding 100 lm/W. Yet, luminous efficacy of radiation values indicate that WT-F-1 and WT-F-2 have the best intrinsic efficacy.

On the exception of WT-F-1, for none of the WT products the entire set of mentioned CCTs is obtained. Especially for WT-F-2 the range seems to be restricted. For WT-F-4, the range is shifted towards higher CCTs. In each case, CRI values are reasonably high and above the EU Regulation threshold value, although the manufacturers state higher values than those reached in practice.

In contrast to DTW products, the power factor of the WT products is high. Although the input power of WT-F-1 and WT-F-3 does not necessitates this, for all 4 WT products, power factor values reach the number of 0.9, threshold value (EU Regulation No 1194/2012) defined for products with an input power exceeding 25W.

To conclude, stabilisation seemed to be problematic for the 3 directional WT products. Especially for WT-F-2 and WT-F-3, where in no case stabilisation was reached after 2 hours. As stated before, measurements were started at that time, even if the stability criterion was not met.

DISCUSSION AND CONCLUSIONS

This study reports on photometric, electrical, and colorimetric testing and performance of 7 DTW and 4 WT LED lighting products. The products demonstrate the variety of performance characteristics that can be found on the market. Since the decision to purchase a product will primarily be based on the data released by the manufacturer or distributor, the performed measurements and results show that the current way of reporting characteristics of colour-tunable products might be far from adequate.

For DTW products, on the exception of the CCT range, manufacturers only report photometric, electrical, and colorimetric quantities at full output. Yet, measurement results indicate that these product characteristics are not obtained over the entire dimming range. Therefore, DTW products require at least an indication of the minimum and maximum value of the described quantities. For our tests, the minimum values of each quantity occurred when dimmed at stable minimum output, i.e. at lowest CCT. Therefore, besides a product evaluation at full output, measurements could also be performed at this setting point, although the limited sample set used in the study might not allow for a generalisation of the conclusions. Keeping in mind the reduction of the test load of the products to a strict minimum, a third and final evaluation at mid-range CCT settings could be performed as a basis for reporting the photometric and colorimetric characteristics of DTW LED lighting products.

Three out of the 4 WT products had some level of discrepancy between the tested range of CCT values and the listed values. While the deviation could be evaluated as being of only minor importance when a limited shift of the CCT range occurs, more substantial deviations, for which the theoretical CCT range is not obtained, were also found. Another important finding for the WT products is that on the exception of one product, the indicated total luminous flux was not obtained at each tested CCT setting. This might not be surprising. Indeed, with multiple LED primaries, it is essentially impossible to maintain the total luminous flux, input power, and luminous efficacy simultaneously while changing the spectral power distribution (i.e. the colorimetric properties). Manufacturers have the possibility to rely on keeping only one of the 3 quantities constant. This can be clearly seen in Figure 1, in which the normalized total luminous flux, input power, and luminous efficacy of all 4 WT products are presented as a function of CCT. A first categorization of WT products could as such be made based on the design method employed by the manufacturer. Furthermore, a second classification could be made based on the type of colour tuning (linear vs. non-linear). This subject was not addressed in this paper, but will be investigated in the near future.

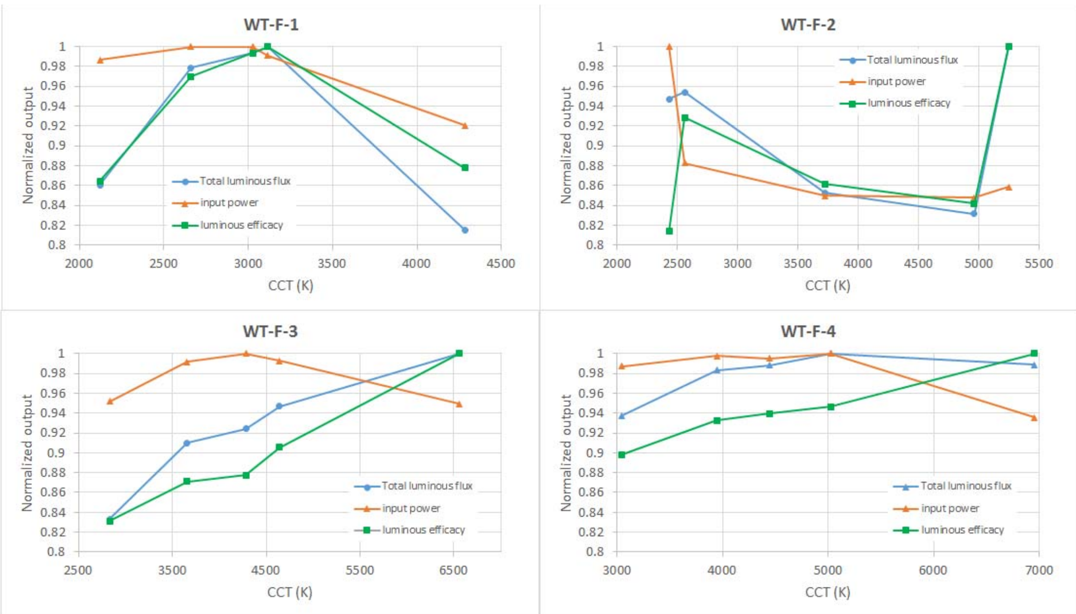

Figure 9. Normalized total luminous flux, input power, and luminous efficacy as a function of CCT for all 4 WT products.

Finally, although it could be assumed that the temperature equilibrium is quickly reached at any position when a measurement has taken place just before the measurement of another setting, our test results demonstrate that for both types of products (DTW and WT) stability before measurement is an issue. In CALiPER Report 23 [3], U.S. DoE advised not to wait for a full half hour when measuring a new setting, as described in IES LM-79-08 [1], as well as to already start the measurement after a shorter waiting time when dealing with luminaires that are clearly unable to stabilize their light output. These allowances will undoubtedly affect the accuracy of measurement. Clearly, further guidelines on how to test and report colour-tunable product characteristics are necessary for products that do not stabilize.

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Research Progress on GaN-based LEDs and Solid-state Lighting in China

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***Abstract*—Optoelectronics related to Gallium Nitride (GaN) based semiconductors, especially light-emitting diodes (LEDs), are cutting-edge technologies that have the potential to far exceed the energy efficiency of traditional lighting sources. As a solid-state lighting source for the next generation, the GaN-based LEDs arouse great interest for their small sizes, long lifespan and energy-efficiency. During the past ten years, the China solid state lighting market has evolved from merely $1 billion to more than $ 70 billion in 2016. Commercially available as GaN-based LEDs are, their light output power still needs improving. The limitation on light output power are mainly attributed to the low internal quantum efficiency, light extraction efficiency and current injection efficiency, which can be improved by optimizing materials epitaxy and devices processing. In this talk, we would like to report our recent progress on GaN-based LEDs and solid state lighting.**

***Index Terms*-- Gallium Nitride, light-emitting diodes, solid-state lighting, efficiency droop**

I. INTRODUCTION

Optoelectronics related to Gallium Nitride (GaN) based semiconductors, especially light-emitting diodes (LEDs), are cutting-edge technologies that have the potential to far exceed the energy efficiency of traditional lighting sources. As a solid-state lighting source for the next generation, the GaN-based LEDs arouse great interest for their small sizes, long lifespan and energy-efficiency. During the past ten years, the China solid state lighting market has evolved from merely $1 billion to more than $ 70 billion in 2016. Commercially available as GaN-based LEDs are, their light output power still needs improving. The limitation on light output power are mainly attributed to the low internal quantum efficiency, light extraction efficiency and current injection efficiency, which can be improved by optimizing materials epitaxy and devices processing. In this talk, we would like to report our recent progress on GaN-based LEDs and solid state lighting.

A. Carrier Localization In Ingan/Gan Multiple Quantum Wells

Although the threading dislocation density during epitaxial growth on a lattice mismatched sapphire substrate is relatively high, it is possible to obtain an $InxGa_{1-x}N$/GaN-based quantum well LED with high quantum efficiency [1]. This is usually due to the localization of the carriers, which reduces the movement of the carriers to the nonradiative recombination centers, resulting in high internal quantum efficiency of the $InxGa_{1-x}N$/GaN based LEDs [2], [3]. Many groups have proposed different mechanisms to illustrate the origin of defect-insensitive emission probabilities in InGaN/GaN multi-quantum wells (MQW). Although some models appear to be reasonable for the InGaN quantum well structure, the origin of the carrier localization effects and the recombination dynamics still need to be further explored.

We have grown InGaN/GaN samples on (1000) plane sapphire substrates and obtained the conventional green LED structure by metal organic chemical vapor deposition (MOCVD). The main emission peak (PL) and the additional weak peak (PH) with different intensities, which are related to the In and the InGaN/GaN MQW regions, respectively, can be observed from the temperature-dependent PL (10K~300K) [4], [5] and the emission energy of the two peaks (PL and PH) shows a large continuous blue shift, which are potentially formed in local resembling In-rich clusters [6].

The energy-dependent TRPL curve of the sample was measured at 10 K to study the carrier recombination dynamics in MQW, The detailed results of decay times of the sample are shown in Fig. 1. Due to the action of the piezoelectric field and carrier localization in QWs, the electron and hole wave functions are spatially separated, resulting in a longer decay time on the TRPL spectrum [7]. In addition, the flat mesa observed in the middle of the life curve divides the line into two parts, which indicates that the two sides of the PL spectrum have different carrier localization effects. According to these facts and the temperature-dependent blue shift of the emission energy, it is proved that both peaks PL and PH should be derived from the localized state of the radiation recombination.

In the In-rich areas, it may form clusters and quantum dot-like structures, resulting in deep traps as localized radiating recombination centers and capturing excitons. In addition, the change in well width is the main reason that our sample is rich in vector-rich positioning. Therefore, the deep traps and shallow traps are derived from the local composition of In and the thickness of the active layer.

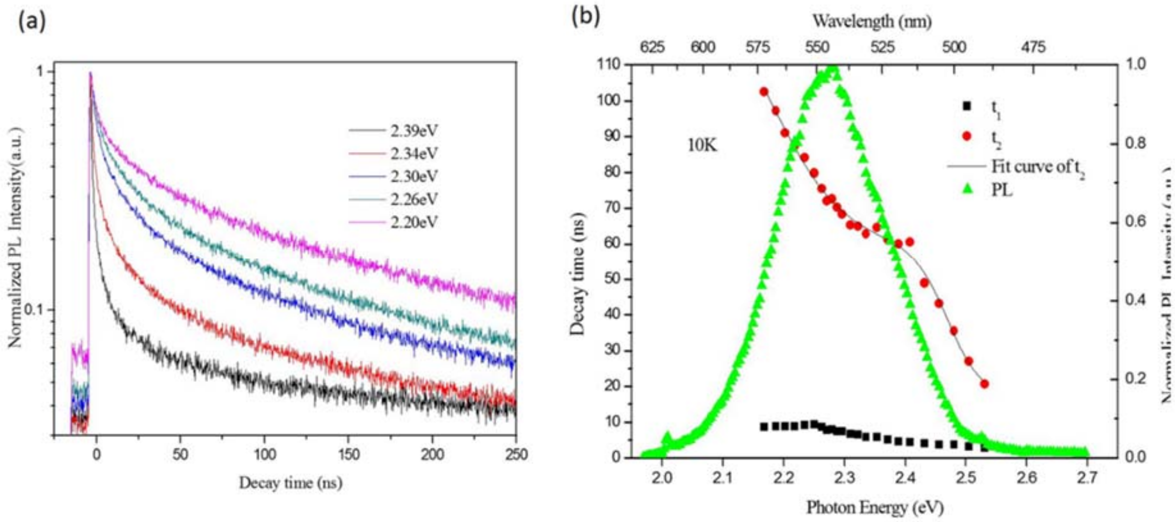

Figure 1. (a) Energy-dependent TRPL curves measured at 10 K. (b) The photon energy dependent decay times integrated with low temperature PL spectrum.

A model is presented to illustrate the origin of these two different carrier localization effects, as shown in Fig. 2. In the case of rich areas, there are quasi-MQW regions, where the distribution of In can be considered as uniformity as normal MQWs, but the thickness of QW changes. In the quasi MQWs regions, the formation of many shallow radiation traps are caused by these morphological fluctuations in the interface, resulting in carrier localization and peak PH radiation emission. In the In-rich regions, because of the strong separation of indium components, the composition of the fluctuations causes these areas to fluctuate, thus forming many deep traps.

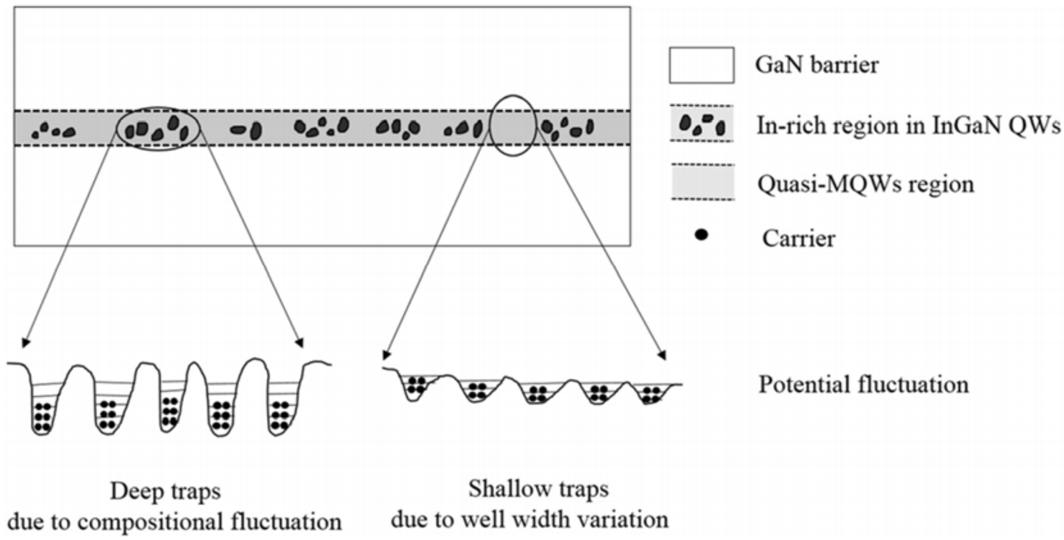

Figure 2. Schematic model to explain the distinct origin of two carrier localizations

The carrier-limited depth of the rich rare earth region (about 60 meV) is twice that of the quasi-MQW region (about 28 meV), which also indicates that the positioning effect due to compositional fluctuations is stronger. It can be summarized that the composition fluctuation of the In content and the variation of the well width correspond to the confinement limiting effect of the indium region and the quasi-MQW region, respectively.

B. Graphene as Transparent Conductive Layer For Vertical Light Emitting Diodes

It is very desirable to use graphene as a functional component in optoelectronic devices such as light emitting diodes (LEDs) thanks to its excellent optical and electrical properties.8-11 With better thermoelectric and optical characteristics, vertical-injection InGaN-based light emitting diodes (VLEDs) are expected to pre-eminently shine in future LED devices, along with the pursuit of high power and high efficiency. Increasing the optical output power and lighting efficiency at large injection currents is a key technical issue that needs to be addressed.

We have fabricated a vertically implanted InGaN-based light emitting diodes (VLEDs) with multiple layers of graphene as the addition of transparent conductive layer (TCL) beneath the top opaque N-electrode,12,13 effectively enhancing device performance in the case of large injection currents. The schematic diagram of the preparation process is shown in Fig.3. The epitaxial layer consisting of unintentionally doped GaN (u-GaN) layer, n-type GaN:Si layer, InGaN/GaN multiple quantum well (MQW) active layers and p-type GaN:Mg layer is sequentially superimposed on the (0001) oriented sapphire substrate using metal organic CVD. After the active layers of InGaN well layer and GaN barrier layer are grown, a high reflective metallization contact is deposited by electron beam evaporation as p-contact. Subsequently, the laser stripping process separates the sapphire substrate from the epitaxial layer and exposes the GaN layer. Followed by copper plating as a substrate, the separated GaN layer is cleaned and the periphery of the chip is passivated. Finally, after the underlying copper substrate was dissolved in the FeCl3 solution, the CVD-grown floating graphene film was transferred to the VLEDs, followed by deposition of the Cr/Pt/Au N-electrode to complete the preparation of the device.

Compared to commonly used ITO, graphene film as TCL layer presents more excellent optical properties with transmittances between 85% and 97% independent with wavelength while the transparency of ITO is approximately 80% in the range of 400~800 nm but rapidly attenuates in near ultraviolet region.

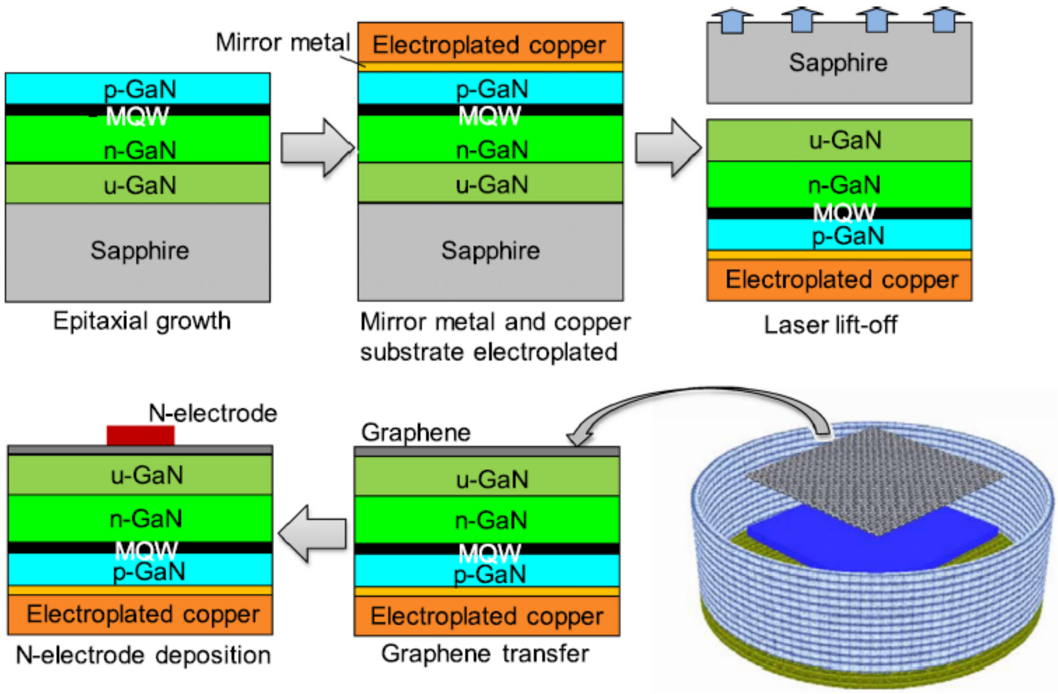

Figure 3. Schematic diagram of the G-VLED fabrication process

The contrast is also carried out in the optical and electrical properties of the devices using graphene and ITO as TCL, respectively. Compared with R-VLEDs (with ITO TCL), it can be observed that the light output of G-VLEDs (with graphene TCL) is increased by 25% according to the light output intensity-current (L-I) characteristics illustrated in Fig. 4(a). Luminescence photographs of G-VLEDs and R-VLEDs in Fig. 4(b) illustrate the G-VLEDs have a relatively uniform current distribution to prevent the current from accumulating below the N-electrode, making it more meaningful for high current levels.

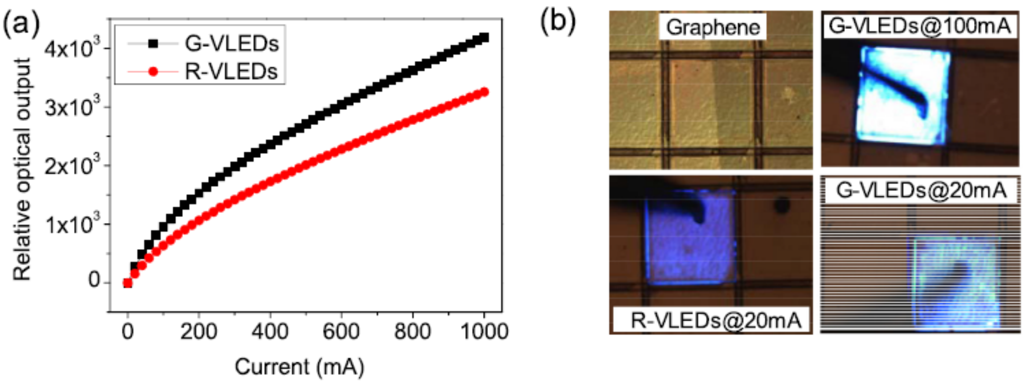

Figure 4. (a) Light output intensity versus current curve for G-VLEDs and R-VLEDs. (b) Emission graph of GVLEDs at different injection current

Regrettably, compared with the remarkably improved optical properties, the electrical properties of G-VLEDs have deteriorated. Thus, the high temperature annealing method is proposed to improve the electrical properties and obtain a forward voltage comparable to R-VLEDs. High temperature annealing has a significant influence on the I-V characteristics of G-VLEDs. By prolonging the annealing time, the samples are treated with RTA for 180s, which can effectively reduce the rise of the forward voltage due to the increment of the large contact resistance between graphene and u-GaN layer.

Furthermore, the depth distribution of the metal elements before and after annealing is investigated and it is proposed that the graphene partially sandwiched between the upper N-electrode and the lower diffusion N-electrode in the N-electrode pattern areas is formed by the diffusion of the metal atoms of the N-electrode and the Ga atoms during the annealing process. Fig. 5 shows the image of the process roughly.

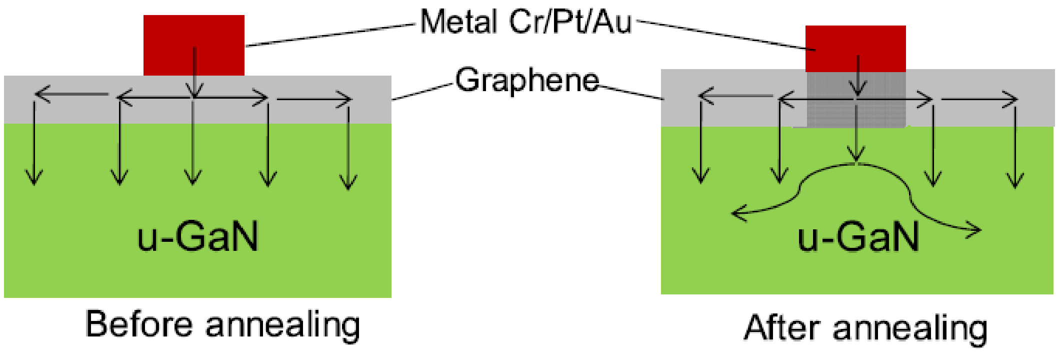

Figure 5. Schematic diagrams of G-VLEDs before and after annealing, inter-diffusion process of N-electrode metal and GaN across graphene.

The presence of sandwich graphene after high temperature annealing makes the distribution of the injected currents more uniform and does not lead to deterioration of the electrical characteristics more crucially, so that can be used as an ideal "current diffusion layer" to effectively improve the overall VLEDs performance. This work has further promoted the practical application of graphene in optoelectronic devices.

C. Micro-Nano Structure Gan-Based Leds

GaN-based white light emitting diodes (LEDs) is excellent for its low energy consumption and long life bearing, leading a revolution in solid-state lighting and display backlight. However, as the most widely used approach to generate white light using LEDs, blue LED with yellow phosphors [14] has some disadvantages need to be overcome. Therefore, the most promising phosphor-free white light LEDs, such as a broad spectral width luminescence of nanorod-based LEDs, are highly desired to realize low-cost monolithic white light emissions. [15], [16] The InGaN/GaN multi-quantum wells (MQWs) grown on nonpolar or semipolar GaN facets are suggested to have effectively increase of the light extraction efficiency and reduce the quantum confined stark effect (QCSE), which makes an increment of the internal quantum efficiency of LEDs by enhancing the radioactive recombination rate in MQWs. [17], [18]

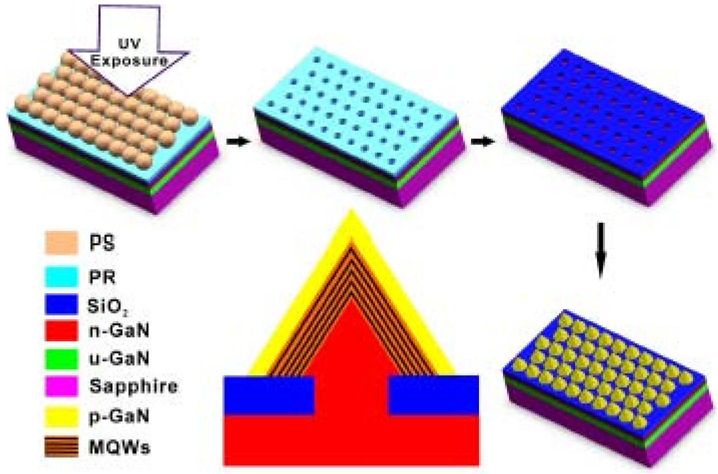

Figure 6. Schematic illustrations of the process for fabricating phosphor-free nanopyramid white GaN LEDs by NLP method.

We firstly fabricated nano-patterned templates followed by the growth of the nanopyramid LEDs with nanospherical-lens photolithography (NLP) through applying selective area epitaxy (SAE) methods. [19] We found along the [10-11]orientations, from outer to inner layer, both the indium incorporation and the thickness of QWs increase little by little. The thickness and indium incorporation of QWs on the {10-11} planes increase linearly towards the substrate. These nonuniform distributions lead to the nanopyramid LEDs with broadband emission.

As indicated in Fig. 6, plasma enhanced chemical vapor deposition (PECVD) was used to deposit a 400 nm thick SiO_2 layer on n-GaN, and the n-GaN template was coated by photo-sensitive resist (PR). The PR spin-coating nanospherical-lens was a hexagonal closed-packed monolayer of spheres of which the diameter is 900 nm . After exposure and developing process, air holes of which the diameter is 400 nm on PR were fabricated. Successively, the patterned PR was baked to bear the following inductively coupled plasma (ICP) etching of SiO_2 dielectric. SAE of GaN nanopyramid LEDs started with a 4 mins growth of Si-doped n-GaN nanopyramid arrays. A high V/III molar ratio of 12000 was set for promoting vertical growth to achieve nanopyramids with {10-11} facets. The total pressure and temperature were set as 200 torr and 1055℃, respectively. Subsequently, for growing the active regions, the temperature decreases to 740–780℃, at the V/III ratio of 4800 and the total pressure of 150 torr. In the last, a p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer with a thickness of 20 nm and 30 nm Mg-doped p-GaN cladding layers were grown.

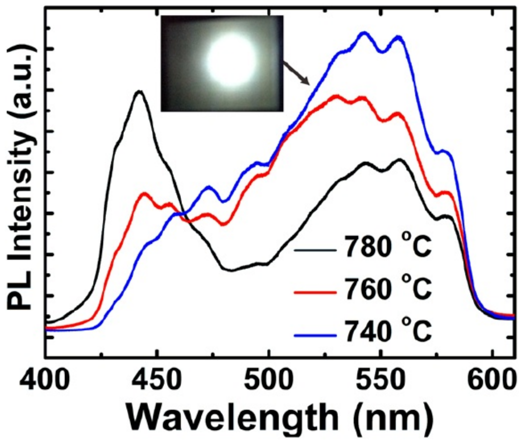

Figure 7. (a) Room-temperature PL spectra from MQWs of nanopyramid LEDs grown on different temperatures, the inset showing the optical micro-scope image taken from PL measurement.

Fig. 7 indicates PL spectra at the room temperature of the InGaN/GaN MQW grown on the {10-11} surface of nanoparticles. As shown in the inset of Fig.7, we have found broad spectral luminescence and white emission. The optical microscope image was taken from PL. With the growth temperature of QWs decreasing from 780℃to 740℃, the peak intensity of PL in the short wavelength emitting region decreases gradually. In contrast, the peak intensity of the yellow emission region increases dramatically. Here, the PL spectrum of MQW grown at 740℃ is similar to the spectrum of sunlight, which is dominated by yellow emission of about 550 nm (the most sensitive wavelength of the human eye).

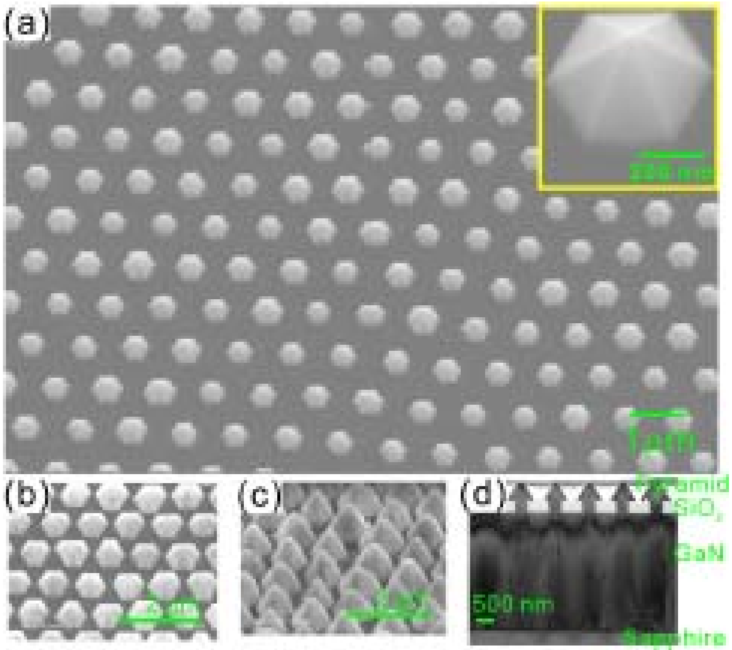

Figure 8. Tilted SEM images of (a) nanopyramid core arrays before MQWs were regrown, (b) nanopyramid LED arrays with SiO2 mask and (c) after removing SiO2, respectively. (d) TEM cross section view of the nanopyra-mid LED arrays. [14]

The core of the nanopyramid LED, a 4 mins growth of Si-doped n-GaN on SiO_2 masked n-GaN templates, is shown in Figure 8 (a). The core of nanopyramid LED is hexagonal and has a highly ordered arrangement of pyramid spires with six equal semipolar {10-11}sidewalls. The sidewalls show a form of circle, as shown in Figure 8 (a). On the core of nanopyramid n-GaN, the grown trend of active region and the p-GaN capping layer are shown in Fig. 8(b). After removing the SiO_2 mask, they obtained a mushroom shaped nanopyramid LED as Fig. 8 (c) indicated. Here, it is found that some of the nanopyramid LEDs show a small platform top, for the Mg-doped GaN on the side grows faster than that at the partial top. Therefore, the relatively thicker p-GaN grows to avoid metallization directly contacting with the MQWs, which may lead to electrical leakages. As shown in Fig. 8 (d), the cross-sectional TEM view of the nanopyramid LED structure reveals typical dislocations terminated beneath the SiO_2 mask. Thus, these nanopyramids can be considered as non-dislocation penetration, which is good for reducing electrical leakage. [20]

II. CONCLUCION

In conclusion, SSL are gradually replacing the conventional lighting applications, such as incandescent and fluorescent lamps. All our research works in China are carried out for developing more efficient SSL source. By combining all the novel technologies, high power white LEDs with efficiency above 200 lm/W has been demonstrated. This value is much higher than the efficiency of incandescent and fluorescent lamps. We have full confidence that the efficiency of SSL will be even higher in the future.

III. ACKONWLEDGEMENT

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Investigation of Wavelength Changes of the LEDs Used for Illumination

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***Abstract*— In this study, the analyses of the wavelengths of the light emitted by the LEDs that are used as a light source for illumination were made. For this purpose, the LEDs were placed in a black box together with the coolers, and the wavelength of the light emitted by the LEDs was measured by means of a radio spectrometer. The measurement was carried out in two separate time periods: short-term measurements and long-term measurements. In the short-term measurements, the measurements were started with the light emitting from the LEDs and repeated in 5 minute intervals for 2 hours. In the long-term measurements, the measurements were made with 15 minute intervals for 48 hours. Due to its importance the temperature of the LEDs was also measured at the same time intervals, from the central point on the roof of the black box. By comparing the obtained measurement results, the changes in wavelength were analyzed and interpreted.**

***Index Terms*-- black box measurement, cooler temperature, irradiation, LED, wavelength**

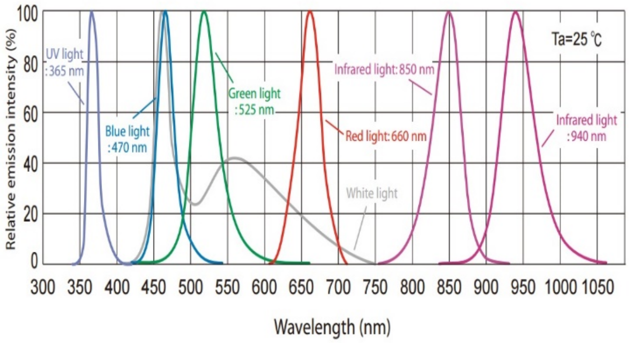
INTRODUCTION

With the improvements made in recent years Light Emitting Diodes (LEDs) have started to replace traditional light sources in many applications due to their various advantages such as high productivity, reliability, long lifetimes, variable colors and low power consumption [1]-[4]. Foremost among these applications are the back lights of mobile phones and LCD screens, interior and exterior automotive lightings including headlights, big signals and screens and signaling applications [5]. Moreover, it has been proven that LED performance is a successful solution for street lights [6]. It is understood that LEDs will introduce completely new functions to lighting systems and thus, increase the ways of using lights to a greater extent [4]. Especially in new generation lighting systems, high brightness or high power LEDs that can provide a visible light spectrum at a low costs and also save energy become the first choice [7], [8]. These high power LEDs ensure a higher level of light discharge than traditional indicator LEDs. Although these LEDs provide high performance levels in terms of productivity and long lifetimes, compared to other lighting technics, they lead to many technological problems. Generally, most of the electrical power of the LEDs is converted to heat, which significantly reduces the brightness of the LEDs. However, there are studies in which LEDs characteristically change the peak wavelengths with increasing temperature. In some of these studies [10], [3], the peak wavelength is observed with an increase in temperature, whereas in others it is stated that it is negligible [11].

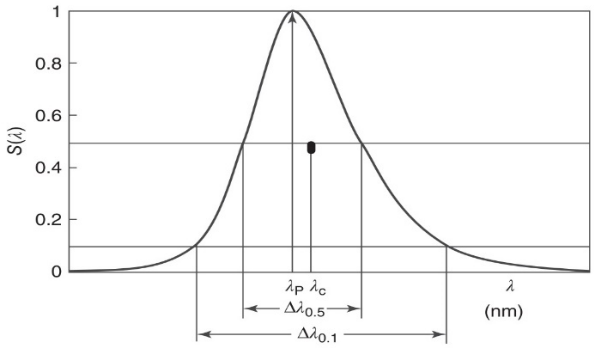
In this study, the working times were determined by considering the usage conditions of different applications where LEDs are used as light sources (street lighting, projection devices, solar simulators, etc.). Within this scope, Osram LB CP7P blue LUW CR7P 6500 K and LCW CQAR 3000 K white LEDs were used. Ever since they were first developed, high brightness blue LEDs and white LEDs have been used increasingly in the field of lighting [12]. The LEDs were placed in a black box with coolers and the wavelengths of the LEDs were measured with the Spectral Evolution SR 500 radiospectrometer. Measurements were carried out in two periods: short-term measurements and long-term measurements. For short- term measurements, the wavelengths of the LEDs were measured at 5 minute intervals for 2 hours. Long-term measurements were made at intervals of 15 minutes for 48 hours. In addition, since the temperature of the LEDs is also important, the temperature of the black box was measured within the same time slots. Due to the increase in the temperature of the LEDs in the measurements made, the temperature of the black box, which is a closed volume, also increased. By comparing the obtained measurement results, the wavelength changes due to temperature were analyzed and interpreted.

SPECIFIC SPECTRAL VALUES OF LEDS

LEDs are narrow band emitting light sources containing a semiconductor [13]. Wavelength is generally used to differentiate colored, ultraviolet (UV) and infra-red (IR) LEDs, but it cannot be used for white LEDs [14] .White LED sources are measured in Kelvin rather than in nanometers (nm). If the Kelvin temperature is low then a white LED light source appears warmer to the eye. Most of our LED light bulbs and fixtures are available in Kelvin temperatures ranging from a very warm, almost candle-like 2700K right up to a crisp white 6000K [15]. The wavelength of the colored LEDs is usually between 360 and 940 nm. The wavelength values of the LEDs from “UV” to “IR” are shown in Fig. 1 (a). Some specific values such as peak wavelength, spectral bandwidth at half intensity level and centroid wavelength used in LED calculations are also given below.



i.



(b)

Figure 41. Wavelength variation per color (a), characteristic wavelengths and wavelength intervals [10] (b)

Peak Wavelength

This is the wavelength at the maximum of the spectral distribution at which the spectral power distribution is usually normalized (see Fig. 1(b)). Note that LEDs exhibit a characteristic shift of peak wavelengths with temperature[10].

Spectral Bandwidth at Half Intensity Level

The spectral bandwidth at half intensity level $\Delta\lambda_{0.5}$ is obtained as the difference of two wavelengths on either side of the peak wavelength where the peak intensity of the LED drops to 50%. The quantity $\Delta\lambda_{0.1}$ can be defined similarly as the difference of two wavelengths on either side of the peak wavelength λ_P where the peak intensity of the LED drops to 10% [10].

Centroid Wavelength

The centroid wavelength λ_C is describe as the “center of gravity wavelength” [16] (see Fig. 1(b)) by Eq. (1).

$$\lambda_c = \frac{\int_{\lambda_1}^{\lambda_2} \lambda . S(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda) d\lambda} \tag{1}$$

In Eq. (1), λ_1 and λ_2 represent the bandwidth limits of the LED emission, the LED does not emit outside the (λ_1 ; λ_2) range. Note that $\lambda_C \neq \lambda_P$ because the relative spectral radiance distribution curve of a typical LED is asymmetric, see Fig. 1(b).

EXPERIMENT

The measurements we used to study the change in temperature at the peak wavelength of the LEDs were made with the high brightness blue, warm white and streetwhite LEDs, all of which are used in illumination. Osram LB CP7P blue, LCW CQAR 3000 K and LUW CR7P 6500 K white LEDs were preferred for this purpose. Four of each LEDs were used to accelerate the increase in temperature. Measurements were carried out in a laboratory for two periods: short-term measurements and long-term measurements. The LEDs on the PCB, which were mounted on the black box, were placed in a cube shaped box with a cross section of 30 cm (Fig.2 (a)). A microprocessor driver circuit was used for the PWM control of the LEDs and the LEDs were driven at maximum load. Wavelength measurements were made from the central point on the roof of the black box using fiber optic measurement equipment. Spectral Evolution SR 500 radiospectrometer and DARwin software were used in the measurements (Fig.2 (b)). For short-term measurements, the wavelengths of the LEDs were measured at 5 minute intervals for 2 hours. Long-term measurements were made at intervals of 15 minutes for 48 hours. Since the junction temperature of the LEDs is transferred through the cooler to the inner temperature of the black box, this temperature was measured within the same time intervals. At the beginning of the measurement, the temperature of the black box was about 25 °C. First the 2-hour measurements were performed. The blue LEDs, warm white LEDs and streetwhite LEDs were all individually lit and their data measured. Then, secondly the 48-hour measurements were performed. The whole system in obtaining these measurements was supported by UPS equipment in order for the power to not be cut off.

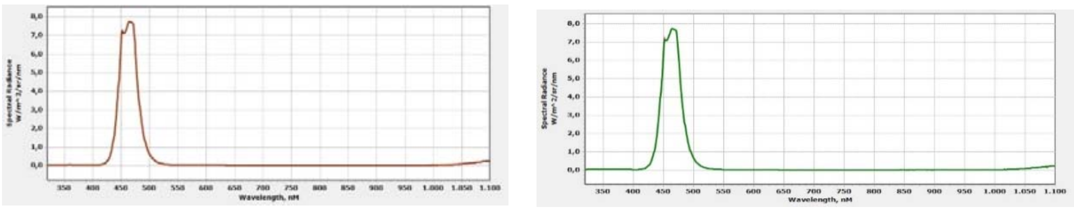
ii. (b)

Figure 42. Installation of the LEDs on the PCB and cooler (a) and test setup (b)

RESULT

A. Short-term Measurements

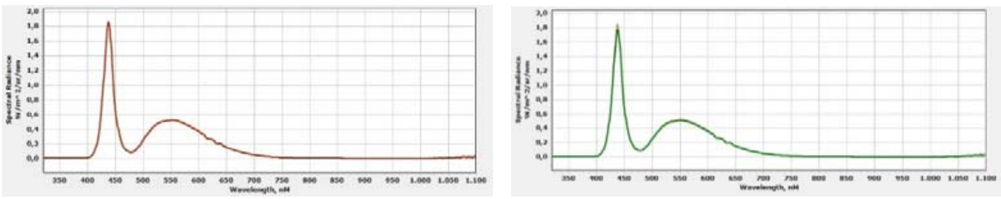
Initially, the blue LED had an ambient temperature of 25.96 °C for the 2 hour measurement, in which the result in Fig. 3 (a) was obtained. The blue wavelength was measured at 470 nm as indicated in the manufacturer datasheet. The irradiance of 4 blue LEDs were about 8 W / m2 / sr / nm. After two hours, the ambient temperature rose to 30.84 °C. The obtained wavelength curve is as shown in Fig. 3 (b). In Fig. 3 (b), the first and last measured values are given together.



iii. (b)

Figure 3. The first measurement of the blue LED wavelength (a) and the measurement after 2 hours (b)

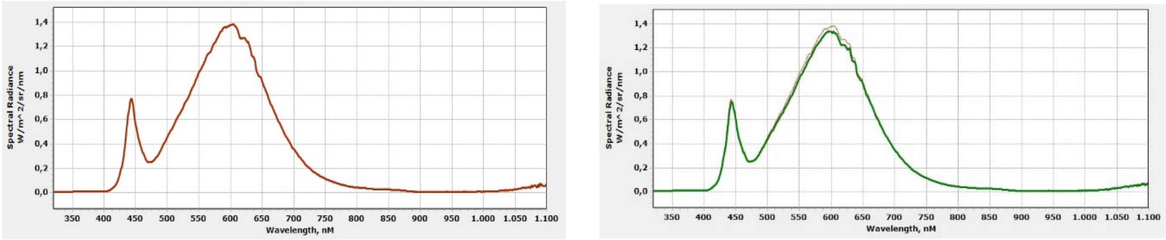
The second short-term measurement was made with the 3000 K LED, which is defined as warm white. It started with an ambient temperature of 26.46 °C and a wavelength corresponding to the datasheet information was obtained. The wavelength value obtained as a result of the measurement is given in Fig. 4 (a). The 3000 K LED reached an ambient temperature of 31.53 °C at the end of the 2-hour measurement and the wavelength was set as shown in Fig. 4 (b). It can be observed here that the intensity of radiation is decreasing even if it is small.



a. (b)

Figure 4. First measurement of the 3000 K white LED wavelength (a) and measurement after 2 hours (b)

In short-term measurements, lastly, the measurements of the 6500 K streetwhite LED were made. The temperature which started at 25.29 °C was found to be 31.58 °C after the 2-hour measurement. The 6500 K streetwhite LED's first measured wavelength is shown in Fig. 5 (a), and the last measured wavelength is shown in Fig. 5 (b).

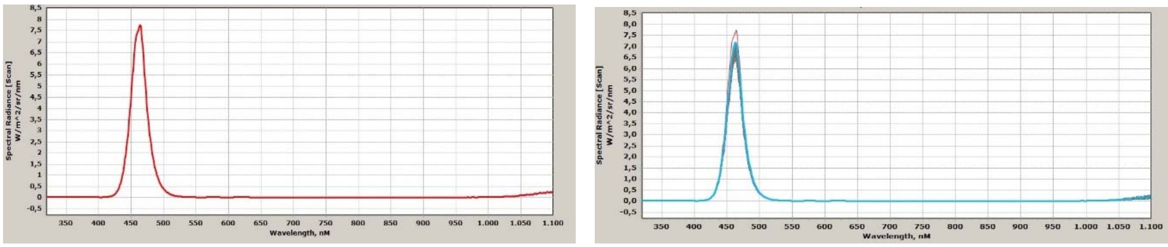


(a) **(b)**

Figure 5. The first measurement of the 6500 K white LED wavelength (a) and the measurement after 2 hours (b)

B. Long-term Measurements

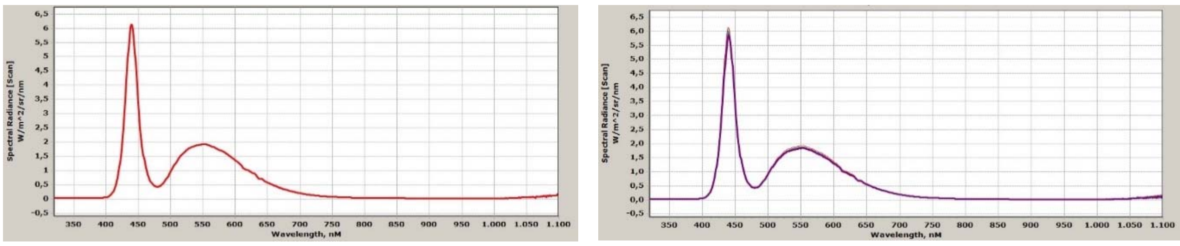
After the short-term measurements were completed, the same process was repeated for the 48-hour measurements in the same sequence. In order to avoid any interruption during the measurement process, the power options of the computer on which the measurement data were received were set to remain on for 48 hours and the system was powered via the UPS. Measurements started with the blue LED, for which the temperature was the temperature was 25.71 °C and the first measurement result is as shown in Fig. 6 (a). The temperature measured after 48 hours was 32.9 °C and the wavelength was measured as shown in Fig. 6 (b). It can be seen that as the temperature increases, the radiation intensity decreases.



iv. **(b)**

Figure 6. The first measurement of the blue LED wavelength (a) and the measurement after 48 hours (b)

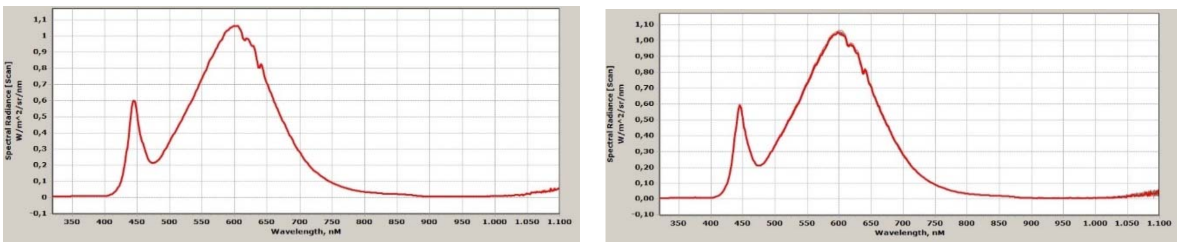
The measurement on the 3000 K LED started at 25.9 °C and ended at 33.55 °C. The first and last curves obtained in this measurement are shown in Fig. 7 (a) and Fig. 7 (b).



a. **(b)**

Figure 7. The first measurement of the 3000 K white LED wavelength (a) and the measurement after 48 hours (b)

The measurement on the 6500 K LED started at 25.6 °C and ended at 32.8 °C. The first and last curves obtained in this measurement are shown in Fig. 8 (a) and Fig. 8 (b).



(a) **(b)**

Figure 8. The first measurement of the 6500 K white LED wavelength (a) and the measurement after 48 hours (b)

CONCLUSION

LEDs are not only used as light sources in everyday life, they are also widely used in various applications today. It is desired that the color and color temperatures of the light sources used in the lighting remain unchanged throughout their economic life. When LEDs with semiconductor circuit elements are preferred as light sources, the changes in temperature and luminescence must be examined. The reason for this is that the increase in the junction temperature during the operation of the LEDs causes a variation in the characteristic values. The light reflection of these variations also visually influence the qualities of lighting.

This study investigates the slip that can be caused by the temperature increase in the peak wavelength of the LEDs commonly used in illumination. As a result of experimental studies the following results were obtained:

- In the initial measurements made at the beginning of study, the spectrum in the wavelength of the data sheet that the manufacturer gave for each LED was obtained.
- It is known that the increase in the junction temperature of the LEDs results in a decrease in light intensity. For this reason, in the study, the change of the peak wavelength was investigated by measuring the temperature of the indoor environment where the heat was transferred through the cooler rather than the junction temperature of the LEDs.
- Short-term measurements indicate that there is no change in wavelength as the ambient temperature increases by approximately 4-5 °C. However, a small change in radiant intensity has been detected on account of the fact that the cooler effectively keeps the junction temperature low.
- Long-term measurements indicate that there is no significant change in wavelength relative to increases of ambient temperature of approximately 6-7 °C. 0.1 to 0.3 W / m2 / sr / nm decreases were observed in the intensity of the radiation.

The data obtained as a result of the measurements performed show that there is no significant change in the peak wavelength value of the LEDs during the 2-hour and 48-hour continuous operation period. For this reason, LEDs can be preferred as a light source in various applications such as solar simulators, in which lighting and wavelength stability is particularly important.

ACKNOWLEDGEMENT

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Inter Laboratory Comparison of LED Measurements Aimed as Input for Multi-Domain Compact Model Development within the Delphi4LED H2020 Project

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***Abstract*— The goal of the Delphi4LED H2020 ECSEL project is to develop measurement, modelling and simulation methodologies that allow using multi-domain compact models of LED packages to be used at different integration levels (from simple LED assemblies up to complete luminaires) to be supported and used by all major stakeholders along the SSL supply chain. The target is to establish the right model topologies along with the right set of model equations and model parameters that connect measured LED characteristics to system level behaviour of a luminaire. To set the right expectations on the desired accuracy of the different models of LED packages the Delphi4LED consortium decided to launch a round-robin measurement of carefully selected LED packages with the participation of the testing laboratories of the consortium members. These testing laboratories include academic and industrial labs as well as accredited testing labs with different levels of expertise in different areas of LED measurements, having more or less similar testing apparatus. Besides the above mentioned goals another goal of this work was to test how the different laboratories can implement LED measurement procedures described in JEDEC and CIE LED testing guidelines.**

***Index Terms*— round-robin testing, LED junction temperature control, LED package electrical properties, LED package light output properties, LED package thermal properties.**

INTRODUCTION

There are a few bottlenecks hampering efficient design of LED based products on different integration levels of the SSL supply chain. One major issue is that data sheet information provided about packaged LEDs is usually insufficient and inconsistent among different LED vendors.

An international consortium of European SSL manufacturers including big and small companies, industrial and academic research labs and companies involved in LED test equipment manufacturing and suppliers of simulation tools has recently set an R&D project [1] – [4] with the ultimate goal of developing standardized methods to create accurate multi-domain LED compact models from testing data. Despite high accuracy expectations of end-users, model accuracy should not be defined higher than the uncertainty of LED measurement data achievable by typical test laboratories performing daily characterization of LEDs.

To assess the capabilities of their laboratories the consortium members with LED measurement facilities decided to carry out round robin testing of selected LED packages which have been defined as the most important ones from the point of view of system level design by Delphi4LED partner companies active in luminaire and lighting design.

In planning this round robin test, the outcome of earlier inter laboratory comparisons [5], [6] were carefully considered. The test protocol of the present round robin test is based on new measurement standards and recommendations published by JEDEC [7] – [9] and recently developed by CIE [10]. Our measurements form the first international round robin test based on these recommendations.

PARTICIPATING LABORATORIES

Different kinds of laboratories participate in this inter laboratory comparison: industrial thermal and optical LED testing labs, research labs from the academia and accredited, independent testing labs providing testing services for the lighting industry and a laboratory of a test equipment manufacturer. There were all together 7 laboratories participating in this experiment, out of which 6 laboratories belong to members of the Delphi4LED consortium [1]. The 7th laboratory is an independent, accredited optical testing laboratory. The participants of this round-robin test were

- Budapest University of Technology and Economics (BME), Department of Electron Devices, Budapest, Hungary (organizing lab);
- Mentor – a Siemens business, Mechanical Analysis Division MicReD thermal testing lab, Budapest, Hungary (participating lab);
- LightingLab Calibration Laboratory, Veszprém, Hungary (participating lab);
- Philips Lighting France, Lyon, France (participating lab);
- PISEO, Lyon, France (participating lab);
- Philips Lighting Research, Eindhoven, The Netherlands (participating lab);
- VTT Research, Oulu, Finland (participating lab).

After careful considerations (taking into account among others their available infrastructure and expertise of their personnel) BME's thermal testing laboratory was chosen as the leading laboratory in this round-robin test.

In terms of their capabilities all laboratories are characterized by different profiles, e.g. some are in the frontend in R&D for combined thermal and optical testing of LEDs. Each laboratory is capable of setting the T_J junction temperature of LEDs for optical measurements and each laboratory is capable of measuring the spectral power distribution (SPD) and the total radiant and luminous fluxes of the test LEDs. Five laboratories out of the 7 participants have transient thermal testing capabilities with the equipment of the same manufacturer which allows the measurement of LEDs' $Z_{th}(t)$ thermal impedance curves and R_{th} thermal resistance. Again, four out of the seven labs have spectroradiometers from the same European manufacturer. Measurement of isothermal current-voltage-total flux (I-V-L) characteristics of test LEDs is daily practice at two laboratories, though, further two laboratories also have the equipment to implement such measurements. Table I lists the major LED testing capabilities of all laboratories.

TABLE I. MAJOR TESTING CAPABILITIES OF THE PARTICIPATING LABORATORIES

Laboratory code	Capabilities
1	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
2	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
3	T_J control capability, Z_{th} meas. capability, SPD, total fluxes
4	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
5	T_J control capability, SPD, total fluxes
6	T_J control capability, Z_{th} meas. capability, isothermal I-V-L capability, SPD, total fluxes
7	T_J control capability, SPD, total fluxes

Each participating testing laboratory was responsible for the calibration of their test equipment; there was no common reference source used in this experiment. This was in line with the goals of the Delphi4LED project, namely, to be aware how testing data of different manufacturers and end-users match and how well modelled and simulated LED characteristics may match these data.

Besides the testing laboratories listed above, further members of the Delphi4LED consortium have also contributed to this round-robin test. TU Eindhoven is responsible for the statistical analysis of the test results (not yet completed at the time of submission of this paper) and based on their expertise, Magillem develops data management schemes for the huge amount of data gathered during this experiment. The worked out scheme provides also the basis of test data management for the entire duration of Delphi4LED project. PI Lighting also contributed to LED selection and determination of sample sizes for the test.

LED SAMPLE SELECTION

Selection of LEDs to be tested in this inter laboratory comparison was driven by the needs of the Delphi4LED project. A major aspect was to include today's mainstream LED package types used in luminaire design. Therefore, mainly high power (HP) LED packages were chosen, but an LED package type also represents the mid-power packages and a CoB LED was also chosen which represents the LEDs used in high flux applications. It was important to see how the different labs can identify the light output properties of LEDs aimed for general lighting applications, different representative phosphor converted white LEDs (cool and warm white, high CRI and low CRI versions) were chosen. Also, to learn about the testing capabilities in different ranges of the visible spectrum and also represent different LED chip and package designs, a red, a green and a blue LED type was also included into the set of test samples. Table II provides a summary of the major characteristics of the selected test LEDs.

The selected blue LED packages connects the colour LED samples to the white ones as it is produced by the same manufacturer as one of the white LED packages and the same blue LED chip is applied in this package as in the corresponding white LED package. This choice allows to study how the applied phosphor affects the different (thermal) properties of the entire assembly. (A preliminary study about the effect of the phosphor on the measured thermal properties of LED packages was published recently [11].) Besides this round robin test, these two LED types have also been selected for further, detailed regular measurements aimed to deliver input data for chip, package and assembly level compact modelling of LEDs in the Delphi4LED project. Further details of LED selection criteria can be found in another conference paper [12].

TABLE II. MAJOR CHARACTERISTICS OF THE TEST LEDS

LED type code	Package style	Colour	Manufacturer	Comment
A	high power	royal blue	1	same package style as B and C
B	high power	cool white	1	same blue chip as at type A
C	high power	red	1	same package style as A and B
D	CoB	warm white	2	"chip on board" devices with a sample holder
E	mid-power	green	2	package with no thermal pad

SAMPLE SIZES, SAMPLE PREPARATION, SAMPLE HANDLING

For the sake of easy handling and reducing measurement uncertainties related to sample mounting, all bare packages of type A, B, C and E LEDs were assembled onto standard star shaped MCPCB substrates. All samples have been provided with individual identifiers laser engraved into their substrates. Also, to comply with the requirements of the considered LED testing guidelines [7]-[10] all LEDs have been equipped with four wire (Kelvin-type) electrical connections (reducing the forward voltage reading errors).

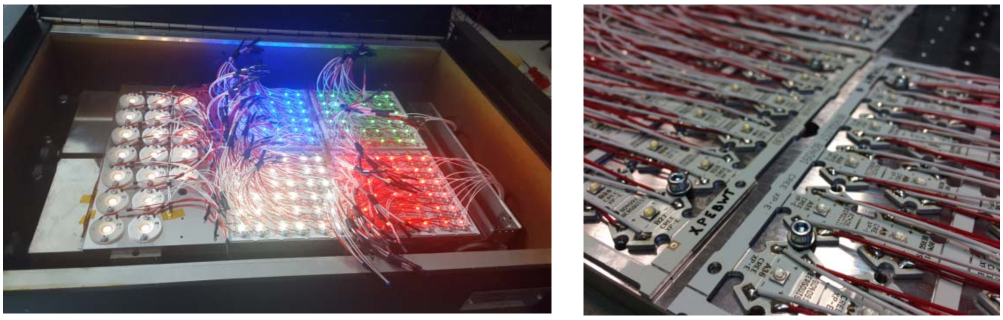

Figure 1. LED test samples in the aging chamber

The sample size chosen was determined also as a trade-off between the available resources and the need for gathering detailed information about the test LEDs. Ultimately, 36 samples of types A, B, C and E and 30 samples of CoB LEDs (type D) have been ordered, prepared for testing.

In their early life, LEDs are subjects to performance (flux, forward voltage, colour point) changes, which can be improvements or degradations. Therefore, 500 hours of ageing was thought to limit the impact of those early variations on the samples leading to more robust conclusions on the round robin test. All type A, B, C and E LEDs on standard MCPCB star board frames were assembled in BME's LM-80 standard compliant aging chamber as shown in Fig. 1. These star board frames occupied 2/3 of the available space in the chamber therefore only 18 pieces of type D LEDs (CoB LEDs) out of the available 30 CoB samples were assembled into the chamber. Thus, 3x36 MCPCB assembled LEDs and 18 CoB LEDs were subject of aging simultaneously. This was a trade-off that had to be made in order to keep the total power dissipated in the aging chamber within the heat-removal capacity limits of the thermostat used with the aging chamber. The remaining 12 CoB LED samples were subject of a second aging process before these samples were dispatched. For the aging the LED test samples were electrically connected in series, this way the same LED types were driven with the same steady forward current. The aging took place at a temperature of 85 ^{o}C. During the aging process 3 samples of type E LEDs went completely wrong.

In case of testing power components on cold plates a common practice is to apply thermal interface materials (TIMs) such as thermal grease or paste between the component's cooling surface and the cold plate in order to lower the junction-to-ambient thermal resistance of the component. Since in this round robin test we decided to measure LED properties at prescribed junction temperatures we decided NOT to use any TIM material in order to avoid possible optical degradation of the LED samples due to contamination of the lenses. Therefore, when measuring the R_{thJC} junction-to-case with the so called transient dual interface method, we had to deviate from the recommendations of the JEDEC JESD51-14 standard [9]. Thus, instead of applying "dry condition" (no TIM applied) and "wet condition" (TIM applied), we prescribed two "dry" conditions between the bottom of the MCPCB substrate (considered as the cooling surface or 'case' surface of the LED assembly): once the LEDs had to be mounted onto the temperature controlled cold plate without any TIM and for the second thermal transient measurement, a thin sheet of thermally insulating material had to be inserted between the cold plate and the MCPCB substrate. Such TIM foils with the right instructions for every LED type were also distributed to the participating laboratories.

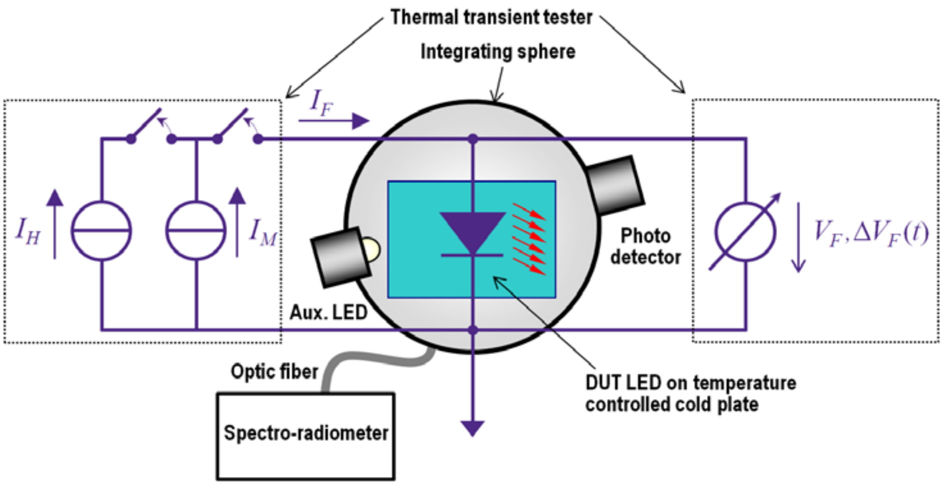

Figure 2. The generic test setup used in the measurements of this experiment. Some of the participating laboratories provided the current sources and the voltmeter integrated in a thermal test equipment, some laboratories provided these as individual units. At all laboratories the test LEDs were mounted onto a temperature controlled cold plate and the light output properties were measured in an integrating sphere with 2π geometry.

Overall test setup and the measurands

Both the latest JEDEC and CIE guidelines for testing high power LEDs [7], [8], [10] recommend the control/determination of the T_J junction temperature of the LED being measured. Therefore, all thermal and optical measurements of the test LEDs had to be performed such that the LEDs under test were mounted onto a temperature controlled cold plate. The optical measurements were always performed with an integrating sphere with 2π geometry, as recommended by [8] and [10]. The sketch of the test setup used by all participating laboratories is shown in Fig. 2.

The participating laboratories were free to choose the method of setting/controlling the T_J junction temperature, following either CIE's coming new recommendations [10] (which are based on a method originally proposed by Zong & Ohno [13]) or using the guidelines of JEDEC's LED thermal testing [7], [8]. Every participating lab has been provided with these recommendations and detailed instructions on sample handling. The test conditions for single operating point measurements are summarized in Table III. For types A, B and C the test conditions are characteristic to the foreseen real-life operating in an application. For types D and E LEDs the properties of the test samples and the available test equipment of the participating laboratories were the major factors to define the test conditions.

TABLE III. Test conditions for single operating point measurements

LED type code	I_F [mA]	T_J [ºC]
A	700	85
B	700	85
C	700	85
D	200	85
E	100	40

For all LED types tested the following parameters had to be measured/calculated and reported for the set forward current and targeted junction temperature: the forward voltage, the achieved junction temperature, the spectral power distribution, the measured or calculated radiant flux, luminous flux, chromaticity coordinates (CIE 1931, 2º), correlated colour temperature (if applicable), radiant efficiency, luminous efficacy, efficacy of source of radiation (CIE ILV term 17-730). The laboratories were also requested to report the steady-state junction-to-ambient thermal resistance of the measured LED samples. Laboratories with thermal transient testing capabilities were required to determine the transient R_{thJC} junction-to-case thermal resistance of the test samples, following the detailed measurement protocol derived from the JEDEC JESD51-14 standard. For all thermal measurements (based on the electrical test method [7]) for all LED samples the measurement current had to be set to 10 mA. For type A LEDs four participating labs volunteered to measure the isothermal I_F-V_F-Φ_e characteristics together with SPD for the combination of the following forward current and junction temperature settings: I_F = 20, 30, 60, 100, 350, 500, 700, 1000 mA, T_J = 30, 50, 70, 85, 110 °C, resulting in a total of 40 different operating points. These points were determined after a careful consideration of the features of the electrical and efficiency characteristics of these LEDs [14]. This is a minimum set of operating points thought to be sufficient to extract parameters for a multi-domain chip level model [15] of such LEDs aimed for simulation by a Spice-like electrical circuit simulation program.

RESULTS AND CONCLUSIONS

At the time of submission of this paper, the pre-characterization of LED samples was completed, establishing the reference values of the measurands for all LED samples distributed. According to the distribution scheme of the test samples, 5 samples of each LED type (altogether 25 samples) are circulated among the participating laboratories and each laboratory received further 3 aged and pre-characterised samples from each LED type. From types A, B and C reserve samples were kept at the organizing laboratory. Control measurements of the circulating samples took place at the organising laboratory after two participating laboratory performed their tests. (This sample circulation and control measurement scheme is a trade-off between the standard practice of round robin measurements, the high samples size of the present experiment and the available time frame and resources.) In order to allow early completion and reaching the final statistical analysis of the single operating point test results, the measurement of the isothermal I_F-V_F-Φ_e characteristics of the type A LEDs takes place in a second round by the volunteering laboratories.

At this stage we can state that except type D LEDs the control measurements did not show significant drift of the measurands. Based on the unprocessed, raw test results of the participating labs having already completed the single operating point measurements, the test results are in the expected ranges. Statistical analysis of the test results of the five samples of each LED type and the statistical analysis of the differences among the participating labs' test results will be published in detail in an open access journal paper.

It is worth noting, that this experiment is the first round robin test of the latest JEDEC and CIE package level LED measurement guidelines. Also, this experiment is aimed at providing actual experimental input for the work of the CIE TC2-84 technical committee which aims to work out recommendations on reporting LED test data aimed as input for automated LED model generation.

ACKNOWLEDGEMENT

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Application of Stray Light Corrected Array-Spectroradiometers

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***Abstract*— This paper describes the possibility of stray light correction for array spectroradiometers and points out smaller or larger benefits depending on the application, lamp type and the spectral region of interest. Application of the stray light correction matrix suppresses the stray light by about one order of magnitude down to a level of 10^{-5}. More precise calibration can be achieved, in particular in the UV range (<400 nm). The measurement of UV-LEDs causes significant error in the determination of the absolute value, already due to the stray light contaminated calibration. Thus, the stray light correction has as a direct consequence about 3-4% higher accuracy in the radiometric value of UV-LEDs. In the case of visible LED spectra the application of stray light matrix leads to improvement in accuracy of the colour coordinates up to 0.0005. One application that could particularly benefit from stray light correction is the evaluation of the blue light hazard of optical radiation.**

***Index Terms*-- correction matrix, photobiological safety, spectroradiometry, stray light, UV-LEDs.**

INTRODUCTION

The main limitation of the performance of an array spectroradiometer in photometry and colorimetry is the occurrence of stray light in the instrument. This means that a particular element of the array detector registers radiation from a different spectral region than the designated one. The reason for the occurrence of stray light can be found in various mechanisms:

- scattered light from the diffraction grating due to manufacturing inaccuracies in the shape and spacing of the lines, or roughness of the surface of the grating,
- higher diffraction orders, particularly for detectors with a wide spectral range,
- double diffraction of the light reflected back on the grating,
- inter-reflections between the detector and other optical components,
- reflection and scattering from surfaces, especially from the inner wall of the spectrograph,
- fluorescence of optical components,
- and the way how the light is coupled into the spectroradiometer.

Thus, the total amount of the measured radiant power contains a part of incorrect radiation, which causes an error in spectral power distribution. The main approach to improve the radiometric performance of the spectroradiometer is to avoid, or at least largely suppress, the stray light by design measures of the spectrograph. When further suppression is technically not possible, the residual stray light can be effectively corrected to a great extent by a suitable method of measuring and calibration, for example, by applying the NIST method [1], as outlined in the following.

CREATION OF THE STRAY LIGHT MATRIX

The calculation of correction functions requires a precise knowledge of the stray light behaviour of the spectroradiometer used for measurements over the full detectable spectral range. The complex stray light behaviour of an array-spectroradiometer can, as shown in [1], be determined with the aid of tuneable laser sources. The idea is that monochromatic radiation can be attributed for the most part to a certain pixel of the detector. The entire light that is measured outside the bandpass function for this wavelength is the stray light contribution of pixel i that is seen from all other pixels j in the detector. The most realisations of the stray light correction are based on this method, such as that described in [2].

In our practical realisation, excitation wavelengths are tuned within the measurement range of the spectroradiometer in 10 nm steps with the aid of OPO laser excitation and one spectrum is recorded for each step. An optical parametric oscillator (OPO) is a driven harmonic oscillator that oscillates at optical frequencies. It converts an input laser wave into two output waves of lower frequency by means of second-order nonlinear optical interaction. The set of all recorded spectra over all excitation wavelengths appropriately interpolated results in a device-specific LSF matrix. If the bandpass function of the real signal is subtracted, one obtains a stray light distribution function (SDF) matrix. The inverse of the SDF matrix can be multiplied with raw spectra in order to obtain stray light corrected spectra.

Our realisation of the stray light correction method is the first commercially available, convenient method for any user. The stray light matrix determined for a certain spectroradiometer can already be numerically applied during the calibration of the spectroradiometer with any accessory. For the subsequent stray light corrected measurements one has to choose the appropriate calibration and the stray light matrix is applied automatically to any measured spectra, without additional time and effort. Depending on the application, lamp type and observed spectral range, a stray light correction of array spectroradiometers provides lesser or greater advantages.

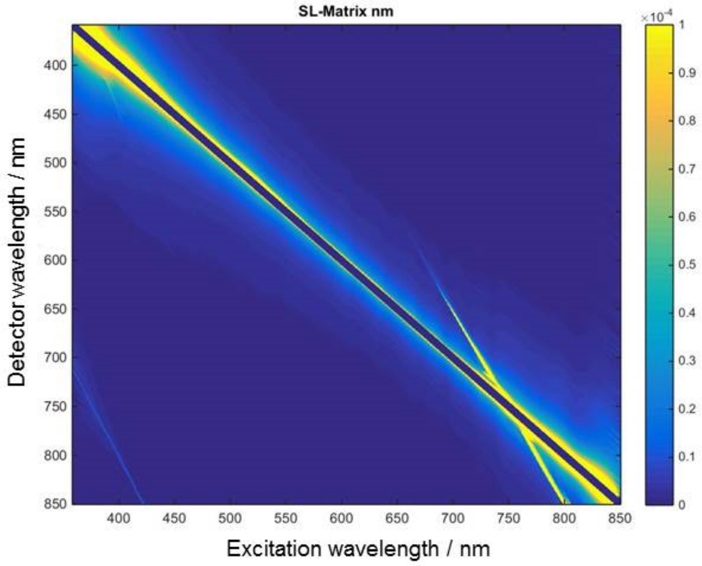

Figure 1. Typical stray light matrix using the example of a CAS 140CT (Model VIS).

ADVANTAGE OF THE STRAY LIGHT CORRECTION FOR SPECTRAL CALIBRATIONS

Broadband sources such as halogen lamps and deuterium lamps are normally used for the spectral calibration of spectroradiometers. The impact of stray light correction on the spectrum of a broadband source is particularly distinct in the UV but also in the IR spectral range, because the detector of an array spectroradiometer has only a very low sensitivity at the edges. Stray light correction of the spectrum used for calibration is particularly meaningful, as in particular errors in the areas of lower sensitivity are intensified due to the division of the measured spectrum by the reference spectrum.

If we compare the relationship of sensitivities with and without stray light correction after calibration, we can recognize a stray light portion of up to 10% in the UV range (Figure 2). Stray light free sensitivity in this range of the already low sensitivity, has a direct effect on the absolute precision. In particular applications based on UV radiometry thus profit from stray light correction, e.g. measurements of UV LEDs, sun simulators or halogen lamps with a high portion of UV radiation.

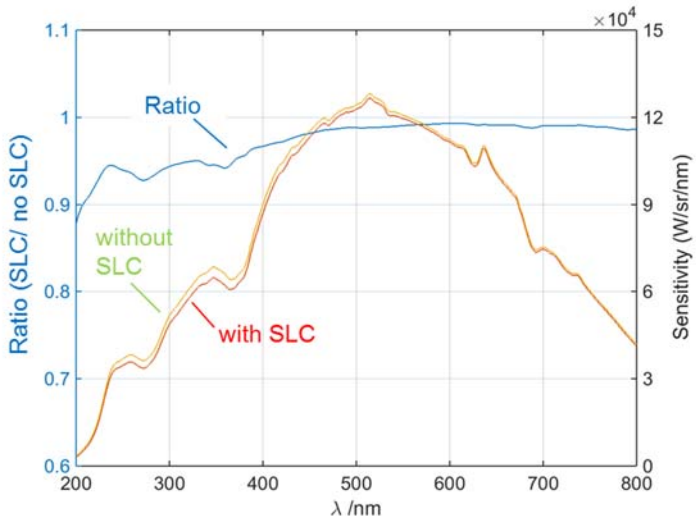

Figure 2. Relationship of sensitivity curves with and without stray light correction.

STRAY LIGHT CORRECTION IN THE UV RANGE

The ultraviolet range is normally subdivided into UVA (320-400 nm), UVB (280-320 nm) and UVC (200-280 nm). UVA radiation is used, e.g. for curing of printing inks, adhesives and coatings. UVC radiation is used, e.g. for disinfection and water purification.

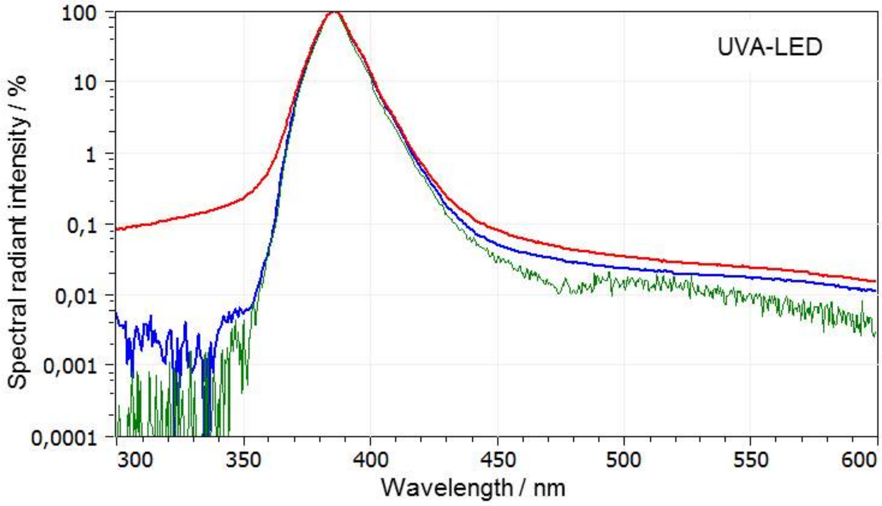

Figure 3. Logarithmic display of the spectra of a UVA LED without (red) and with stray light correction (blue) and measured with a double monochromator (green).

Figure 3 shows by way of example the spectra of a UVA LED with and without stray light correction in logarithmic presentation. The suppression of stray light in the spectral course by somewhat more than one order of magnitude in the UV range to almost 10^{-5} is clearly recognizable. Beyond this, we measure about 3% more precise radiant intensity in this example with the use of stray light correction. The impact of stray light correction is somewhat greater for UVC LEDs. It almost reaches the stray light level of a double monochromator and about 4% more precise radiant intensity (Figure 4). While the peak wavelength (257 nm) does not change at all with the stray light correction, the centroid wavelength shifts by about 0.8 nm in the direction of the peak wavelength.

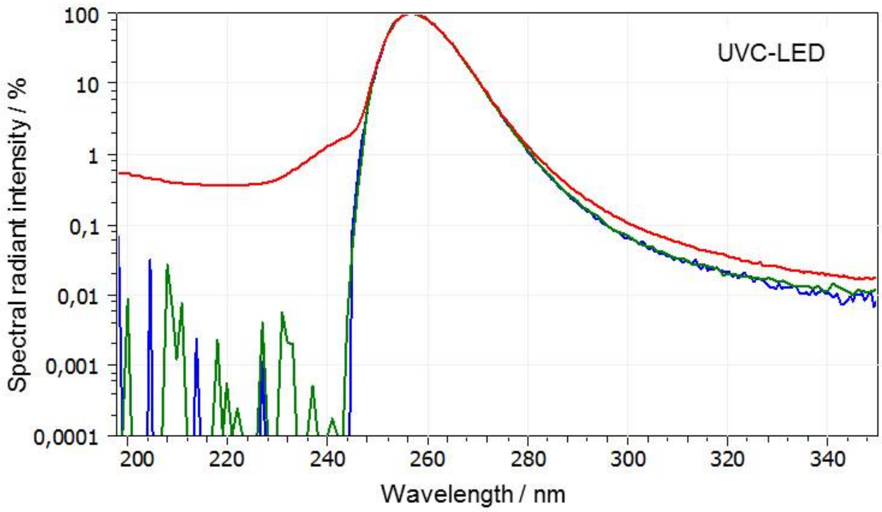

Figure 4. Relationship of sensitivity curves with and without stray light correction.

In the measurement of UV LEDs considerable errors are made in the determination of the absolute value alone by reason of stray light contaminated calibration. As a direct consequence stray light correction thus has a higher precision in radiometric evaluation. All applications based on UV LEDs profit from this, e.g. curing of adhesives and coatings, lithography, scanning heads, horticulture lighting, biomedical devices, combatting of hospital infections,…

INFLUENCE OF STRAY LIGHT CORRECTION ON COLOUR LED MEASUREMENTS

Figure 5 shows an example of the spectra of LED standards in the colours white, blue, green and red, in each case with and without stray light correction. The LED standards refer to stabilized and temperature-controlled LEDs. These were measured in a luminous intensity measuring adapter in the I-LED-B configuration with an array-spectroradiometer CAS140 CT (UV-VIS-NIR) with and without application of the stray light correction matrix.

The logarithmic presentation of the spectra clearly shows the impact of stray light correction in the marginal zone and the signal around zero. In ranges with a generally low signal, particularly in the blue and UV range, the stray light level is corrected up to one order of magnitude and reaches a level of 10^{-4} down to $5 \cdot 10^{-5}$.

The impact of stray light correction on the x, y colour coordinates with up to 0.0005 is not to be neglected, if we bear in mind that high-quality array spectral radiometers exhibit measurement uncertainties of ±0.002 to ±0.0015 and the LED industry strives for an ambitious tolerance of ±0.001. Any increase in measurement accuracy is thus very welcome.

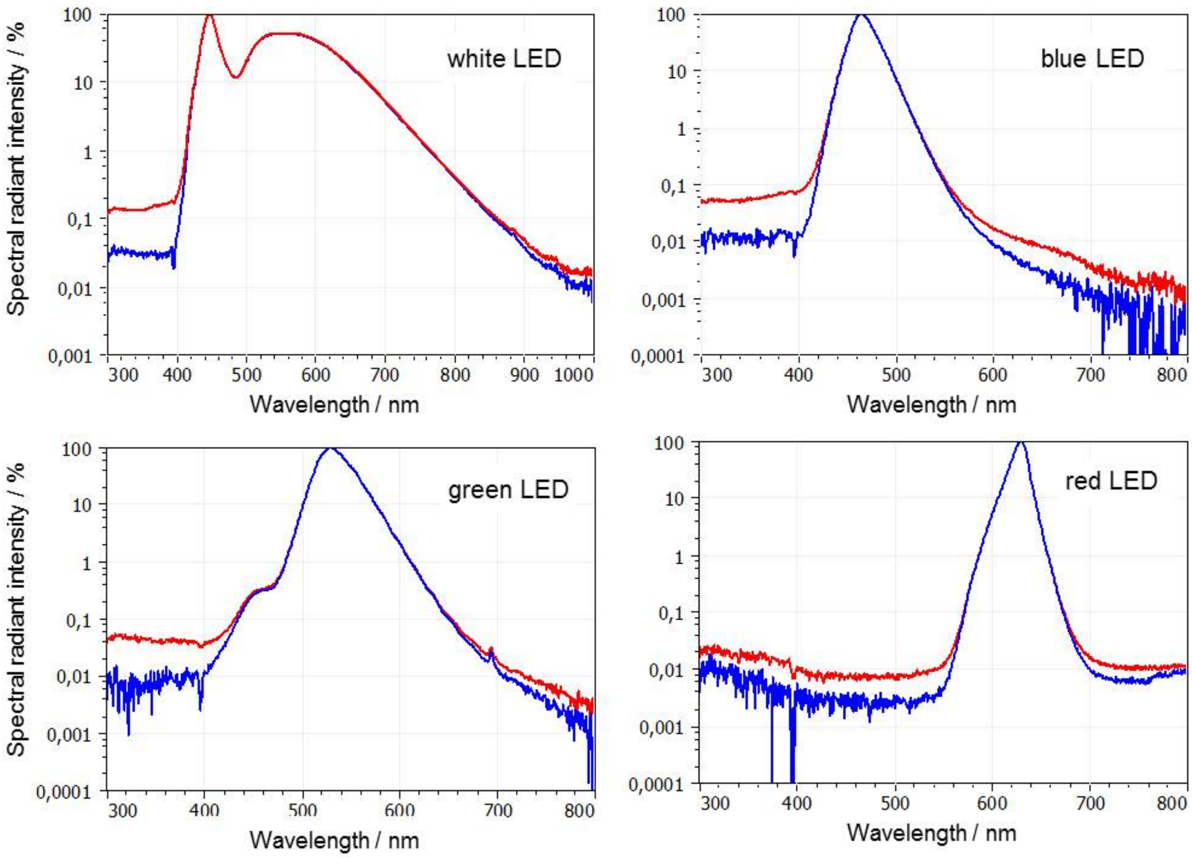

Figure 5. Logarithmic display of the spectra of white, blue, green and red LED without (red) and with stray light correction (blue).

OUTLOOK: PHOTOBIOLOGICAL SAFETY

One application that could particularly benefit from stray light correction is the evaluation of the photobiological hazards of optical radiation, in particular the blue light hazard on the human eye. The blue light hazard is defined as the potential risk of photochemical damage to the retina, caused by radiation in the wavelength range 300-700 nm, with the greatest effect in the range between 400 and 500 nm. So far, the standards EN 62471 recommends complex and expensive double monochromators as measuring instruments, in particular due to the extremely low stray light level. The higher stray light level in the area of greatest impact in the blue and UV range can simulate a non-existent hazard. With the correction of the stray light a greater measurement accuracy and measurement dynamics can be achieved in this range. Due to stray light correction the array spectroradiometer could become a more convenient and lower-cost alternative to the monochromator for determining the blue light hazard.

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HCL – Human Centric Lighting

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Abstract— **Light has always been part of human nature and development process. The Human centric lighting presents three important parts of artificial lighting. Visual effect has been there for centuries, where the second two effects are still in progress of development which are emotional and biological effects. These three effects combined together, are forming additional topic in artificial lighting, which is human centric lightning called HCL.**

***Index Terms*—HCL, Circadian rhythm, eye structure, luminaire development, spectrum analysis**

HCL – HUMAN CENTRIC LIGHTING

The three effects of artificial lighting are visual, emotional and biological. In this paper we take a look on all three effects, but mostly we will focus on the last two effects. With the first effect, we already have standardization for illumination, uniformity, vertical and cylindrical lighting among with UGR factor described in the standard SIST EN 12464-1. All of these requirements are still in the first place considering artificial lighting.

The second effect is the emotional where we feel comfort and well-being, with changing the colour temperature (later CCT) from warm white to cold white depending our feelings. For example, when we are hardworking and focus, recommended CCT is cold white and on the other side when we feel tired or sad, we feel more comfortable when we are exposed to worm white CCT.

The last but not least effect is non-visual or biological effect. This effect is helping stabilising the Circadian rhythm, maintaining alertness, balancing hormone Cortisol and Melatonin, helping humans on better recovery process, better blood circulation and metabolism, etc.

NON-VISUAL EFFECTS

A. Circadian rhythm

The circadian rhythm or often called circadian clock is biological process that displays an endogenous oscillation of about 24 hours. This 24-hour rhythms are driven by circadian clock and they have been widely observed in plants, animals, fungi and cyanobacteria.

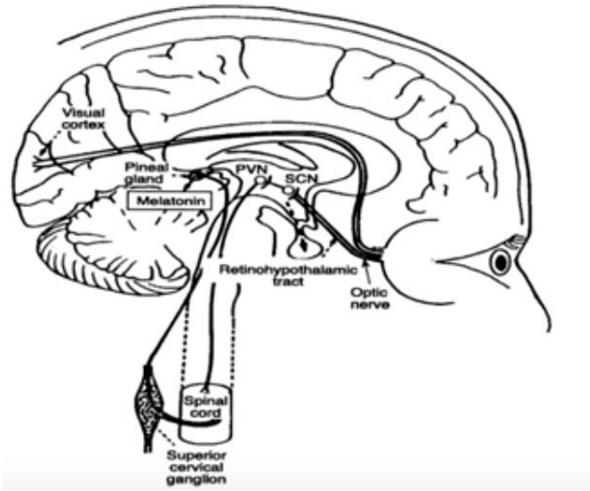
The formal study of biological temporal rhythms, such as daily, weekly, seasonal and annual rhythms, is called chronobiology. Although circadian rhythms are endogenous ("built-in", self-sustained), they are adjusted (entrained) to the local environment by external cause called Zeutgeber (from German, "time giver"), which include light, temperature and redox cycles. Circadian rhythm allows organisms to anticipate and prepare for precise and regular environmental changes.

The primary circadian clock in mammals is located in the suprachiasmatic nucleus (or nuclei – SCN), a pair of distinct groups of cells located in the hypothalamus. Destruction of the SCN results in complete absence of regular sleep-wake rhythm. The SCN receives information about illumination through eyes. The retina of the eye contains photoreceptors ("roods" and "cones"), which are used for conventional vison. Retina however also contains specialized ganglion cells that are directly photosensitive, and project directly to the SCN, where they help in the synchronization of this master circadian clock.

The cells contain the photo pigment melanopsin and their signals follow a pathway called the retinohypothalamic tract, leading to the SCN. If cells from the SCN are removed and cultured, they maintain their own rhythm in the absence of external cues.

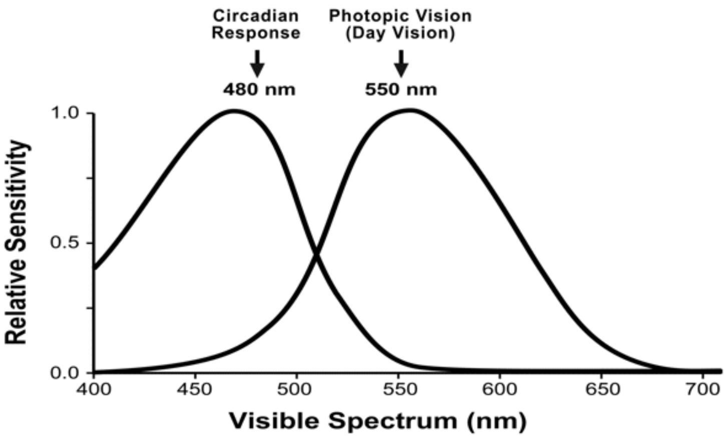
The eye has 6-7 million cones and 120 million rods inside the Retina. The rods are most numerous photoreceptors, and the most sensitive to the light, but not sensitive to colour. They are primarily responsible for dim light vision. The rods peak in the blue wavelength range light spectrum and have almost no response to red light.
Known as the scotopic photoreceptor system, the peak wavelength is 507 nm, blue-green colour range. The cones cells are colour sensitive and divided primarily into 64% red sensitive cones, 32% green cones with a small percentage of

blue cones, of only 2%. The cones are responsible for high resolution vision known as photonic photoreceptor system. The cones cells have peak wavelength sensitivity of 555 nm, the green colour wavelength spectrum.



Picture 1: Visual and Biological Pathway

The part of the retina photoreceptors which contain melanopsin, so they are sensitive to light, are ganglion cells called ipGRC (intrinsic photosensitive Retinal Ganglion Cell). These cells have developed inside of the retina on the bottom side of the retina. This is also easily to explain. Over the centuries the humans are living under the blue sky. The light is entering the eye, for the most of the time, under 45° angle. The blue sky is also the reason why the ganglion cells are most responding to the short wavelength blue light in the range of 446 nm to 483 nm. Called the action spectrum, the blue light wavelength band plays a major role in aligning and resetting the body clock through the control and release of the sleep hormone, melatonin.



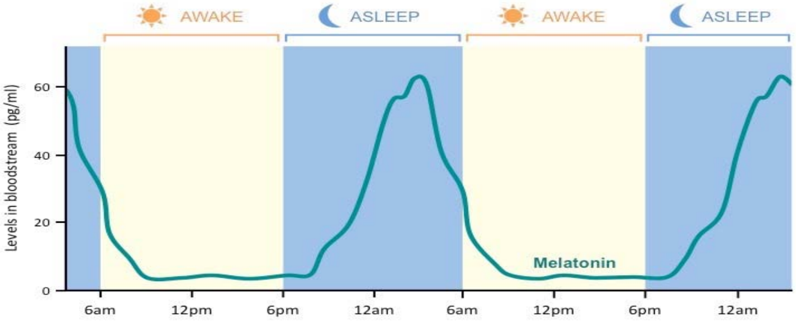
Graph 1: Action Spectra of Circadian and Photopic Light

B. Circadian Rhythm Disorders

Circadian rhythm disorders are typically related to sudden and/or extreme change in the relationship between exposure to environmental light and activity. For example, circadian rhythm disorders are known to be associated with change in geographical location (jet lag), aging and night activity.

Irregular Sleep-Wake Rhythm, are most common with shift workers which preform night shifts. During the regular sleep time, they are exposed to artificial lighting and during the day they need to go to sleep. Changing these shifts can have an effect on Sleep – Wake Rhythm.

Another circadian disorder is called SAD – Seasonal affective disorder. This is most common in winter season when the duration of daylight is reduced. Due to decreased light exposure melatonin production continues during the waking hours. This is also characterized by symptoms such as lethargy and depression.



Graph 2: Melatonin suppression

Newer studies have used white (Desan et al., 2007) or blue LEDs (Lockley et al., 2003; Warman et al., 2003; Wright, 2004; Cajochen et al., 2005; Glickman et al., 2006; Strong et al., 2009) which have a far greater intensity in the 460 - 500 nm region than fluorescent lighting [Figure 3]. These lamps efficiently trigger non-visual photoreception (Desan et al., 2007) with less light intensity and exposure time. Natural morning sunlight with its high intensity in the 460 - 500 nm region, also relieves the symptoms of SAD (Kent et al., 2009). The antidepressant response to visible light takes approximately 3-4 days to take effect. Treatment needs to be continued throughout the winter months to avoid withdrawal symptoms.

DEVELOPING THE CIRCADIAN EFFECTIVE LUMINAIRE

As we now know the background of light and its effects, we can begin to include those facts in development of the light that will include all of three effects. As we said the first and most important one is still visual effect so we can use the luminaire for illumination of the rooms, the light will be installed in. The second part is the emotional part, where we will be also including the warm white CCT LED's, to create comfortable light zone. And biological or non-visual light that will help us to suppress the melatonin during daytime, meaning using the cold white LED's. Together with combination of warm white and cold white light colour we are covering the HCL topic.

For illumination of the offices and hospitals the most appropriate lighting is with direct and indirect lighting, where the part of this kind of illumination is also the part which is helping reducing glare (UGR).

A. LED Spectrum

For melatonin suppression, the blue wavelength spectrum is the most important one. Beside the energy emitted in blue peak wavelength of 445 ~ 455 nm by the white 4000 K LED diodes, this energy has to be increased, so additional monochromatic blue LED diode with wavelength of 465 ~ 470 nm is added. The combination of both LED diodes present higher activation factor. Activation factor can be calculated with dividing spectrum energy from 380 nm to 580 nm with spectrum of whole visual spectrum wavelength. The activation factor is showing the efficacy of suppressing melatonin when exposed to this light. This can increase the performance on cognitive task, because of the suppressing of the melatonin.

$$a_{mel,v} = \frac{X_{e,mel} = \int_{\lambda_0=380nm}^{\lambda_0=580nm} X_\lambda * S_{mel}(\lambda) * d\lambda}{X_{e,\,vis} = \int_{\lambda_0=380nm}^{\lambda_0=780nm} X_\lambda(\lambda) * V(\lambda) * d\lambda}$$

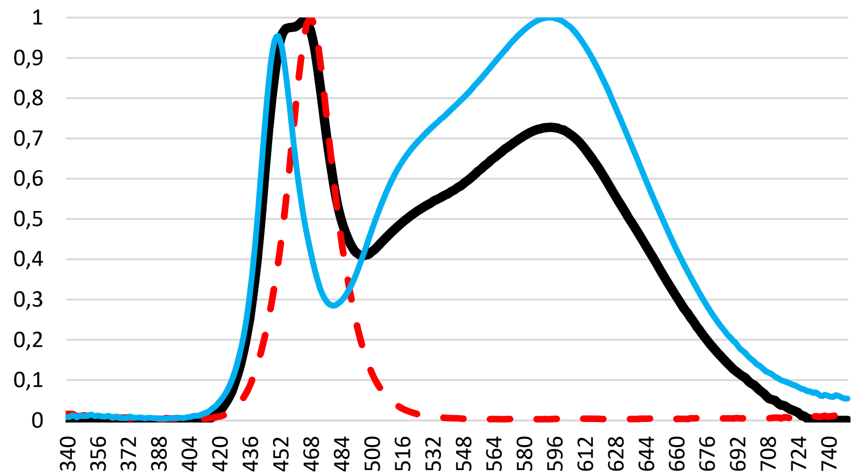
In the morning, the activation factor should be high, causing melatonin suppression, increasing alertness. On the opposite site, in the evening the activation factor should be low, meaning the melatonin will start to develop itself again, so the light should include much smaller amount of energy emitted in the narrow blue wavelength.

For getting the human centric light, where we are looking to suppress the melatonin we need to take a look also on the spectral sensitivity of the human visual perception. Like we talked before we have the photopic and scotopic luminosity functions or V lambda curve and C lambda curve. Scotopic luminosity function is there for visual task performance and we usually look at this curve when we are measuring the illumination of the task area. However this function is not enough when we wish to observe the activation factor of biological lighting. The V lambda curve is effecting on two out of five types of photoreceptors in the human eye and it is based on long wavelength and short wavelength sensitivity. When we are observing the light that is effective on the biological functions we need to take a look at scotopic luminosity functions or C lambda curve. This give us a totally different idea on how the eyes are sensing the blue wavelength. The light energy emitted from the luminaire and the energy that is coming into our eyes.

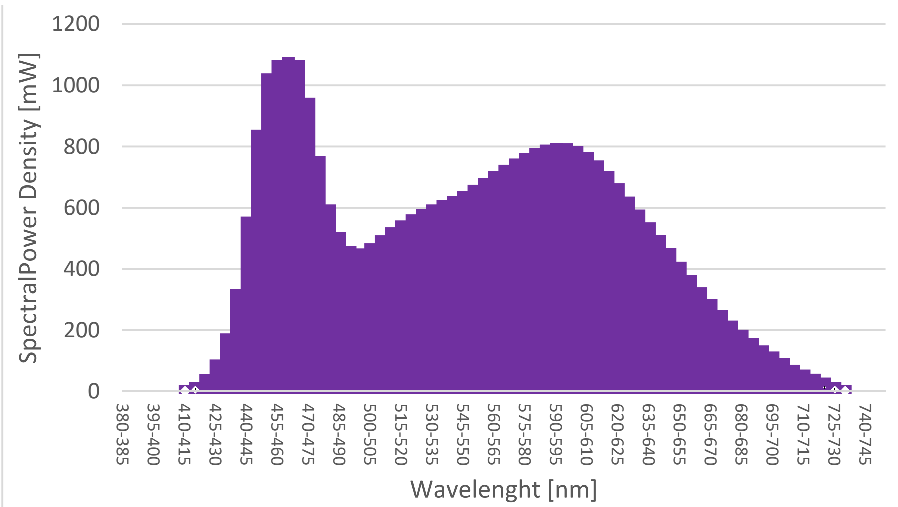
B. Developing the Light

Developing of the light spectrum that will result in high activation factor due to melatonin suppression require combination of a different LED diodes. With mixing the monochromatic and standard white LED diode, we need to consider the required end CCT, Emitted power, peak values in blue wavelengths and of course the luminous flux. When we are adding the monochromatic blue LED diode to the standard white one the obvious result will be higher CCT and CRI factor. To get the best activation factor we need to have high spectral irradiance in range from 380 nm to 580 nm. The white LED have the peak value usually at 450 ~ 455 nm. This peak is also wary much involved in LED's efficacy and CRI factor. On the market you can get the white LED's with the blue peak at 445 nm, but the efficacy is around 20% lower. The research has begun with different LED diodes manufacturers where we test the different combinations of the LED's types.

The results of the measurements has pointed out the best performance and the combination of the LED where we get the activation factor of 0,647. The blue line on the Graph 3 is presenting the white LED of 4000 K and the red line is presenting the blue LED with peak value of 468 nm. The CCT at this combination results in 5100 K with CRI factor 91. Energy emitted in interval of 455-480 nm was 5016 mW, with peak spectrum power density at 465 nm, 218 mW/nm.



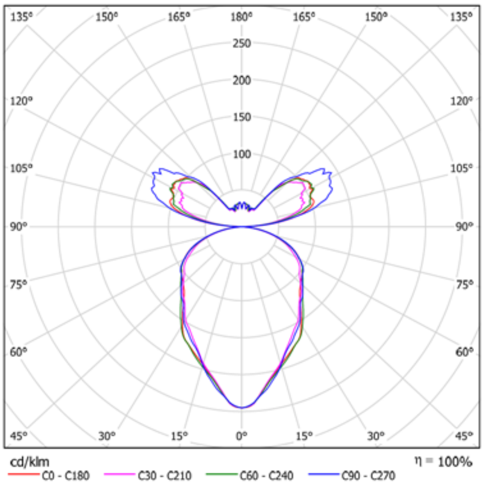
Graph 3: Relative Spectral Irradiance



Graph 4: Spectral Power Density

Exposure to light spectrum like this the melatonin will be suppress efficient enough. But we need to consider also that the melatonin will start to reproduce before sleep. In this stage we need to change the spectrum to opposite, meaning we need to lower the spectral power density in wavelengths from 380 nm to 580 nm, resulting in use of LED with lower CCT of 3000 K.

Already mentioned before the parallel developing process beside the LED spectrum and the LED diodes, is the media which we will use to transfer the photons from the LED diodes into the room. We chose to go with indirect and direct photometric distribution where the ratio of up-light is 40% and the down-light 60%. The PMMA material with special laser printed pattern is providing the batwing photometric shape on upper light and the lambert on the down light. The light is coming into the PMMA plate from the side, where the most important thig is the distance between diodes and the distance between the LED and the PMMA. The second one should be from 0,6 mm to 0,8 mm, for reaching minimum light losses on the light. Major roll also plays the beam angle of the LED diode. More narrow angle is resulting in much more direct light entering the PMMA and among with this better efficacy. However the efficacy of luminaire like this cannot be compared with standard LED luminaires on the market. Using monochromatic LED with efficacy of only 25 lm/W, we can reach the maximum efficacy from the luminaire to only 95 lm/W for the double spectrum. The worm white colour can reach up to 115 lm/W. But we need to understand the background of the development and also the actions factor for circadian light.



Picture 2: Photometric results SKY LUM

Conclusions

The HCL topic is still an ongoing developing subject, where there is still a lot to learn. The situation, where knowledge is incomplete and there are many potential intervening variables, how can a claimed effect of lighting be evaluated? For some parts of this topic, yes, we can claim that the changes are happening in human bodies, how effective these changes are is another thing as they are depending on lots of other influence from environment as well. Right now, the first effect that HCL have on human bodies is circadian rhythm, where we developed the solution for keeping it synchronised in environments where the leak of sunlight is happening. Our development of the luminaire has started with this reason. The first step of development was to get the basic done correctly, meaning good performance of the luminaire. The efficacy might improve during next years and new technologies of LED might come to a market, improving the luminary performance. The next steps of development will be creating the smart system to control those lights and will improve user comfort. As the testing of the light influence on the human bodies is still developing there and as there will be more and more studies that will support this HCL topic, we can ensure that this lighting topic represent breakthrough in our understanding of the complete effect of light on humans.

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Standards:

DIN SPEC 67600:2013-04 Biologically effective illumination - Design guidelines
DIN SPEC 5031-100:2015-08 Optical radiation physics and illuminating engineering - Part 100: Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra

Important Aspects of Serious HCL-Design

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***Abstract*—The term "Human Centric Lighting" (HCL) already manifests itself in the marketing of numerous luminaire manufacturers. Frequently "HCL" is equated with a product which has more than one colour temperature. Human centric lighting design is, in many cases, pursued half-heartedly and defeats the objective. There are, however, still many questions to be answered about "HCL-design".**

Index Terms—Circadian Rhythm, Dynamic Colour Temperature, Human Centric Lighting, LED, Lighting Design

Human Health Artificial Lighting

This presentation will address many of the challenges which may arise when lighting designers make a serious attempt to develop a HCL concept. It is more than just including a few dimmable luminaires with dynamic colour temperatures. In lighting design HCL means that the planning of artificial light should support man's circadian rhythm. The result should be lighting which is conducive to the health and well-being of the individual. In fact, what it really should be called is »Human Health Centric Artificial Lighting«.

How Does HCL function?

The retina of the human eye is not only made up of rods and cones which predominantly serve visual perception but also intrinsic photosensitive retinal ganglion cells (ipRGC). In 2007 it was discovered that these cells contain melanopsin and are therefore sensitive to light. The maximum sensitivity for the melanopic effect of light is at a wavelength of 490 nm (blue). That means that melanopsin is especially well stimulated at this wavelength.

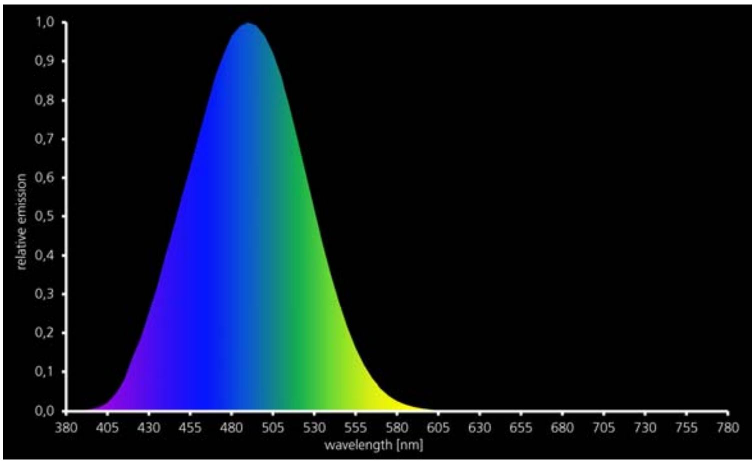

Figure 1: Effective spectrum for the melanopic effect of light S_{mel} (λ), in accordance with DIN SPEC 5031-100: 2015-08 (Graphics: DIAL)

The effect of this stimulation is that a suppression of the production of the hormone melatonin takes place in the pineal gland. The hormone melatonin plays a central role in the circadian rhythm of man. Especially in the evening, when we are tired, our blood has a high concentration of melatonin which drops as we sleep so that the melatonin level is considerably lower in the morning. Daylight, with its high proportion of blue light (especially in the morning), also contributes to the suppression of melatonin.

»Human Centric Lighting« aims at imitating a sort of »daylight progression« with different colour temperatures and, sometimes, different illuminances, to provide a form of compensation for humans who mostly suffer from a chronic lack of daylight. Frequently, this is primarily intended to activate a human being, that is to suppress melatonin with neutral or cold white light colours. This is done with luminaires containing different colour temperatures which can be controlled separately and are often called »tuneable white«. Usually an appropriate control is included in the products so that light colour and illuminance are adjusted automatically according to the progression of daylight.

Basically, HCL is not a form of lighting design which can only be implemented with the aid of LEDs. There was HCL ten years ago with fluorescent lamps. However, LEDs do offer some benefits since they are available in different colour temperatures and can be integrated very easily next to each other in luminaires because of the very small space required.

The Quality Of Daylight

Everyone agrees that natural daylight is the ideal light source for human beings. Creating HCL-design which is supposed to be in line with the dynamics of daylight raises some questions which have not yet been answered.

A. *Colour Temperature*

We know that daylight consists of two different components: direct sunlight and diffuse skylight.
Both components change their colour temperature during the day. But they do this in opposite directions. At sunrise the sun has a correlated colour temperature below 1 500 Kelvin. It is similar at sunset. At noon it changes to approximately 6 000 Kelvin. However, the colour temperature of the clear blue sky is very cool in the morning (> 25 000 Kelvin), changes to 9 000 Kelvin – approximately 20 000 Kelvin during noon and becomes extremely cool again after sunset. The dynamic of the colour temperature even exists at an overcast winter sky (Fig. 2).

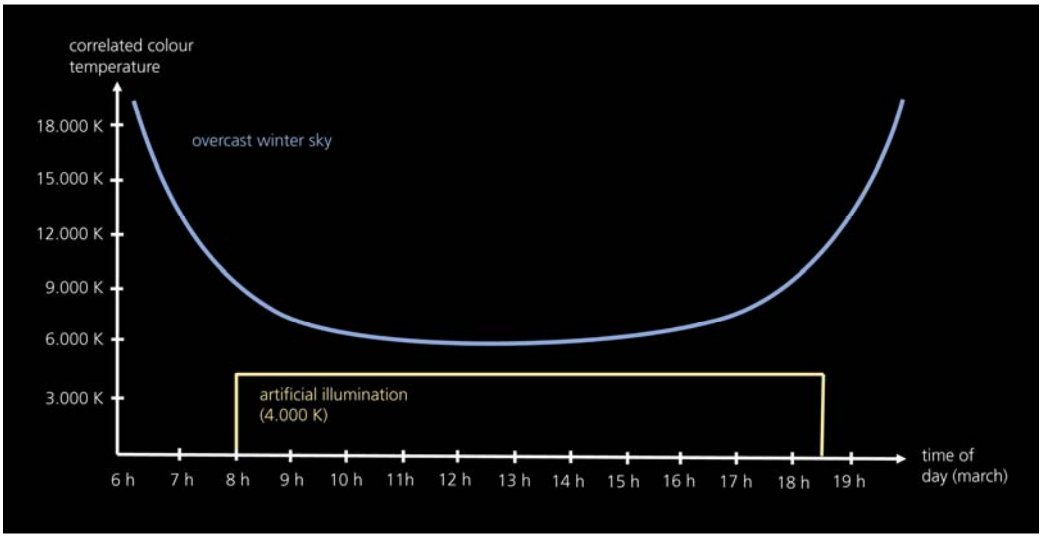

Figure 2: Dynamic of the colour temperature. (Graphics: DIAL)

So which sequence should we adopt in HCL-design? Which dynamics of colour temperature should be used for reference? The colour temperature of the sun or the colour temperature of the sky? Maybe a mixture of both?

B. *Illuminance Level*

In addition, we should not neglect to consider that at work places in indoor rooms there is only a fraction of the illuminance present outside. Illuminance outside during the day fluctuates from approx. 3 000 lx on a dull winter's day to over 100 000 lx in direct sunlight. A work place in an office is illuminated with just 500 lx, in accordance with ASR A 3.4 (Germany) and EN 12464-1: 2011-08. Higher illuminances are more likely to activate humans. What is decisive, in the final instance, is how much illuminance actually reaches the retina of the human eye. A level which is reached outside on a dull day cannot be achieved indoors for reasons of energy consumption. However, we should really only view the obligatory 500 lx as an absolute minimum requirement.

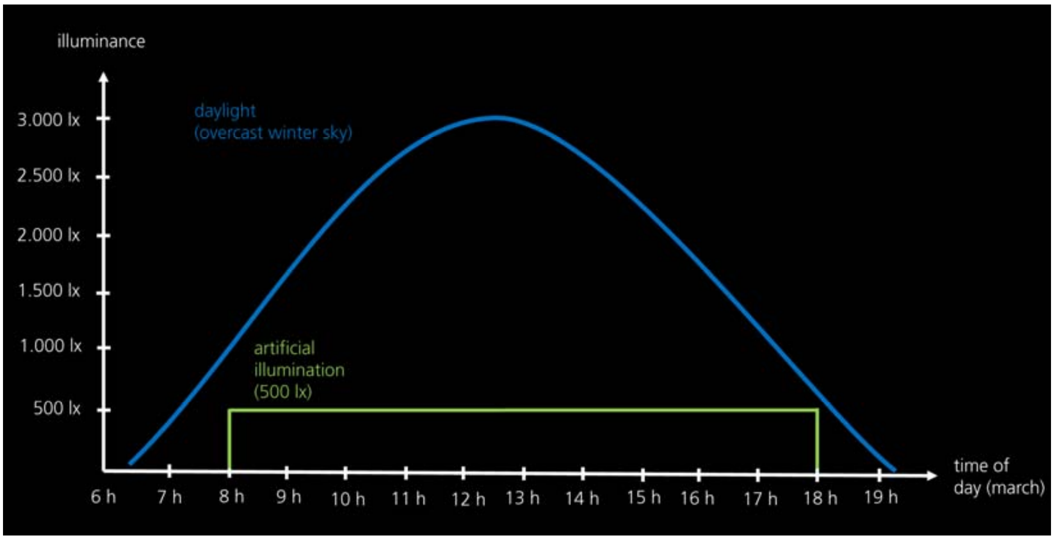

Figure 3: Dynamic of the daylight illuminance. (Graphics: DIAL)

Consideration Of Dynamics

Although, in the working world, the intention is, first and foremost, to activate humans with artificial light, we should at least, at certain times of the day, try to give humans a chance to calm down. Activation with cold white light in the evening can lead to sleeping problems/insomnia or to less restful sleep. An illuminance of a mere 30 lx is enough to significantly reduce the melatonin concentration in the blood.

Permanent activation also has nothing to do with the natural circadian rhythm. Generally, daylight should be taken as a role model. Here the situation is permanently dynamic as far as illuminance and colour temperature are concerned. An attempt should be made to consider this when planning human centric lighting. However, the changes should never be abrupt or in visible steps but should take place slowly and almost unnoticed, as in the natural world.

Spectral Distribution

We must not make the mistake of assuming that LEDs can create »daylight« The spectrum of daylight is fundamentally different from the spectrum of LEDs - regardless of the colour temperature. White LEDs have a peak in the spectrum at a wavelength of approx. 450-460 nm. Since this range is very close to the maximum for the melanopic effect of light of 490 nm, they are generally very suitable for stimulating melanopsin. The same is true for warm white LEDs, even though here the peak is more pronounced, the higher the colour temperature.

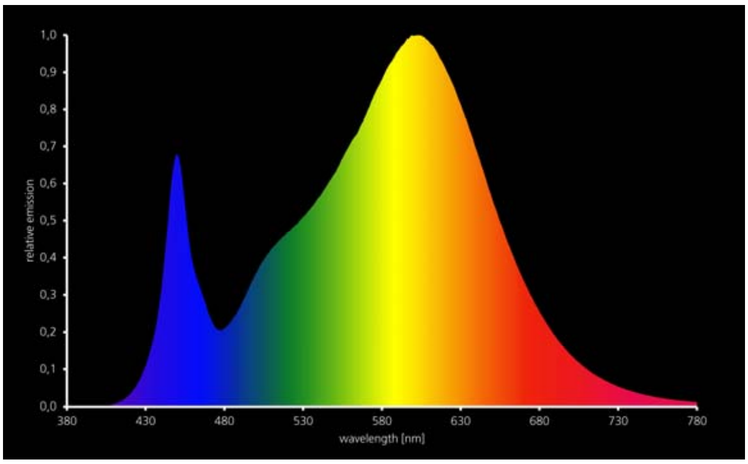

Figure 4: Spectral distribution of an LED with a colour temperature
of 3 000 K (Graphics: DIAL)

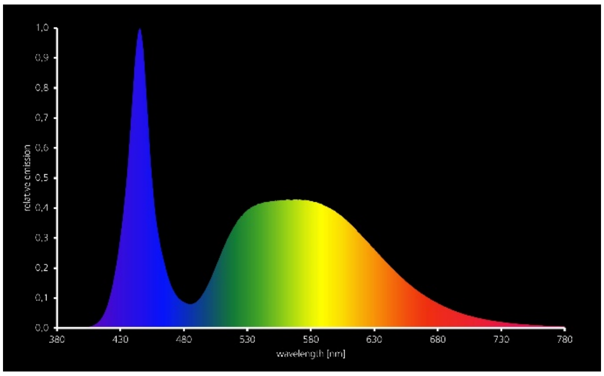

Figure 5: Spectral distribution of an LED with a colour temperature of 5 000 K (Graphics: DIAL)

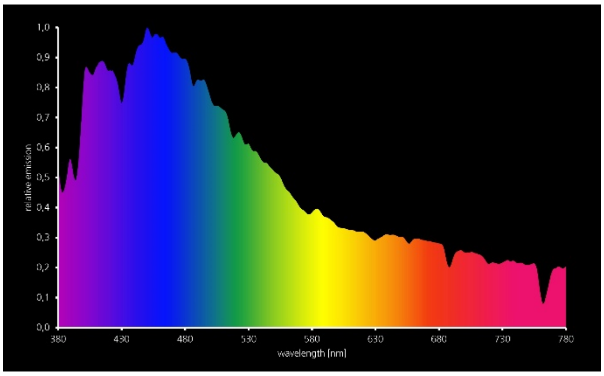

Figure 6: Spectral distribution of a blue sky in the morning with a colour temperature of 18 000 K (Graphics: DIAL)

Besides this we always talk about spectra between 360 and 780 nanometer when we talk about lighting design. The wavelengths beyond 360 and 780 nanometer are undesirable and inefficient. But today we know that even some infrared wavelengths have curative effects on the retina. Furthermore UV-B radiation is relevant for the vitamin D_3 production. If daylight, which contains both ultraviolet and infrared radiation and which obviously has an influence on the human body, is the ideal to aim for, is it being serious to talk about “human centric lighting” without these wavelengths in our lighting design?

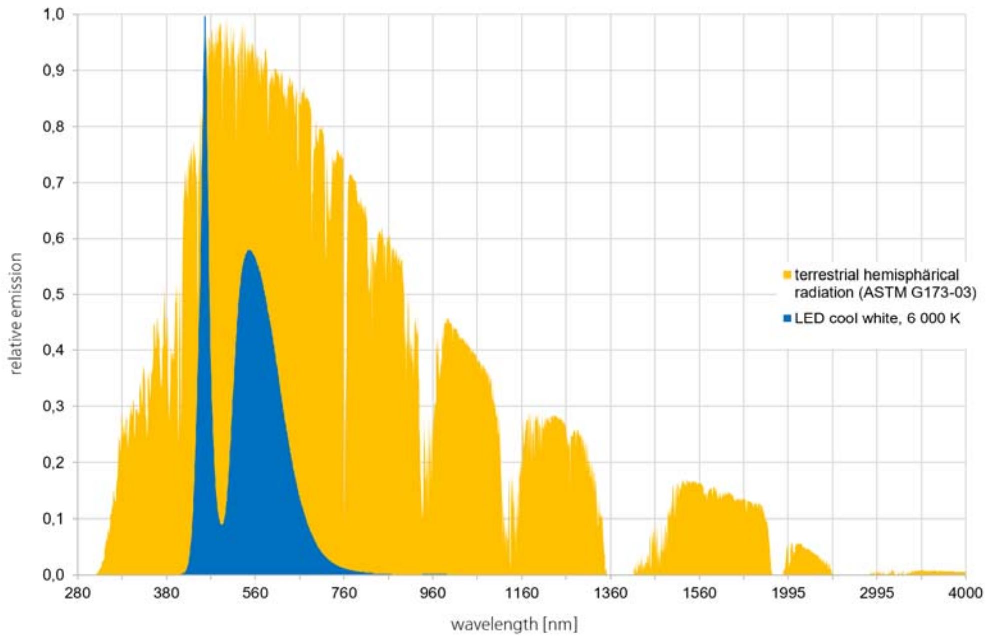

Figure 7: Spectral distribution of a cool white LED in comparison with the terrestrial hemispherical radiation (acc. ASTM G173-03), (Graphics: DIAL)

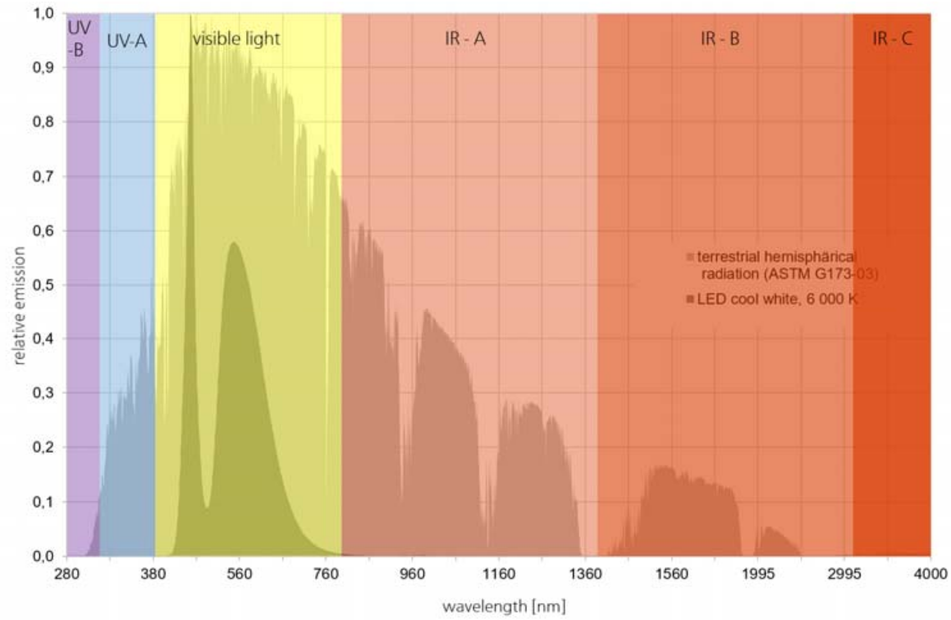

Figure 8: Spectral distribution of a cool white LED in comparison with the terrestrial hemispherical radiation (acc. ASTM G173-03), (Graphics: DIAL)

THE DIRECTION OF LIGHT

In this context it is important to give more consideration to larger areas within man's field of vision when designing lighting. Circadian efficiency can certainly not be achieved with accent lighting. The approach to be adopted for planning is found outdoors: diffuse light from the sky takes up a large area in man's field of vision. This should be taken into consideration, especially when activating humans with neutral or cold white light provided by indirect lighting.
For activation, ambient lighting over a large area in the upper half of the room (e.g. through indirect lighting) plays a big role since this has a greater biological effect than in the lower half of the room. This light reaches the lower half of the retina in which most ipRGCs are found. This is comparable to diffuse, cold white light from the sky outdoors (correlated colour temperature approx. 10 000 to 25 000 Kelvin). After sunset general cold white lighting in the upper half of the room should be avoided unless conscious activation is intended. In this case warm white lighting should be used. However, the direction of the light should also be considered. Warm white indirect lighting with a correlated colour temperature of 3 000 Kelvin feels strange and unnatural since it has no parallel in nature - except during a red sunset. Here it is an advantage to work with warm white accents which make the upper half of the room consciously darker - similar to the dark sky outside.

SHIFTWORK

Another topic which is not yet clear is: What does HCL mean for shift work? In the past, as LED technology took over, lighting designers tried to install extremely efficient lighting. Very often this meant illumination at 6.500 Kelvin or more – a good example being industrial buildings. But this is exactly what we do not want when we take night shifts into account in HCL design. On the one hand, people should not fall asleep during their work, on the other hand human centric lighting should not work against the natural circadian rhythm. There seems to be a conflict between supporting people with an illuminance level suitable to their task and allowing them to stay within their regular circadian rhythm during night shifts.

CONCLUSION

Basically the idea behind HCL is good. Unfortunately, in practice HCL lighting design is only carried out half-heartedly and does not achieve its aim. Attention must therefore be given to the previous items if this kind of lighting design is to influence the circadian rhythm.
Nevertheless, we should not underestimate the importance of »genuine« daylight. Going to work in the morning sun or taking a short walk outside during the lunch break certainly contribute far more to man's feeling of well-being than the best HCL lighting at the place of work. Even the best HCL lighting design is no »substitute « for genuine daylight.

Investigating a Dose-Response Curve for Daytime

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***Abstract*—Light can increase people's alertness and cognitive performance, both during the night and day. However, most experiments on increasing alertness and performance have used a limited number of light levels, making it difficult to determine the optimal level for daytime situations. A dose-response curve has been established for nighttime exposure, but since melatonin secretion and homeostatic sleep pressure are higher during nighttime, this relationship cannot be generalized to diurnal conditions. The current study aimed at investigating the optimal light intensity to induce acute non-image forming effects of white light during the day. More specifically, we wanted to explore whether it would be possible to construct a dose-response curve for daytime light exposure, with respect to both subjective and objective indicators of alertness and cognitive performance. The results will be reported at the conference, but cannot be disclosed in this paper on account of a foreseen publication in a scientific journal.**

***Index Terms*—Alertness, Cognitive Performance, Daytime, Lighting**

Introduction

When light enters our eyes, it is processed through different pathways, one of them being the non-image forming (NIF) pathway. The NIF pathway is mainly driven by activation of intrinsically photosensitive retinal ganglion cells (ipRGCs) and leads to circadian and acute effects. Since the discovery of these ipRGCs a large amount of research has been performed towards these non-image forming effects. The acute effects have been reported to influence alertness, vitality and performance during actual light exposure, both during the day and night. But how much light exactly is required to induce such alerting effects is still an open question, particularly for daytime exposure. There is one study that has established a dose-response curve for alertness [1]. In this dose-response curve it can be clearly seen at what light intensity the alerting effect starts and when the maximum alerting effect has been reached. Moreover, it showed that 50% of the maximum alerting nocturnal effect is already reached at 100 lux. However, given that this study was performed during nighttime, when melatonin secretion and homeostatic sleep pressure are high, these levels may not be indicative for the daytime situation, when circulating melatonin levels are negligible and sleep pressure is low. Studies performed during daytime do indicate that light can have an acute alerting effect; bright light has been found to influence subjective sleepiness and alertness [2]-[7]. However, because most studies have used a limited number of light levels and in some cases increased the baseline sleepiness or reduced prior light exposure, it remains difficult to conclude at what light intensity alerting effects will occur in normal daily life. Moreover, the results are not always consistent, sometimes showing null-effects [8] – [10].

In the current study, we set out to investigate a dose-response curve for diurnal exposure for day-active persons (i.e., after a 'normal' night of sleep). Our study is aimed at developing meaningful guidelines for lighting settings in day-to-day office situations; because of this we explicitly chose not to apply any sleep- or light restrictions. We investigated the acute alerting effects as a function of light intensity during daytime, employing a large range of illuminance levels (20 – 2000 lux at the eye), measured through a variety of objective and subjective measurements of alertness. Measurements were performed continuously during a 1-hour light exposure, after a 30-minute baseline (100 lux at the eye). Measurements consisted of non-visual cognitive tasks, questionnaires and physiological measurements. To take into account possible differences between the morning and afternoon, participants joined two sessions, one in the morning and one in the afternoon. The study was performed under naturalistic conditions, meaning participants were not fatigued and not sleep- or light-deprived before the experimental light exposure.

Method

A. *Design*

The experiment followed a 20 (illuminance level, between) x 2 (morning vs. afternoon exposure, within) design. Participants were exposed to a single illuminance (manipulated between subjects) for 1 hour, with a baseline exposure of 100 lux for 30 minutes beforehand. Illuminance levels at the eye ranged from 20-2000 lux; per illuminance level we assigned two participants. For the measurements, both subjective and objective indicators for alertness and cognitive performance were used. Each participant came back to the laboratory twice on separate visits, once in the morning and once in the afternoon (counterbalanced) and were exposed to a single illuminance level.

B. Participants

In this study, 38 healthy Dutch speaking subjects participated of which 14 male and 24 female (mean age = 21 years, SD = 3.75, range 18-38). The participants were recruited through the J. F. Schouten School for User-System Interaction Research database. The selection criteria were Dutch speaking, healthy and between the age of 18 – 45.

C. Procedure

Before the experiment, all participants completed the Munich Chronotype Questionnaire. Three days before the first session in the lab, participants signed an informed consent, picked up study materials and were instructed to keep to their habitual sleep pattern during the 3 days before the experiment. After the 3-day sleep protocol, participants came to the laboratory, where they took part in a 90-minute session. Upon arrival participants were instructed about the session and seated in one of the cabinets. Participants attached the sensors for physiological measurements according to an instruction sheet, after which they were asked to wear the headphones, read the instructions on the laptop and start with the trial tasks. When the trials were completed, there was an opportunity to ask questions, after which the actual experiment started, which lasted 75 minutes. After the first session, arrangements were made for a second session, there had to be at least three days in between the sessions. After the second session, participants were debriefed, thanked and compensated for their participation.

D. Setting

The experiment was conducted at the Eindhoven University of Technology in a light lab in the Vertigo building. In the lab two cabinets were created of which the dimensions were 1.20 m x 2.50 m. Participants were seated facing a light panel (Philips Strato, TPH170) measuring 1.20 m x 1.20 m. Each light panel contained six fluorescent tubes of 28W, of which three tubes of 2700 K (TL5-28W/827) and three tubes of 6500K (TL5-28W/865). In each cabinet there was a small desk (55 cm x 40 cm) placed 55 cm from the light panel on the wall, with a chair, laptop, mouse, headphones and a physiological measurement device. In the current setup it is possible to achieve a light intensity range of 100 – 2000 lux (at the eye) with a CCT of around 4000 K. To achieve the light intensities below 100 lux, a neutral density filter (Rosco E-Colour+#211:.9) was used.

E. Measures

1) Prior Measurements

Before the actual experiment, we measured sleep and light history of the participants. This was done by using an Actiwatch, pen and paper sleep diary (as a backup) and a lightlogger. Sleep was measured the three nights before the experiment, light history on the day of the experiment session.

ii. Performance tasks

Three different auditory performance tasks were employed in this study. The first performance task was a 5-min auditory Psychomotor Vigilance Task (PVT) to measure alertness and sustained attention. The second performance task was a 5 min auditory “Go/No Go” task to measure inhibitory capacity. The last performance task was an auditory N-back task. In this study we used the 2-Back version, in order to gain information upon working memory.

iii. Self-reported sleepiness, vitality, tension and positive/negative affect

The Karolinska Sleepiness Scale (KSS) was used to measure subjective sleepiness. Vitality, tension and positive affect were measured using 8 items: Energetic, Sleepy, Sad, Calm, Alert, Depleted, Happy and Tense. Participants had to indicate for each item how they felt on a 5-point scale, 1 being “Not at all” and 5 being “Totally”.

iv. Physiological measurements

During the sessions in the lab, physiological measurements were performed. Through the use of a Mobi8 device, heartrate, heartrate variability and galvanic skin response were measured continuously.

v. Light Appreciation

At the end of their second session, participants were asked to evaluate the lighting in the room using 6 bi-polar scales: pleasant/unpleasant, comfortable/uncomfortable, warm light/cold light, disturbing/not disturbing, bright light/dim light, stimulating/calming.

vi. Questionnaire

At the end of each session, participants completed a questionnaire about the situation before the experiment, e.g. how much caffeine they drank before the experiment and how much time was spent outside. At the end of the second session participants were asked about their general vitality, light beliefs and their sensitivity towards light.

F. Statistical Analysis

For the analysis of the data, Linear Mixed Models (LMM) were used in SPSS. In this study we used 20 illumination levels and only 2 participants were assigned per condition. Therefore, we not only investigated the illuminance levels separately, but also used clustering by dividing the 20 conditions in four categories: 20 – 65 lux, 82 – 189 lux, 239 – 614 lux and 778 – 2000 lux.

RESULTS

As indicated in the abstract, we cannot disclose the results here, as we are submitting the study to a peer-reviewed scientific journal. PVT reaction times, Go/No Go reaction times and 2-Back accuracy were assessed with Linear Mixed Models. We explored main effects of illuminance as well as interactions between light condition and time of exposure.

Similar analyses were performed on self-reported alertness (KSS), self-reported vitality, self-reported tension, self-reported positive/negative affect and physiological indicators. In parallel, we explored effects on light appreciation, and controlled for potential moderating effects of prior light history with lightlogger data, sleep-wake behaviour during the prior night based on actiwatch data, chronotype and various questionnaires.

The results revealed a smaller effect of light on the different variables than we had expected beforehand.

DISCUSSION

In the current study, acute effects of light intensity on alertness and arousal during the day were tested, employing a large range of illuminance levels. The results, however, revealed smaller effects of light intensity on indicators of alertness and arousal than we expected based on the aforementioned studies.

The findings deviate substantially from the results reported by Cajochen and colleagues [1], who were able to construct a dose-response curve for light intensity and alertness (also assessed with the KSS). There are however some significant differences between this study and the aforementioned study, the main differences being duration and timing of the light exposure. Whereas we exposed the participants to the light intensities for 1.5 hours during the day, their participants were exposed to the light for 6.5 hours in the early biological night. Even though many studies have shown alerting effects both during the day and during the night [2][4], the alerting effects seem to be stronger and more robust during nighttime. As mentioned, the duration of light exposure also differs between the studies, 1.5 hours in the current study versus 6.5 hours in Cajochen's study. This leaves open the possibility that a longer exposure period would induce stronger alerting effects, however, other diurnal studies have found acute alerting effects of light within an hour of exposure. [3][6][7]

In the current study, the participants came to the laboratory in their 'natural state', meaning they were not light or sleep deprived beforehand. In other studies mentioned, participants were sleep or light deprived before the actual experiment, which possibly makes the alerting effect of light intensity larger. In this study we found it important to provide a high ecological validity, meaning that we wanted our participants to behave like they normally would on a daily basis.

Based on the current findings, two subsequent steps were taken. First, we considered that light history may have played an important role in the acute alerting effects of bright light. In the current study participants followed no strict protocol with regard to light exposure prior to the experimental session, so it is well possible some had been exposed to a lot of bright light before the experiment. This prior light dose may have influenced their light sensitivity, explaining some of the results found. Importantly though, participants wore light loggers throughout the day of the experiment, allowing us to explore moderating effects of light history. Second, we reflected on the period in which the experiments were performed: May, during springtime. In spring participants are more likely to have been exposed to more light, since there are more sun hours in a day during spring than in winter. The influence of the season on sensitivity to the acute alerting effect of light is relatively unknown, however a recent study has shown that there is a possible moderating effect of season [11]. In response to this, we decided to replicate this study in winter. Possibly we find the larger, expected, effects in winter and additionally it allows to make a good comparison between summer and winter. Currently the analysis of the winter study is in progress and the results will be reported at the conference.

In general, the results found indicate that there are possibly large differences in light sensitivity between night and day. This suggests that we cannot generalize the dose-response curve for nighttime by Cajochen et al. [1] for daytime situations. However our winter study is still in progress and it is clear that more research is necessary in order to define optimal, potentially personalized, lighting scenarios.

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Impact of Spectrum and Illuminance on Alertness – A Quasi-Field Study in A Lecture Hall

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***Abstract* — This experiment studied the impact of the spectral power distribution and illuminance at eye level on alertness in a lecture hall. Time of day was also considered as influence factor. 86 students executed a d2R-test and a questionnaire including the Karolinska-Sleepiness-Scale (KSS) before and after each lecture. One of four lighting conditions was shown during the lectures: reference, bright, warm white or cool white. A significant effect of lighting condition with the d2R-test is very likely explained by a continuing learning effect and not by an impact of the lighting. KSS results show no significant effects of lighting condition, but a trend of time of day which fits well with the human circadian rhythm.**

***Index Terms*-- alertness, lecture hall, light and health, non-visual effects, spectrum**

INTRODUCTION

Can we support students learning with lighting that takes into account non-visual effects? Remaining alert is a key factor to keep a fit mind and to understand the lecture. A number of studies show that an increased illuminance at eye level as well as an increased short wavelength part of the spectrum can improve alertness during the day. However, recent studies show contradictory results: no significant improvement or even a deterioration of alertness [1], [2].

A possible reason can be the quite low number of participants in several studies [3]. The lighting conditions of studies are sometimes not well enough documented as well, even though the spectral power distribution and the lighting conditions at eye level are crucial for non-visual effectiveness. Furthermore, lighting history and time of day are often not considered impact factors. Reference [4] conducted a study in a lecture hall using the Karolinska-Sleepiness-Scale [5] (KSS) to investigate the difference between 17.000 K to 4.000 K lighting. One conclusion is that also the timing of the light exposure plays an important role. This might be the case because of the individual performance rhythm through the day.

In addition to that, the d2R-test, which is frequently used as an operationalization for alertness, has a strong learning effect, which can affect the results. A pre-test in our laboratory showed that the learning effect lasted over two to four d2R- executions, but continued the next day again for about two d2R-executions [6]. A training phase for participants in repeated measures designs is required.

The above-mentioned aspects were considered in the current study, which investigated if an increased melanopic illuminance [6], E_{mel}, due to adjusted spectral power distribution and / or an increased illuminance at eye level, E_{eye}, improves the alertness. The focus of this experiment lied on a high number of participants. The application of a real lecture hall allowed to study a multitude of participants at the same time under constant environmental conditions. Lighting conditions were set to be comparable to a recent study in our laboratory [8] and the influence of the time of day was included as a second research question in our study.

METHODS

A. Design

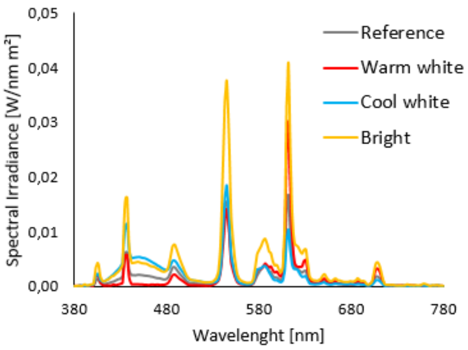
The experiment took place during a series of lectures in the winter semester, from October 2016 until February 2017, at the TU Berlin. The course consisted of two 90 min lectures a week, once in the morning and once in the afternoon, to study the effect of time of day. During these lectures one of four lighting setting was shown as variation of the independent variable. The participants performed a d2R-test and a questionnaire as measures for alertness before and after each lecture. The group of participants remained the same during the semester, resulting the experiment is a repeated measures design.

B. Participants

From about 250 students of the lecture "Basics of electrical engineering" held by the same professor throughout the semester, 86 students (13 female) volunteered to join the experiment. The age was between 18 – 30 years and all had a visual acuity over 0.8, which was checked with a test card [8]. The participants received 100 € before the Christmas holidays and 150 € at the end of the experiment. 4 students left the experiment in 2016 (resulting N = 82) and 14 students left in 2017 (resulting N = 68). 8 participants just took part one day a week. The participants were not told about the changing lighting conditions and the official reason was "concentration over season and influence of environmental conditions", but the change of lighting conditions was visible and could have been perceived by the participants.

C. *Lighting Conditions*

The independent variables of the experiment were the illuminance at eye level (E_{eye}) and the spectral power distribution, which is characterised by the melanopic illuminance (E_{mel}, calculated with the toolbox from [6]) and the correlated colour temperature (CCT). The lighting conditions in the lecture hall were realised by means of five types of fluorescent lamps: cool white 5.100 K, warm white 2.700 K, red, green and blue. These were mixed to four lighting conditions as shown in Fig. 1. All lighting conditions had a colour rendering index about 85. Because of technical issues high illuminances could just be reached with the neutral CCT. The participants had to sit in the area of the lecture hall, were the lighting condition was almost constant ($\Delta E \sim 25\%$, $\Delta CCT \sim 5\%$). Controlling measurements with the spectrometer and luxmeter were performed before and after each lecture. The room had no windows, so there was no daylight contribution.



Lighting conditions	***Illuminance at eye level (E_{eye})***	***Correlated Colour Temperature (CCT)***	***Melanopic illuminance (E_{mel})***
Reference	200 ± 20 lx	4.000 ± 100 K	130 melanopic lux
Bright	400 ± 40 lx	4.000 ± 100 K	260 melanopic lux
Warm white	200 ± 20 lx	2.300 ± 50 K	70 melanopic lux
Cool white	200 ± 20 lx	9.000 ± 1.000 K	230 melanopic lux

Figure 1. *Lighting conditions spectral power distribution (left) and table (right)*

D. *Measures*

The dependent variable in this study was alertness, evaluated by means of a d2R-test and a questionnaire. Both measures were chosen because of their easy and fast usage in large groups and an overall maximum duration of 15 minutes, to allow the students to reach their next lectures in time.

The d2R-test is a concentration test from Brickenkamp [10]. The task is to cross out the letter d with two dashes and not to cross out other symbols like ds with more or less dashes or the letter p. The time limit is set to 15 sec for each of the 14 rows of the test. The number of correctly crossed symbols minus the errors leads to a concentration performance value. The advantage of the test is its standardization, the common use in other studies to compare with and the very easy usage in groups. A disadvantage is the reported learning effect [11], which has to be treated with care.

A questionnaire was developed for the subjective response of the participants (can be downloaded here: [12]). There was a digital version for smartphones or laptops and a paper version. It consists of the Karolinska-Sleepiness-Scale [5] (KSS): a 9 point Likert-scale from 1 extremely awake until 9 extremely sleepy/ fighting sleep) and seven items about well-being on a 7 point Likert-scale (well, concentrated, interested, stressed, quiet, motivated, exhausted). It was also asked how exhausting the d2R-test was perceived and if there were any distractions. The opinion about the environmental condition was asked after the experiment with ten items including lighting, room climate and the lecture itself. It was also asked, if the subjects felt a change in their well-being. Before the lecture they also reported about their caffeine consumption, their meals, their lighting history concerning time and duration of their stay outside this day, their daily routine and any special circumstances e.g. having a cold. At the beginning of the experiment the participants completed a questionnaire about general information (age, sex, and glasses), health (SF12), chronotype (MEQ), stress (PSS), depression (PHQ9) and sleep quality (PSQI).

E. *Procedure*

The d2R-Test and the questionnaire were conducted 15 min before and directly after the 90 min lecture. The two weekly lectures were Thursdays from 14:15 – 15:45 pm and Fridays from 8:15 – 9:45 am. During these two lectures one of the four lighting condition was shown. See Fig. 2 for a weekly plan of the lighting conditions. Because of pre-tests, it was expected that after two weeks of training (8 performed d2R-tests) under reference light no further learning effect would occur. Then three experimental conditions followed and the reference light finished the first part of the experiment in 2016. This procedure was repeated with a different order of the experimental conditions after three weeks

Christmas holidays in 2017. The reason was to minimize other influences like the difficulty of the lecture and individual reasons for variations.

Figure 2. *Plan of the experimental weeks and their lighting conditions: grey – reference, yellow – bright, red – warm white and blue – cool white. The Christmas tree symbolizes three weeks Christmas holidays.*

Results

The results of the d2R-test and the KSS are shown here. The analysis with respect to the environmental conditions and further questionnaire items are not included in this evaluation.

A. D2R-test

The output value from the d2R-test is concentration performance (CP). There are four CP values each week: Thursdays before the lecture (T_1), Thursdays after the lecture (T_2), Fridays before the lecture (F_1) and Fridays after the lecture (F_2). The CP values of the first two training weeks are still in progress, because the calculation of these values is very time-consuming. In Fig. 3 the means with confidence interval of each four CP values per week are shown with a colored box around each week that shows the lighting condition.

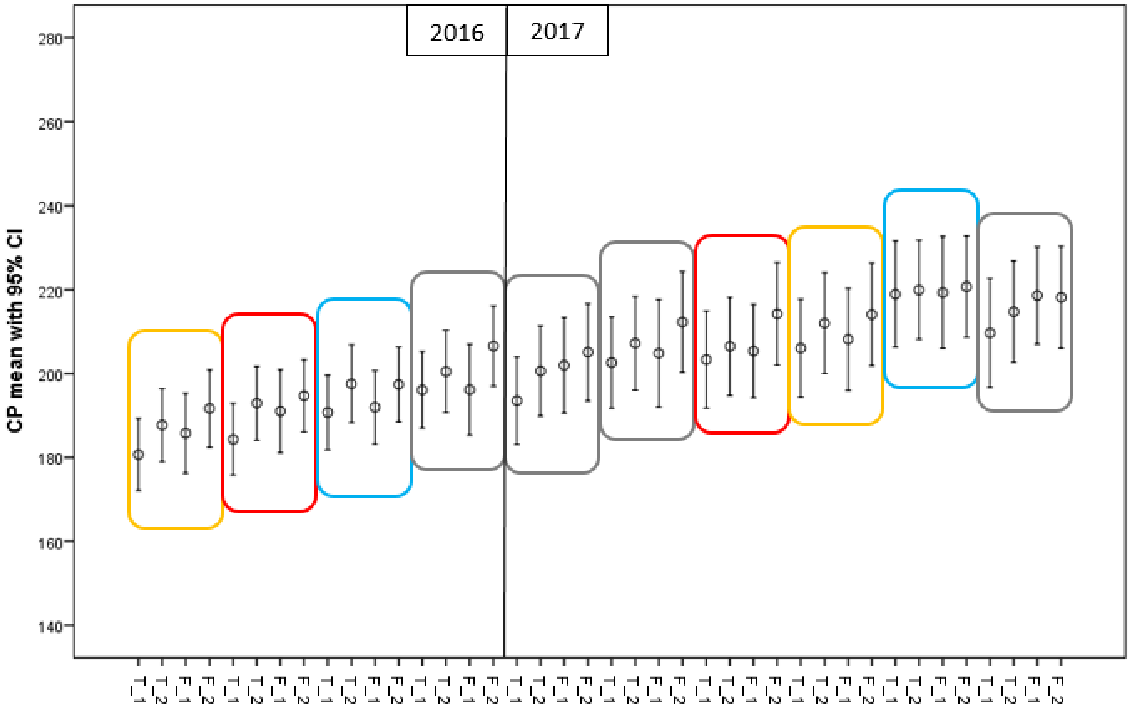


Figure 3. *Graph with means of concentration performance with confidence interval. The lighting conditions are grey – reference, yellow – bright, red – warm white and blue – cool white.*

The most obvious fact are the rising values over time. The expected stop of learning effect after the training weeks did not happen. For this reason, the statistical analysis was conducted separately for 2016 and 2017. Normality of the CP values was checked with q-q plots. Statistical analysis was conducted with a repeated measures ANOVA with the factors lighting condition (4 levels) x time of day (2 levels) x before/after lecture (2 levels). The effect of lighting condition was significant in both cases (2016: $F(3,31) = 12.19$, $p < 0.001$, $N = 34$ and 2017: $F(3,17) = 4.01$, $p = 0.025$, $N = 20$). An expected interaction effect of lighting condition x before/after the lecture, which would mean that the change in CP values during the lectures was moderated by the lighting condition, was not found ($p > 0.05$). The reference conditions in the beginning and the end of 2017 served as reference measure: a repeated measures ANOVA with 2 levels of lighting condition results in a significant difference between the reference conditions ($F(1,35) = 22.26$, $p < 0.001$, $N = 36$). Missing data (participants e.g. were late or ill) was a difficulty here and greatly reduced the number of included cases in the ANOVA. As possible solution the analysis in 2016 was repeated with imputed data (missing data replaced by group mean), what led to a similar effect of lighting condition ($F(3,70) = 10.50$, $p < 0.001$, $N = 73$).

The significant effect of lighting condition could be due to an effect of lighting or due to an effect of learning. CP values from the reference conditions at the beginning and the end of 2017 differ from each other although the lighting condition is the same. The different order of lighting conditions in 2016 and 2017 does not lead to different results as visible in Fig. 3: a change from bright to warm white condition in 2016 leads to higher CP values while a change from warm white to bright condition in 2017 also leads to higher CP values. An explanation with impact of lighting seems unlikely and the persistent learning effect is the more plausible explanation.

B. KSS

Fig. 4 shows the mean values of the KSS in a similar way like Fig. 3 for the d2R-test. Normality of KSS values was checked with q-q plots. The same statistical analysis for 2016 and 2017 as with the d2R-test was conducted here: a repeated measures ANOVA with the factors lighting condition (4 levels) x time of day (2 levels) x before/after lecture (2 levels). The difficulty with missing data and reduced number of included cases in the ANOVA remains the same: N = 24 in 2016 and N = 16 in 2017. The ANOVA was then repeated with imputed data. Both analyses with original ($F(3,21) = 0.07$, $p = 0.975$) and imputed data ($F(3,71) = 0.67$, $p = 0.575$) showed no significant effect of the lighting condition and no significant interaction effects of lighting condition x before/after lecture ($p < 0.05$). A difference of KSS values between the early and late sessions is visible in Fig. 4: Participants in the early session seemed to start more tired and become more awake during the lecture while participants in the late session seemed to start more awake and become more tired during the lecture. This trend could be explained by the changing human performance level during the day because of the circadian rhythm.

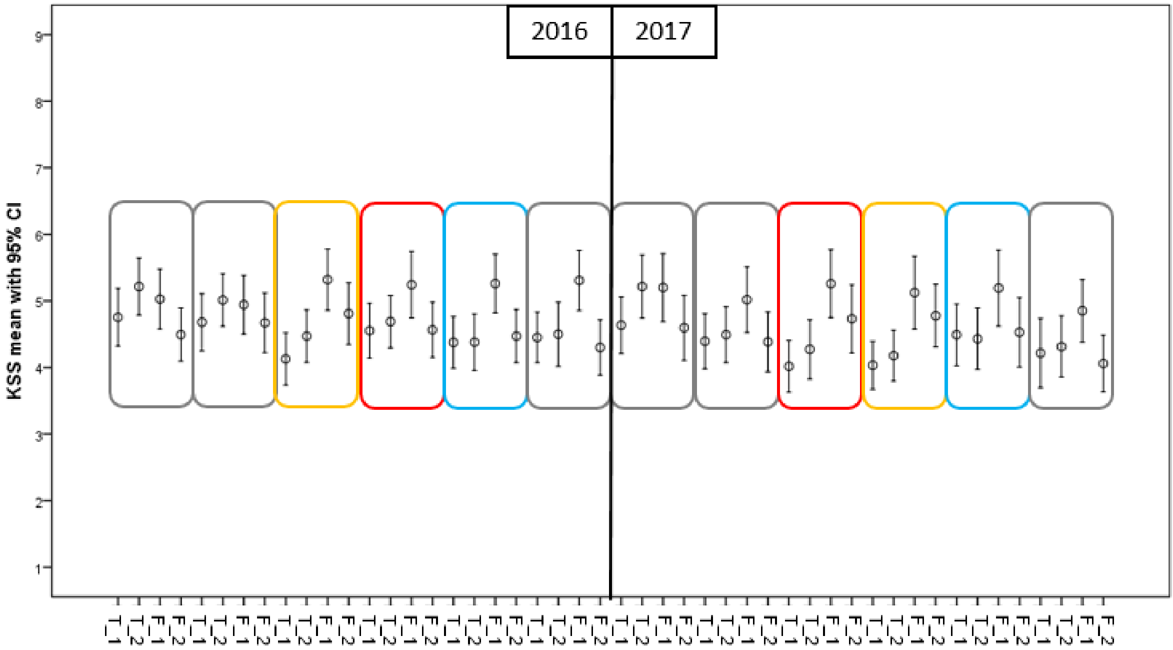


Figure 4. *Graph with means of KSS with confidence interval (1 – extremely awake … 9 – extremely sleepy). The lighting conditions are grey – reference, yellow – bright, red – warm white and blue – cool white.*

CONCLUSION AND DISCUSSION

The impact of an increased short-wavelength part in the spectral power distribution or an increased illuminance at eye level on alertness was studied in a real-life application of a lecture hall. D2R-tests and questionnaires including the KSS were performed by the participants before and after the lecture. One of four lighting conditions was shown during each lecture and the time of day varied.

The hypothesis, that a higher illuminance at eye level or a higher short-wavelength part in the spectral power distribution can enhance the alertness, could not be confirmed with our study. The findings of a significant effect of lighting condition with the d2R-test are very likely explained by the continuing learning effect. No significant effect of the lighting condition was found with the KSS from the questionnaire. A trend for the time of day was found with the KSS. Students began Friday morning more tired than Thursday afternoon. On Fridays students got more awake during the lecture and on Thursdays students got sleepier. This perfectly fits the performance curve during the day because of our circadian rhythm.

One possible reason why the expected effects were not found was a number of confounding influences, because the real-life situation was very complex. The questionnaire item about disturbances during the d2R-test shows, that many participants felt disturbed by the environmental noise caused by other non-participating students. The questionnaire also reported of many participants coming ill to the experiment, having slept too little or feeling very stressed. The participating students sometimes were late or forgot to fill in the questionnaire or did not take care with the d2R-test, what lead to a great number of missing data. Imputation of data (missing data replaced by group mean) solved this difficulty but is not optimal, because it leads to reduced variance of data, which makes differences easier to find. Original data and imputed data showed the same trends, so this procedure seems justified.

It was expected that the learning effect of the d2R-test would be eliminated after two weeks of training, instead it lasted through the whole experiment which consisted of 48 tests. A possibility to estimate the learning effect and correct the values would have been an option in an experiment with different groups and a permuted order of lighting conditions. This was considered before the start of this experiment. A similar lecture at the same times and with the same environmental conditions ideally with the same professor and the same content would have been necessary. This was not possible here. As conclusion the d2R-test is not suitable for repeated measures designs, because the learning effect is greater than the hypothesised lighting effects. The test has another difficulty in between subject designs with small groups (see lab study with 30 participants per group in [8]): the very high inter individual variance, which also masked the potential lighting effect. With this knowledge other studies that used the d2R-test should be considered with great care.

More extreme lighting conditions would have been preferable to have a higher varying range. Reference [4] found using the KSS that student's alertness decreased less during the lecture in a 17.000 K situation compared to a 4.000 K situation. Laboratory studies often use 1.000 lx at eye level compared to 200 lx at eye level [1],[2]. Both, higher illuminances or more extreme colour differences, were not possible here, because of technical reasons and the readability of the slides of the lecture. It is also questionable if these extreme conditions are reasonable for real applications.

The next task is to analyse the implications of the other items of the questionnaire to the current results. The well-being items might show the same trend like the KSS, but there might be an influence of the lighting detectable. The evaluation of the lighting will show, if participants favoured one lighting condition over another and how they were generally accepted. Chronotype would be an interesting group variable, but in our experiment most participants were neutral types (51) and morning (10) or evening (25) types were rare. Reference [2] showed a different reaction of stressed vs. not stressed participants. With the PSS questionnaire this also can be evaluated in our experiment.

Future research in this field should include long-term experiments to examine if spectral power distribution or illuminance at eye level have influence on alertness in longer duration of light exposure. A broad range of measure instruments including not only different concentration tests and questionnaires but also biomarkers should be considered.

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Measurement of the Effect of Dynamic Lighting on Alertness, Mood and Sleepiness

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Abstract— **The lighting in the workplace is known to have a significant effect on the workers' well-being and alertness. It also affects sleep/wake-cycles and mood. The aim of this pilot study is to investigate a method to evaluate non-visual effects of variable lighting in workplaces using both self-assessed and physical data. The lighting in two offices was varied according to pre-programmed schedules, including daylight simulating scenario for two weeks and activity promoting scenario for two weeks. The method was successful and provided interesting results on the measured physical data. The resting pulse was lowered and the sleep quality improved for the test subjects during the weeks of dynamic office lighting.**

Index Terms—**Activity, Human Centric Lighting, Dynamic lighting, Office Lighting, Sleepiness**

INTRODUCTION

For many people, most hours of a working day are spent indoors. Thus, the indoor environment has a large effect on people's comfort, well-being and productivity. An important part of the indoor environment is the lighting as light is essential to perform any visual task. A well-balanced illuminance, absence of glare and sufficient colour rendering properties of the light are typical factors that have a positive influence on visual task performance. However, there are also less direct psycho-biological effects of light. The importance of these so called non-visual effects, how it affects our attention, alertness and mood, as well as how it can help adjust our circadian rhythm have been recognized and shown in several studies in the past decade [1-2]. The interaction of light with the photosensitive cells modulates the production and suppression of different hormones, e.g., melatonin and cortisol that regulate our sleep- and wake-periods. A disrupted daily cycle affects psychological and physiological functions. One example of this is depression, which is increased during the dark winter months in northern countries like Sweden. Research indicates that symptoms of depression, to some extent, can be managed or repressed with light therapy. For this, artificial light with spectral content more similar to natural daylight than traditional lighting can be used. It has also been shown that the photosensitive cells are connected to other parts of the brain [3] but how this affects our activity levels, perception and behaviour is not yet fully understood.

Thus, lighting affects people through both visual and non-visual experiences. These combine to have an effect on well-being, concentration and tiredness. Lighting designed to attempt to promote positive effects is called human centric lighting (HCL) and is currently installed in work places throughout Europe. The European standard for lighting of indoor work places EN 12464-1 [4] specifies requirements and guidelines for a lighted indoor environment regarding basic visual parameters. With the emerging interest and research on human centric lighting, a DIN standard with design guidelines for biologically effective illumination [5] has recently been developed.

With the deployment of indoor illumination based on LED and its possibility of active steering, there are also new possibilities in creating a lighting environment with dynamic illumination where both intensity and spectral content (i.e., correlated colour temperature (CCT)) are varied. The parameters can be varied to mimic the continuous variations of natural daylight or other schedules based on particular needs and preferences. In many offices, schools and other work places so-called HCL-lighting is installed and the number of companies selling and promoting these concepts are growing. However, although it is recognized that there are both qualitative and quantitative aspects of workplace illumination and that the lighting affects mood, alertness, concentration and general well-being, it is not clear how this is optimized, how much is individual preferences and so on.

The present paper reports on a pilot study where research subjects work in offices with controlled variable lighting for five weeks. The lighting is varied in different programmed scenarios and the sleepiness, mood and activity of the subjects are monitored by questionnaires, including self-assessment sleepiness scales, and activity bracelets. The activity bracelets monitor pulse, exercise and sleep quality. The aim of this study is to contribute to research on biologically effective lighting as there is still no real consensus on how this should be achieved.

METHOD

A. Lighting Setup

In a living lab at RISE Research Institutes of Sweden, two single person offices were installed with programmable tuneable 60×60 cm LED-panels (Modul RC-LED, Glamox Luxo, Glamox AS, Oslo, Norway) in the ceiling. The luminaires have a prismatic diffuser and the CCT of the emitted light can be tuned by mixing three different LED-sources in the panel (blue, white and red LEDs). The area of each office is 4 m^2 and there are two LED-panels in each room. One of the offices and a close up of the luminaires are shown in fig. 1. The amount of natural daylight in the offices is very small since the offices do not have windows to the outside but are located at the inner end in a larger room.

Figure 1. One of the offices in the living lab (left) and close up of the luminaires (right).

The control system was programmed to vary the lighting according to three different schedules. The scenarios used are constant, daylight adapted, and activity promoting as described in the DIN standard on biological effective lighting [5]. The horizontal illuminance in the centre of the office desk was varied between 500 lux and 1000 lux. The CCT was varied between 2500 K and 7000 K. The sequences are shown in fig. 2-4. The constant scenario was running for one week, followed by the daylight adapted scenario for two weeks and finally the activity promoting scenario for two weeks.

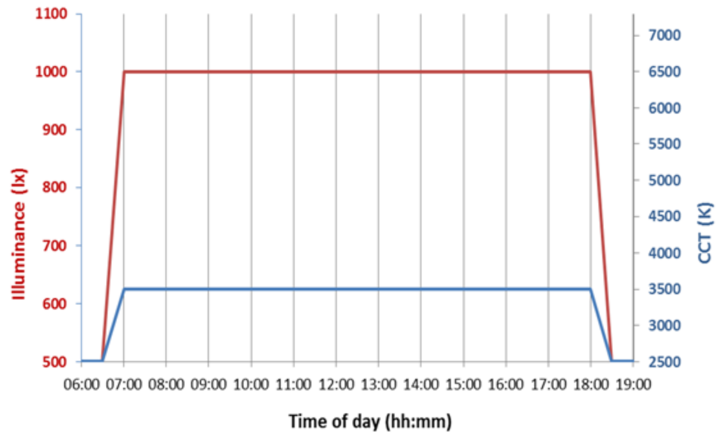

Figure 2. Static reference lighting (week 1). Constant colour temperature (3500 K) and constant illuminance on the desk (1000 lux) for all work days during one week.

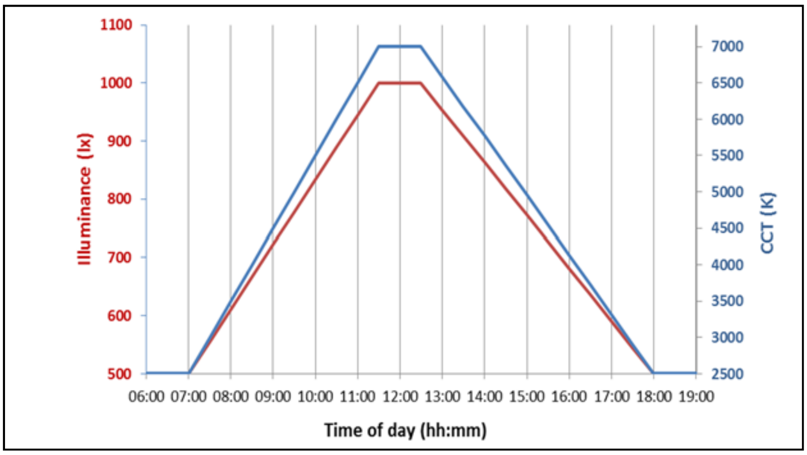

Figure 3. Daylight adapted lighting (week 2-3). The illumination is increased gradually from 500 lx in the morning to 1000 lux in the middle of the day. In the afternoon the illumination is decreased gradually from 1000 lux to 500 lux. The colour temperature is set at 2500 K in the morning and reaches 7000 K at noon. In the afternoon it is decreased gradually to 2500 K. The setup runs for two weeks.

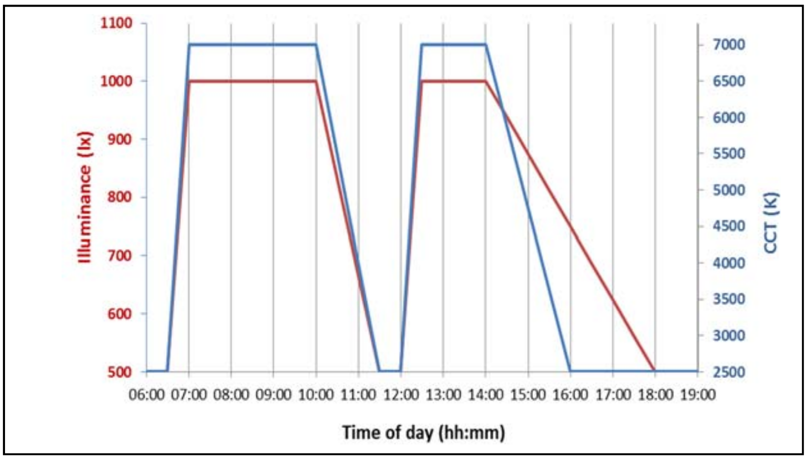

Figure 4. Daytime Activity supporting scenario (week 4-5). A boost of 1000 lux/ 7000 K light in the hours between 07:00-10:00. Just before lunch the illuminance and CCT decrease to minimum levels 500 lux/ 2500 K, followed by a second boost after lunch. At 14:00 the illuminance decrease gradually to 500 lux and the CCT decrease to 2500 K. This setup also runs for two weeks.

B. Test Subjects

Two male employees of RISE Research Institutes of Sweden, age 53 and 55 years respectively, were recruited as test subjects to perform their daily work in the offices with programmed lighting. The subjects were healthy without medical or sleep disorders, as assessed by an interview prior to the start of their participation in the study. They were informed about the test and signed a written consent form before the start of the test period. The study was performed during five weeks in March and April of 2017 in the city of Borås, Sweden.

C. Study Design

The subjects were evaluated continuously through questionnaires and activity bracelets. The commercial activity bracelets (Fitbit Charge 2, Fitbit Inc., San Francisco, USA) monitor the subjects' pulse, exercise (number of steps during the day, number of stairs climbed, etc.) and movement during sleep. It also calculates an estimated daily resting pulse and number of occasions during the night when the subject have been restless, based on the measured data. An activity bracelet was also worn by a reference person, male age 49, working in an office with non-variable lighting. The activity bracelets were kept on both days and nights, also during weekends for one of the subjects and the reference subject. The other test person did not agree to be monitored outside of working hours. In the evaluation, the average value of the resting pulse during the two week sessions is calculated, as well as the average number of occasions during night when the subject have been restless. As these values are highly individual, only changes as compared to constant lighting conditions were considered.

The questionnaires were filled out at the end of each working week (i.e., Friday afternoon). The questionnaires had five sections. The first section contained a validated sleepiness scale, the Epworth Sleepiness Scale (ESS) [6] where the subjects assess how sleepy they usually feel in different daily situations. The ESS was only included in the questionnaire for the first week as this scale is reflecting a person's habitual sense of sleepiness. The second scale for self-assessed sleepiness is based on the Karolinska Sleepiness Scale (KSS) [7] where the subjects are reporting on instantaneous sleepiness, i.e., how tired they felt at different times of the day (e.g. in the morning, in the evening, at bedtime and so on). In the first section there were also two scales for self-assessment of energy and mood at different times during the day. The second section includes questions on alertness, breakfast, time spent outside, amount of coffee and sweets consumed etc. The third section contained questions on sleep, e.g., bedtime, time to fall asleep, difficulties getting up in the morning, if the subjects felt they had a good night sleep and if they woke up during the night. In the fourth section the subjects were asked to take a reaction test online [8]. The fifth and last section contained questions on the lighting comfort. The subjects were asked to indicate their attitudes and opinions on pleasantness, discomfort, glare, colour temperature, light intensity, light distribution, if the lighting is relaxing or activating and if the lighting makes it difficult or easy to concentrate.

RESULTS

The information obtained from the bracelets show that the resting pulse of the test subjects decreases during the weeks of varied lighting (scenario 1 is constant, scenario 2 is daylight adapted scenario and scenario 3 is activity promoting scenario). This is shown in fig. 5, where the resting pulse is reported for each test subject and the reference subject. The standard deviation for the daily resting pulse in each scenario is indicated by error bars. Furthermore, the sleep quality is improved for the test subject that agreed to be monitored during the night (fig. 6). During these weeks, the resting pulse and sleep quality of the reference subject showed only minor variations. For the reference subject the three scenarios were constant.

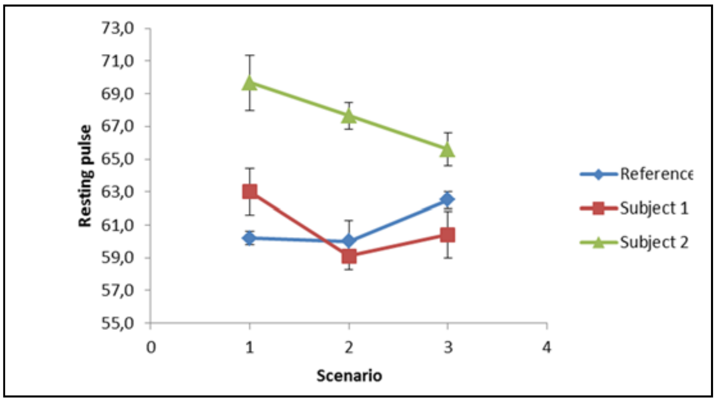

Figure 5. Resting pulse (mean during each scenario) for the two test subjects and the reference subject during the test period.

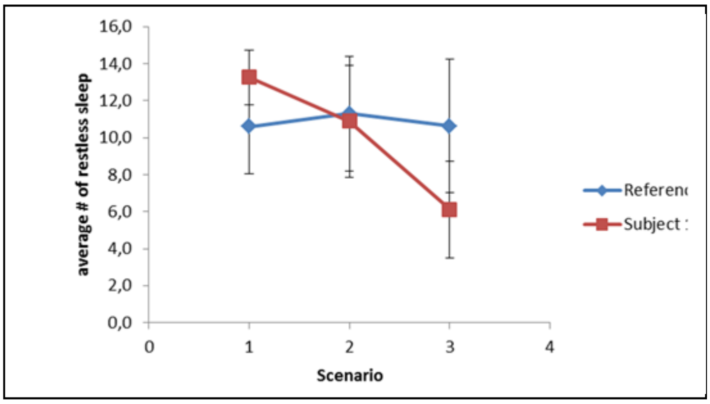

Figure 6. Sleep quality for one of the two test subjects and the reference subject during the test period. The second test subject did not agree to be monitored during the night.

Even though there were changes noted in the sleep quality for one of the subjects, the times for going to bed and getting up in the morning were unchanged for both subjects during the test period. They slept approximately 7 hours per night as shown in table 1. Also most other daily routines remained more or less unchanged during the five weeks, including the amount of coffee and sweets consumed and time spent outside each day. Both subjects reported spending only a short time (20-25 min) outside each workday

TABLE I. BED- AND RISE TIMES OF THE TEST SUBJECTS SHOWN AS MEAN, EARLIEST AND LATEST TIMES OVER THE FIVE WEEK TEST PERIOD.

Subject No.	Bed- and rise-time	
	Bedtime (mean, range) (hh:mm)	***Rise time (mean, range) (hh:mm)***
1	22:49 (22:30-23:05)	06:07 (06:00-06:37)
2	23:39 (23:00-00:15)	07:00 (06:30-07:30)

The results of the questionnaires do not indicate that the self-assessed sleepiness and mood are significantly affected during the five week test period. Further results from the different sections of the questionnaire are summarized below.

Sleepiness: From the self-reported data it was found that both subjects were more tired in the morning during the weeks with the daylight adapted lighting than during the week with the constant lighting. The morning tiredness in the activity promoting lighting scenario was intermediate between the other two.

Energy: The subjects reported having more energy in the evenings during the weeks of variable lighting compared to the week of constant lighting. This is in line with another study [9] where it was found that lighting conditions in the office during the day influence the subjects' energy in the early hours of the evening. Both subjects reported having less energy at bedtime (i.e., later in the evening) during the four weeks of variable lighting although the effect was more pronounced in the energy scale for one of the subjects. The other subject reported much shorter time between bedtime and going to sleep during the weeks of daytime activity promoting lighting which could indicate less energy in the late evening.

Mood: One of the subjects reported being in a better mood at bedtime in the first week (constant lighting) compared to the other scenarios. The same subject was in a better mood in the morning during the weeks with variable lighting.

Reaction time: For the reaction time test, one of the subjects performed about the same every week while the other subject improved the reaction time for each week. This might however be an effect of training.

Visual comfort: The different lighting scenarios did not significantly affect the visual comfort for either of the test subjects.

DISCUSSION AND CONCLUSION

Obviously many factors not related to the indoor lighting will influence the outcome of the tests and assessments performed in this study. With only two test subjects and one reference subject participating, it is not possible to draw unequivocal conclusions regarding possible causal links between the obtained data and the lighting scenarios. Similar complications have been recognized in other studies investigating effects of variable lighting, where some of the results are not all conclusive due to individual differences, time of day, etc. [10]. On the bright side, the compliance with the experiment, wearing the activity bracelet and filling out the questionnaires was excellent and it was clearly beneficial to enhance questionnaires with physical measurements. Other conclusions to be drawn from this study are that it would have been better with daily questionnaires (with fewer questions) to reduce the possible "mood of the day" effect. Nevertheless, as a pilot study it has given valuable knowledge to be used in future studies in this field. The method was successful and provided interesting results on resting pulse and sleep quality and the authors will attempt to follow up these tests with an expanded study incorporating a larger number of test subjects.

ACKNOWLEDGEMENT

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A New Standard for Daylight: Towards a Daylight Revolution?

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***Abstract*— One of the main qualities of daylight is its variability. Good daylight design accounts for changes that happen throughout the day and the seasons, to deliver a consistent and comfortable light level in the space. Natural lighting conditions are never exactly the same and this makes it also difficult to predict. Thanks to a more sustainable approach in every sector of our societies and an increased awareness of its benefits, daylight is back on the agenda in recent years. Contemporary design reintroduces daylight into the mainstream of architecture. In this context a new standard was developed at European level to support and stimulate this evolution.**

***Index Terms*—Daylight, daylight provision, daylight metrics, standard, visual comfort.**

Introduction

Daylight has been recognized for its benefits to the occupants and is considered as an added value for buildings. Local and national regulations (as the 'Right to Light' in UK), have been established to guarantee minimal access to daylight, especially in dwellings but also for any space people tend to occupy for long periods of time, such as work places. Daylight can help reducing energy use, in particular for highly insulated and airtight buildings where the relative share of energy consumption for lighting tends to surge. The path towards very low-energy buildings results in aggressive energy performance requirements which should not be at the expense of a comfortable and healthy indoor environment. It is thus necessary to establish strong comfort criteria to balance the mandatory energy requirements. Nowadays many national building regulations as well as the sustainable building certifications programmes (BREEAM, HQE, LEED…) underestimate the importance of daylight.

To offer an adequate daylighting of a space, multiple factors need to be considered, such as local climatic conditions, site context, building envelope, the furnishing and user activities. Furthermore, the dynamic nature of daylight makes accurate daylight assessments complex, so that simplified approaches had to be developed. But no unique reference method to achieve good daylight practice emerged and targets levels were often diverse throughout Europe.

A new European standard is being developed for daylight in buildings (EN17037) [1]. This new standard proposes minimum recommendations for a set of four daylight indicators, ranging from daylight provision, protection against glare and exposure to direct sunlight to possibilities for viewing out. These indicators are not equally important and sometimes even contradict each other. They have thus to be correctly balanced. For a space, to be considered as daylit, the minimum target values have to be reached for each indicator. The standard also suggests higher performance levels allowing developers to set more ambitious targets for their project. The aim of this new standard is to encourage building designers to ensure comfortable daylit spaces. It will help building designers, operators and owners to better communicate on their expectations for the daylight aspects. This standard is a first step to a possible harmonization of the different approaches in European countries.

Effects of Light on Human Health

Over the ages, humans have evolved under the influence of outdoor daylight conditions and have developed a variety of physiological and psychological responses to its characteristics, more specifically the light–dark cycle is an essential stimulus for our circadian rhythm. In general daylight has the potential to produce positive effects on health and well-being [2] [3] and also on mood and productivity. Based on an extensive literature review, Aries [4] found that many studies omit to detail daylight exposure levels, which makes it hard to find consistent conclusions and recommendations regarding daylight influence, especially knowing the daily and seasonal variability. Various studies on preferred physical and luminous conditions have been conducted in office environments [5] [6] [7]. Galasiu [7] concluded, for example, that in office environments a consistent strong preference for daylight was observed.

Daylighting for health issues (circadian rhythms, etc.) has until now be neglected and will also not be explicitly addresses in this new standard. Further research is needed in order to enable the designers to consider and implement correctly these effects. Most importantly for this, the spectral aspect has to be better understood and characterized: the spectral composition and distribution of daylight [8], the spectral reflectance and transmission properties of different materials and surfaces, the spectral response of circadian system are all important factors.

As people spend more and more time indoors, lighting and shading systems must provide luminous conditions that are suitable to the building's occupants and that are flexible enough to adapt to ever-changing conditions. In absence of scientific evidence, we should strive to offer daylight conditions that are as close to outdoor conditions as possible. Clear (or extra-clear) glazing and movable external shading devices are frequently a prime option to be considered.

Nevertheless, even in the best daylit buildings, lighting levels indoors will not completely meet the human needs. Buildings and cities should also stimulate people to go outdoors in order to be occasionally exposed to high light intensity and the full radiation spectrum (including ultraviolet and infrared radiation).

ASSESSMENT OF DAYLIGHT IN BUILDINGS

A. Historical Basis

In the age before electrical lighting, assuming adequate daylight in a building was as essential for its use, as ensuring its stability. In medieval buildings as i.e. churches, daylight even has a powerful symbolic role and over the centuries the design gradually improved to offer us the spectacular effects we still can experience is some cathedrals. In the late 19^{th} century the poor living conditions in dense cities compelled regulators to provide urban planning rules that could ensure the availability of daylight and sunlight. The advent of air-conditioning and the introduction in the early 20th century of new light source enabled architects to design buildings without the need to exploit daylight. Since then, many buildings have been constructed that rely on artificial light and energy intensive building services to provide habitable conditions. In recent years the qualities of daylight in building is being rediscovered and completely blind or too deep buildings are now discouraged.

A common assessment method, the 'Daylight Factor' (DF), was developed when calculation tools were far more limited than today. Static metrics such as DF are still often used today but they do not account for the temporal variations of daylight and are only a relative illuminance value under one specific sky condition. This approach does not convey any information on how daylight qualities differ over time for the positions in space, neither can it guarantee real occupants comfort. Typically, daylighting recommendations are made in the form of average daylight factor levels between 2% to 6% depending on localisation, building type and activity.

According to weather conditions and time (daily and seasonal variations) at each geographical location, the intensity and distribution of daylight changes. Assessments using DF are only appropriate as an indicator in climates where the diffuse sky contribution is predominant. In order to account for the strongly dynamic nature of daylight illumination other metrics are needed. More than ten years ago dynamic climate based metrics were proposed [9] [10] but they have been slow to penetrate into the designers practice.

Daylight is often evaluated solely on basis on quantitative aspects. The qualitative and more subjective parameters are evenly important. For example, the request for uniform illumination is certainly defendable when focussing on visual tasks but in some spaces, such as assembly rooms in elderly homes, offering a variety of lighting situations could be more stimulating, whereas a perfect uniformity would be less desirable. A daylighting strategy aims to maximize daylight provision and reveal the aesthetic quality while addressing its major concerns such as glare, thermal discomfort (overheating). Architects often consider daylight design as an intuitive skill but the results are not always correlated with the real user's experience. A design approach based on strong field experience of the architects reinforced with robust yet comprehensive design tools should be the most beneficial.

B. General Approach Of The New European Standard

The new European standard on daylight specifies recommendations for achieving a subjective impression of adequate daylight in a space. It applies to all spaces that are regularly occupied by people for extended periods. Four criteria are defined: daylight provision, view out, exposure to sunlight and protection against glare. All indicators are described in the standard in terms of definition, metric, criterion and performance levels (minimum, medium, high). Different calculation methodologies and verification processes are suggested which should facilitate the implementation.

The four criteria given in the standard are interdependent and need to be considered in conjunction and with all other building parameters. The standard gives recommendation for daylight at the level of a space and does not rate entire buildings. A building is a collection of spaces where the daylight requirements can vary and should be weighted appropriately. In a hospital building, for example, the daylight requirements in patient's room are certainly not the same as in treatment rooms or service spaces. It should be noted that it is imperative to consider the surrounding environment. In an urban context specifically, adjacent buildings and structures could result in unexpected reflected light (glare and heat gain) and the appropriate reflectivity of the glazing should be known during design stages and addressed.

As the daylight availability is climate-specific the requirements have to be fitted to local conditions. The basic criteria for each indicator are expressed in absolute values in order to offer the same visual comfort all over Europe. To reach the fixed daylight targets, different building typologies are needed in different climates. The daylight performance of buildings should be analysed based on climate data and predictable sky luminance distributions [11].

C. *Daylight Provision*

The new European standard on daylight specifies recommendations for achieving a subjective impression of adequate daylight in occupied spaces. Daylight openings should be sized and placed carefully as to provide sufficient daylight and the normal light transmittance of the glazing should be as high as possible (frequently at least 70%).

In order to comply with this criterion a space must provide a target illumination (the target level is set to 300 lx for a minimum performance) on at least a consistent area of the space and for at least 50% of the daylight hours. As default the reference plane is taken as a horizontal plane at 0.85 m above the floor. Complementary a minimum value for daylight illuminance (the minimum target level is 100 lx for a minimum performance level) on all points is required to ensure an acceptable uniformity. A 5% tolerance is considered to allow for spaces with singularities (e.g. internal columns, alcoves, ceiling recesses, etc.).

D. *View Out*

Numerous qualitative and quantitative studies have identified and reported the importance of establishing a visual connection with the natural world outside the building. Demonstrable benefits have been found associated with faster post-operative recovery and improved treatment. In relation to eyestrain, people should have the possibility to focus on distant objects, for example, by means of a view outside.

The new standard gives criteria and recommendations for view out in a space. The assessment of view out in a space is based on the view width, characterized by the horizontal view angle at windows, a minimal outside distance and the content of the view. A good view out should comprise layers of sky, city or landscape, and ground.

E. *Exposure To Sunlight*

We know that we all derive certain benefits from the sun. The benefits of exposure to solar radiation such as vitamin D synthesis, blood pressure reduction, suppression of autoimmune disease and a feeling of wellbeing. For many years maximal sun protection and sun avoidance have been the strategies promoted by dermatologists, governments and industry. The benefits have been considered as secondary to protection but are important in the promotion of good health.

Exposure to sunlight is especially important in habitable room in dwellings, patient rooms in hospitals, play rooms in nurseries and all places where people tend to remain for long periods. In the new standard the assessment of direct sunlight is done at one specific point of each window and the minimum target level to be reached is 1.5 hours. The calculation of the direct sunlight exposure duration has to consider all external permanent obstructions, such as adjacent buildings, overhangs, balconies or even the façade thickness, for example when deeply recessed windows are provided.

But direct sunlight can also be the cause of thermal discomfort and glare. So that, this requirement should therefore be carefully balanced the other comfort parameters.

F. *Protection Against Glare*

Managing glare presents one of the most important challenge of daylight design [12]. The perception of glare is dependent on the luminance distribution in the field of view and is therefore strongly dependent on the position and the line of sight of the occupant. Glare sensations is also found to be more tolerated under daylight conditions than in situation with artificial lighting exclusively. Discomfort glare metrics such as Unified Glare Rating (UGR) cannot be used for daylight glare as the glare source is usually much larger. In real conditions, daylight and artificial light often coexist and further research is being carried out to address these knowledge gaps.

In the new standard the Daylight, Glare Probability (DGP) metric is used [13]. The minimum recommendation for glare protection is that the DGP for the occupied space does not exceed a value of 0.45 in more than 5% of the occupation time of the relevant space. Glare is to be assessed in all spaces where activities are similar to reading and working on computer screen and the user is not able to choose freely its position. In practice not all positions can be assessed and only the most critical situations should be evaluated.

To assess glare from daylight, the luminance distribution within the field of view and the size, intensity and location of the glare source have to be determined [14]. Software that can calculate accurately illuminance distributions are not necessarily adequate to produce correct luminance distributions, as this requires more advanced algorithms. This criterion implies that the designer can either predetermine correctly the luminance distribution in the space, either he has to rely on a simplified assessment. A simple evaluation method for most typical solar shading devices and different viewing and climate conditions is also provided in the standard.

CONCLUSIONS

This new standard on daylight can support and force a renewed interest in daylighting from designers, authorities and clients. It will certainly also help to harmonise the daylight practice in Europe, raise the interest of regulators to set ambitious but realistic targets and contribute to ensure healthy and comfortable conditions for the people. Sustainable buildings must not only reduce environmental impact, they must also be fit for people. This daylight revolution will be achieved if people recognise and apply this new standard. So in the future a good daylight design will no longer be a vague recommendation, but a strong reality.

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New Daylight Solutions for Energy and Health

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***Abstract*—Providing proper daylighting in buildings is a complex task. It's not sufficient to open the façade by increasing the glazed part, it is much more important to care about an intelligent usage of the right amount and distribution of daylight. Standard façade systems usually cover only one aspect, e.g. sun shading or glare protection. The aim of a complex daylighting system is to integrally fulfill all (sometimes contradictionary) requirements as far as possible. Bartenbach and research partners are developing new daylight solutions, including new optics, new integrated day- and artificial lighting controls, and a novel dosimetric model for achieving non-visual light effects during the day. The latest research results of these studies and the conclusions for daylighting and façade techniques will be presented.**

***Keywords*— daylight, energy, health, complex fenestration system, façade.**

INTRODUCTION

Utilizing daylight in buildings is a complex task: providing sufficient and properly distributed daylight within the room, allow solar gains for heating in winter and provide sun shading to protect from overheating in summer, and finally allow a view to the outside. At the same time, the technology has to care for visual and thermal comfort, and as far as possible for exploiting the health potential of daylight: daylight should serve people not only for good vision but also for non-visual (biological) light effects on mood, cognitive performance, sleep and in the long-run for health.

On May 19, 2010, the European Parliament adopted a directive on the energy performance of buildings [1]. In Article 9 they state that "Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". To reach this ambitious goal, a major task is to reduce the energy demands for cooling, heating and for artificial lighting.

Figure 1. Example of a unique daylight solution: ZVK Wiesbaden (Arch. Herzog & Partner) © Bartenbach.

To allow the designers to calculate all these effects of different daylight solutions, climate-based daylight modeling methods together with integrated heating, cooling and lighting energy calculations meanwhile has found its way from academics into the practice over the past few years [2] - [6].

Summarizing, the challenge is to increase the daylight utilization and the positive health impacts while at the same time controlling the visual and thermal comfort and solar energy inputs.

General requirements to Daylight Solutions

A. General Lighting Requirements

To provide a lighting environment optimally adopted to visual perception it is essential to meet several preconditions:

- Adequate amount of daylight: Only if enough daylight is available for productive work it is not necessary to switch on artificial lighting systems. Especially room areas far from the façade tend to be exposed to low daylight levels
- Suitable daylight distribution: Concepts to guide daylight into the depth of the building as well as properly distributing daylight throughout the adjacent rooms.
- Glare protection: Not only the sun itself but also opposite façades or clouds illuminated by the sun yield problems concerning visual comfort particularly for computer workplaces. The luminance distribution in the field of view must be free of bright spots to allow for a stable visual perception facilitating high work performance.
- View to the outside: A decisive factor for human well-being is a good contact to the outside. The view of the surroundings opens the architectural space and the natural variation in light stabilizes the circadian rhythm.

B. Energetic Requirements

The façades and particularly the fenestration systems are a decisive factor for the thermal management of a building. Heating and cooling nowadays consume vast amounts of natural resources (electricity, oil, …).

In the design of an intelligent daylight system it is thus inevitable to take into account these aspects of building physics. To reduce cooling loads, the solar heat in summer must be shaded efficiently. On the other hand, solar gains help to reduce the heating costs in winter.

C. Comfort Requirements

Humans, staying indoors, want and need daylight for their well-being. Research over the past 60 years, primarily focusing on daylight effects through windows, clearly confirm this statement. Essential components of this effect are a view to the outdoor environment, which in the best case allows watching a countryside, and the excellent spectral quality of daylight. However, beneficial effects of daylight on human comfort and wellbeing vanishes in cases of discomfort and disability glare and high thermal loads.

Within the standards DIN EN 14501 ‘Blinds and shutters – thermal and visual comfort – Performance characteristics and classification’ (2006) [7] and DIN prEN 17037 ‘Daylight of buildings’ (currently available in a preliminary version [8]) valuable specifications are given to fulfil comfort requirements in daylit indoor environments.

D. Non-Visual Requirements

Currently, there exists strong scientific evidences that either exposure to bright light or light with enhanced portions of short wavelengths cause non-visual light effects (alterations in circadian rhythms, sleep parameters, cognitive parameters, mood) if applicated at specific times of the day. Sensitive times are in the evening (up to 2 hours before sleep onset), at night (during typical sleep periods) and in the early morning (up to 2 hours after awakening).

The following non-visual light effects are commonly known: modification of circadian physiological parameters (e.g. phase delay, phase advance, decrease or increase of the amplitude), increase of alertness and decrease of subjective state of sleepiness, increase of cognitive parameters associated with attention and working memory and improvements of mood e.g. in seasonal affective disorders.

To generate non-visual light effects in humans five parameters are crucial:

- irradiance reaching the eyes: higher levels generate stronger effects during the day and night
- spectral power distribution reaching the eyes: shorter wavelengths of the visible light spectrum have stronger alerting and melatonin suppression effects than longer wavelengths
- light history: low levels of light exposure in the past over several hours increase the current non-visual light effects, high levels of light decrease these effects
- exposure duration: several hours of light exposure are necessary to trigger beneficial light effects on mood and circadian rhythms
- timing of exposure: high light levels during the morning lead to circadian entrainment, whereas light exposure in the evening hours or at night-time provoke alerting effects and disruption of circadian rhythms.

Today, mainly three models, which give recommendations for the generation of daytime non-visual light effects, exist:

The term "circadian stimulus (CS)" is a metric reflecting non-visual light effects in terms of irradiance and spectral power distribution of light reaching the eyes. The model predicts acute night-time melatonin suppression and calculates values between 0 % to 70 %. To induce a beneficial light effect on sleep and circadian rhythms. Figueiro et al. (2016) recommended a light exposure of CS ≥ 0.3 for at least one hour in the morning [9]. This threshold corresponds to 180 lx for a daylight light source (D65; overcast sky). In a recently published study [8] it was shown for the first time, that office workers who received CS ≥ 0.3 during the morning hours (8 a.m. – 12 p.m.) had significantly better circadian entrainment, higher sleep quality, shorter sleep latency onset and lower depression scores compared to office workers who received CS ≤ 0.15.

Another method to measure non-visual light effects determines the melanopic illuminance, expressed in "equivalent melanopic lux (EML)". The calculation is based on the melanopic spectral efficiency function by Enezi et al. (2011) [11] and Lucas et al. (2014) [12]. The WELL - Building Standard [13], within which requirements for a circadian lighting design are described, defines a minimum threshold for circadian lighting effects at 250 EML for at least 4 hours at any time of the day. 250 EML corresponds to 226 lx for a daylight light source (D65; overcast sky).

Based on findings from Cajochen et al. (2000), who described night-time alerting effects during neutral-white light exposure over 6.5 hours [14], and Phipps-Nelson et al. (2003), who found alerting effects of bright light exposure (1000 lx at eye level) during the day after 5 hours of exposure [15], Andersen et al. (2012) built up a model which measures the effectiveness of vertical illuminances to cause alertness in humans [16]. The authors proposed a ramp-function (Fig.2) to generate daytime alerting effects of light, suggesting 0 % efficacy at 210 lx vertical illuminance and 100 % efficacy at 960 lx when being exposed to a light source similarly to the visible spectrum of sunlight (D55).

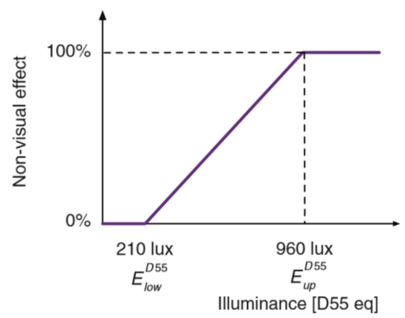

Figure 2. daytime a from Andersen et al., 2012]

Currently, models to quantify non-visual daytime light effects refer to studies which measured acute effects of light on alertness and night-time melatonin suppression. In contrast, it is well known that health-related effects of light are linked to circadian entrainment and chrono-disruption. Light at night and low levels of light exposure during the day contribute significantly to these factors, leading to negative impacts on human health.

In the project 'VisErgyControl', Bartenbach consequently developed a model which quantifies circadian entrainment effects of bright light during the day. The model is based on a daily light-dose paradigm and additionally suggests exposure to light with reduced intensities and short wavelengths during the evening, night and seasonal periods with reduced daylength.

SYSTEM DESIGN APPROACHES

A. Optical Designs

Complex Surfaces are reflectors or lenses where the points on the surfaces are calculated point by point using numerical methods. Mathematical algorithms allow determining the geometry of such systems for daylight sources like the sun (very small sold angle) or the sky (up to hemisphere, i.e. a solid angle of 2π). This computationally demanding task can be mastered utilizing high-performance computing as well as especially adapted numerical techniques. Such Freeform Surfaces must guide artificial light or daylight according to specified requirements to guarantee technical functionality as well as to provide optimal conditions for visual perception. Principles of daylight guiding design are presented in **Napaka! Vira sklicevanja ni bilo mogoče najti.**.

In general daylight is not a static light source comparable to electrical lamps used in luminaires. Thus, the design of adequate target functions is complex. A daylight system cannot be calculated for a single input distribution, but needs to be optimised for typical lighting conditions over a full year derived e.g. from climate data files.

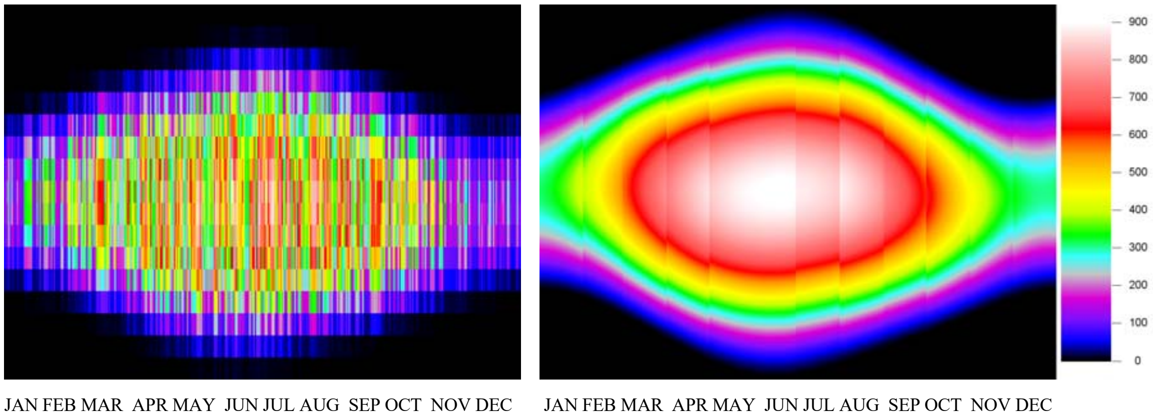

Figure 3. Climate Data for Graz / Austria. Global horizontal irradiance [W/m^2]. EnergyPlus Weather Data (EPW) compared to theoretical values according to DIN 5034/2.

During the last years, intensive research on the calculation and application of freeform surfaces for artificial lighting and daylighting has been performed within projects funded by the Austrian Research Promotion Agency (FFG). The project FFF-TaliSys dealing with freeform daylight systems for façades and skylights in cooperation with industrial and academic partners will be finished 2018. Promising but currently confidential results are on the horizon and will be reported later on.

The basic idea is to use novel methods and algorithms successfully applied to design e.g. luminaires consisting of freeform surfaces also for the development of daylight systems.

To evaluate such systems taking into account climate data in-house tools have been developed that use the direct-diffuse transmission as well as the angular dependent Solar Heat Gain Coefficient (SHGC) that can be measured in our climate chamber.

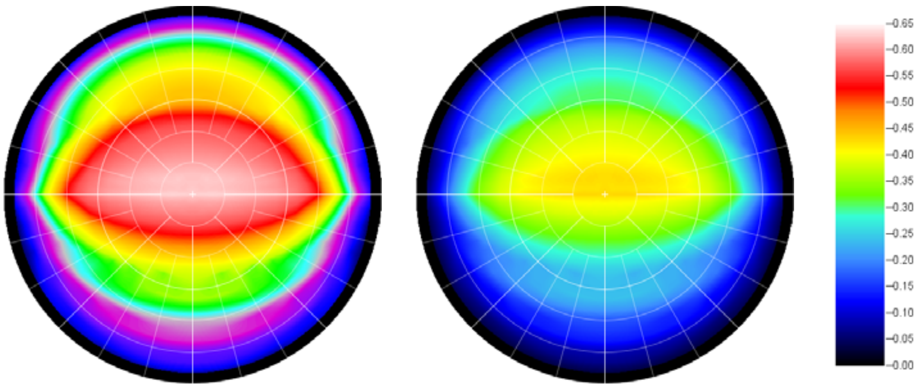

Fig 4. Wing-Lamella, 0° perforated: Direct-diffuse transmission $\tau_{g\,g}$ and angular dependent Solar Heat Gain Coefficient.

Even more interesting to engineers, characterizations based on the bidirectional scattering distribution function (BSDF) can be used in publicly available software (e.g. RADIANCE, DIALux evo and ReluxDesktop) to be able to take into account the impact of daylight systems in lighting calculations. This innovation will in the future dramatically ease the competent utilization of daylight in the planning process. User-friendly tools as DALEC incorporating also the energetic aspects are a further step to the implementation of this technology in practice.

B. Integrated Control Design

To reach the goal to generate daytime non-visual light effects in indoor environments, the implementation of an integrative daylight- and artificial lighting design is a necessity. Control systems and their control strategies are the backbone of these lighting designs which aim to maximize the usage of available daylight, to minimize the usage of artificial light and to fulfil non-visual human needs.

Core components of this integrative lighting design approach are a location-, time- and building-oriented daylight design. Additionally, an artificial lighting design, which comprises sensor technology, a control system which is embedded in the building automation and intuitive user-interfaces, complement the daylight design. The usage of sensors, measuring the presence of humans and the levels of daylight, enables an energy-efficient switching and dimming of artificial lights. To increase user satisfaction, users are, to a certain extent, free to manipulate the lighting control strategy (e.g. switch off and dimming lights without changing the daytime-specific colour temperature).
If permitted, an additional feature of this integrative day- and artificial lighting design is the storage of time-stamped data recording user interactions, sensor values and status of luminaires. These data enable an analysis of the daily usage

of the lighting system and, if necessary, an adaption of the lighting control strategy (e.g. in times, where user frequently change the pre-defined light control strategy). Finally, data can be utilized to offer additional services (e.g. room/space occupancy, maintenance of the lighting system).

CONCLUSION

Increasing comfort and energy requirements will stimulate the application of new daylight systems. New findings in light impact research additionally will strengthen the role of daylighting in buildings, thus create new architectural and daylighting solutions. New optical development methods with complex surface designs as well as sophisticated manufacturing possibilities enable solutions which are able to exploit direct sunlight without causing discomfort and overheating. The integration of daylight design with artificial lighting design and building controls by modern building simulation tools will allow architects, building designers and technicians to realize such solutions in future buildings.

ACKNOWLEDGEMENT

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RESEARCH PROJECTS

Research projects concerning freeform surfaces for artificial lighting and daylighting:
Berechnung von Freiformflächen für die Lichttechnik (Austrian Research Promotion Agency FFG 1998/99)
Freiformflächen - Berechnungsverfahren (Kompetenzzentrum K-Licht, KPZ I 2002 – 2005)
Freiformflächen für ausgedehnte Lichtquellen (Kompetenzzentrum K-Licht, KPZ II 2006 – 2009)
High performance calculation and tolerancing for Complex Surfaces, CSHP (Kompetenzzentrum K-Licht, COMET Application Intermediate Funding, 2009/10)
Berechnung und Planung von Tageslichtsystemen mit Freiformflächen, TL+FFF (Austrian Research Promotion Agency FFG 2010 – 2014)
Freiformflächen-Tageslichtsysteme für Fassaden und Oberlichter, FFF-TaliSys (Austrian Research Promotion Agency FFG 2015 – 2018)
Research projects concerning integrated control designs and simulation tools for artificial and daylighting:
VisErgyControl – Visual Energy Control: Integrale Tages- und Kunstlichtsteuerung für hohen visuellen und melanopischen Komfort bei hoher Primärenergieeffizienz (Austrian Research Promotion Agency FFG 2014 - 2017)
DALEC – Day- and Artificial Light with Energy Calculation (Austrian Research Promotion Agency FFG, 2015 – 2017)
LightSIMheat – Gekoppelte Gebäude- und Lichtsimulation für komplexe Fassaden (Energy Mission Austria 2013 – 2016)
Integrated Day- and Artificial Light (COMET K-Project K-Licht, project P01, 2010-2015)

Key Learnings about Daylight Performance in a Demonstration Building and Potential Outcomes

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***Abstract*— Daylight is vital for our health. But do Europeans think of their homes as a key to being healthy? Do they know what to expect from a healthy home and daylight provision? And, what have we learned from demonstration buildings? This paper present the results from the daylight analysis of a demonstration building against Active House specifications and the proposed European Daylight Standard, as well as key findings from a one year post-occupancy period, with a family of four persons, during which we monitored the energy consumption and indoor climate of the house.**

***Index Terms*-- Daylight, Residential Buildings, Health and Well-Being, prEN 17037, User Experience**

INTRODUCTION

Today, we know that our homes have a huge impact on our health and wellbeing. We live 90 % of our lives inside buildings; in our homes 2/3 of this time, with the remaining third spent in workplaces, schools, and other public spaces [1]. We can also see a rising interest among building designers about the importance of 'good' daylighting design for buildings. Moreover, an increasing number of studies have proven that daylight provides an array of health and comfort benefits that make it essential for buildings' residents. As an example, the study by RIBA and Ipsos MORI [2] showed daylight is the single most important attribute in a home, with over 60% of respondents ranking it as important. Within Europe, residential buildings cover about 75% of the building stock, with 60% of European households living in single-family homes and 40% in multi-family homes [3]. However, many European guidelines and standards for daylighting have hardly changed over the last decades, especially for residential buildings, and the downgrading of daylighting in the overall consideration of building design is apparent in today's building stock [4].

BACKGROUND

During 2009-2011, VELUX built six demonstration buildings - Model Home 2020 - and the houses are designed following the Active House principles [5] with the three main elements: Comfort, Energy and Environment. The houses have been occupied by test families in periods of one year or longer and have been tested and monitored in use. The intent of the demonstration buildings is to get insights in how we can create a healthy and pleasant home environment with our current knowledge and technology. Along this line, the Active House Vision as formulated by the Active House Alliance [6], the VELUX Group initiated the Healthy Homes Barometer to investigate European citizens' attitudes and behaviour regarding home comfort, energy consumption and environmental impact.

A. Healthy Homes Barometer

The Healthy Homes Barometer (HHB) is an analysis presenting key findings from a pan-European study investigating European citizens' attitudes and behaviour regarding home comfort, energy consumption and environmental impact. The first two Healthy Homes Barometers were published in 2015 and 2016 with 12 respective 14 European countries, giving a total of 12-14,000 answers from European respondents [7,8]. The number of respondents from each country was set to ensure statistical representation, and the surveys represent more than 430 million Europeans. In the 2015 and 2016 editions, the barometer considered how Europeans experience the difference a healthy home makes. The objective of the Healthy Homes Barometer is to measure scores for different indicators, each addressing a key aspect of European citizens' attitudes and behaviour related to their life at home in terms of comfort, energy consumption and environmental impact. The 2017 barometer takes the 2016 findings one step further by analysing the impact buildings have on Europeans' health [9].

The Healthy Homes Barometers clearly show that improving home comfort and well-being or reducing energy costs by energy efficient solutions, are both a positive motivation factor and equally important for Europeans in their decision to improve their homes. The 2015 and 2016 barometers give key directions of what actually matters most for Europeans to improve their health, comfort and the indoor home environment, as well as key drivers for improving home satisfaction ([7,8]). The barometers showed that 37% lack daylight in their living room, and a total of 20% of Europeans say that they are too dependent on artificial light during the day. This is an energy consumption challenge, but even more challenging is that 76% of Europeans report that they need to turn on the light during the day when there is daylight outside. This means that a large number of Europeans are too dependent on artificial light. Additionally, the barometer from 2017 using the Eurostat database EU-SILC 2012 (Survey on Income and Living Conditions) show that approximately 6% of all EU households state that their home is *too dark* or *do not have enough daylight*, and if they perceive their home is too dark, they are more likely to report poor health (15%) [9].

B. European Daylight Standard And Activehouse Specifications

Aside from the building design itself, daylight performance in an interior space depends largely on the availability and properties of natural light at the building's location (i.e. the prevailing climatic conditions). The proposed European Daylight Standard (prEN 17037 Daylight of Buildings, [10]) suggest to change the basis of daylight evaluations to include `daylight factor targets' based on the occurrence of outdoor illuminance levels. The `climate connectivity' of the proposal states that a space should achieve a target daylight factor at work plane height across a specified percentage of the relevant floor area for half of the daylight hours in the year, where the target daylight factor is based on the provision of an interior illuminance higher or equal to 300 lux. In addition, a minimum target daylight factor based on the provision of an interior illuminance higher or equal to 100 lux is required over the entire work plane. The method can easily be introduced since it requires only modest enhancements of existing daylight prediction tools. In addition, the proposal will provide a sound `footing' for the eventual progress to evaluations founded on full-blown climate-based daylight modelling. The table below presents an example of target daylight factors for different location in Europe.

TABLE I. MINIMUM VALUES OF D FOR DAYLIGHT OPENINGS TO EXCEED AN ILLUMINANCE LEVEL OF 100 OR 300 LX FOR A FRACTION OF DAYLIGHT HOURS $F_{TIME,\%}$ = 50% FOR SELECTED 3 CAPITAL CITIES OF CEN NATIONAL MEMBERS [10].

prEN 17037	**Climatic properties and daylight requirements**			
	Geographical latitude φ [°]	***Median External Diffuse Illuminance $E_{v,d,med}$***	***Minimum value of D to exceed 300 lx during 50% of daylight hours***	***Minimum value of D to exceed 100 lx during 50% of daylight hours***
Copenhagen	55.63	14200	2.1%	0.7%
Paris	48.73	15900	1.9%	0.6%
Rome	41.8	19200	1.6%	0.5%

The Active House Specifications [5] focus on three main challenges faced by residential buildings in today's societies: comfort, energy and environment. The comfort related aspects put a strong focus on good daylight conditions, thermal comfort and fresh air from natural ventilation. The specification for daylight conditions, based on BS8206-2 [11], use the average daylight factor method measured at work plane height, where different performance class can be achieved, with 5% D_{avg} or more being the highest level of performance. Rooms with an average DF of 2% or more can be considered daylit, but electric lighting may still be needed to perform visual tasks. A room will appear strongly daylit when the average DF is 5% or more, in which case electric lighting will most likely not be used during daytime [12]. The table below presents the 4 performance classes and corresponding daylight factor levels.

TABLE II. THE ACTIVE HOUSE SPECIFICATIONS FOR DAYLIGHT CONDITIONS MEASURED AT WORK PLANE HEIGHT [5].

Active House	**Daylight factor requirements**
Class 1	D_{avg} > 5%
Class 2	D_{avg} > 3%
Class 3	D_{avg} > 2%
Class 4	D_{avg} > 1%

C. Demonstration Building

The demonstration building included in this paper, Maison Air et Lumière (France), was built in 2011 (see figure 1) [13]-[14]. The architectural concept is based on different roof pitches, and carefully positioned façade and roof windows to bring in sunlight from all directions. The 130 m² floor area extends over one and a half storeys and a window-floor ratio about 1:3. The house has an automatic system installed to optimize indoor environmental conditions, for instance opening and closing windows and solar shading. Sensors are installed in each of the main rooms to register indoor environment conditions (temperature, CO2 levels, relative humidity, lux). A weather station on the rooftop register outdoor weather conditions (temperature, rain, global illuminance, hours of sunshine and wind direction). These data are used to adjust the indoor environmental conditions to ensure high comfort of the residents. In all Model Homes 2020 demonstration buildings, a family lives in the house for a full year to help measure, monitor and assess what they think about the house [15]. The family of Maison Air et Lumière moved in September 2012 and lived in the house for a complete year.

Figure 1. Photo of the Maison Air et Lumiére (France) to the left and the Carbon Lighthouse (UK) to the right (Photo by Adam Mørk).

RESULTS

In this section, we present results from the daylight analysis of Maison Air et Lumière against Active House specifications and prEN 17037, as well as key findings from a one year post-occupancy period, with a family of four persons, during which we monitored the energy consumption and indoor climate of the house.

A. Simulation

Table III and figure 2 below present the daylight analysis' results for all main living spaces in Maison Air et Lumière. It's possible to observe that all rooms achieve good daylight conditions, whether located on the ground or first floor. Both the D_{300} (i.e. 1.9%) and D_{100} (i.e. 0.6%) targets for prEN 17037 are met in all rooms of the house with levels far exceeding the base requirements. The house also performs well with regards to the Active House Specifications for daylight with most room achieving the highest class for daylight performance (i.e. higher or equal to 5% D_{avg}), and two rooms meeting the second class (i.e. higher or equal to 3% D_{avg}). The daylight analysis uses the VELUX Daylight Visualizer, which is a professional and validated simulation tool for the analysis of daylight conditions in buildings [16].

TABLE III. DAYLIGHT ANALYSIS FOR ALL MAIN LIVING SPACES IN MAISON AIR ET LUMIÈRE

Maison Air et Lumière Daylight Analysis	**Daylight factor results**		
	prEN 17037 D_{300}	***prEN 17037 D_{100}***	***Active House (average)***
Kitchen	5.2% D_{300} (pass)	2.9% D_{100} (pass)	5.8% D_{avg} (class 1)
Dining/living room	6.3% D_{300} (pass)	1.7% D_{100} (pass)	6.3% D_{avg} (class 1)
Study room	3.4% D_{300} (pass)	0.9% D_{100} (pass)	4.8% D_{avg} (class 2)
Bedroom 1	2.5% D_{300} (pass)	1.2% D_{100} (pass)	3.8% D_{avg} (class 2)
Bedroom 2	4.5% D_{300} (pass)	1.8% D_{100} (pass)	6.4% D_{avg} (class 1)
Bedroom 3	6.7% D_{300} (pass)	1.5% D_{100} (pass)	8.0% D_{avg} (class 1)

Figure 2. Daylight factor simulation with the VELUX Daylight Visualizer of the Maison Air et Lumière ground floor (left) and first floor (right).

B. *Interior Measurements And Post-Occupancy Evaluation*

Measurements of indoor environment included light, thermal conditions, indoor air quality, occupant presence and all occupant interactions with the building installations, including all operations of windows and solar shading. Each room is an individual zone in the control system, and each room is controlled individually. There are sensors for humidity, temperature, CO2, presence and lux in all main rooms, used for both control and data recording. The results show that good daylight conditions and high daylight levels can be achieved without overheating [14].

High window-floor ratio and carefully positioned façade and roof windows show good daylight distribution within the main rooms (see section III.A Simulation and Table III). One of the hypothesis was that if room has an average DF of 5% or more, then the electric lighting will most likely not be used during daytime [12]. Figure 3 is a temporal map to show the monitoring data from all the electrical sockets within the living room. It is a complete year of measurements (September 2012-13) and equivalent to the time the family lived in the house. The electric lighting measurements mainly focused on lighting use in the kitchen and in the living room, and the switching probability is evaluated according to the time of day and year, the outside weather, week-days and week-ends etc.

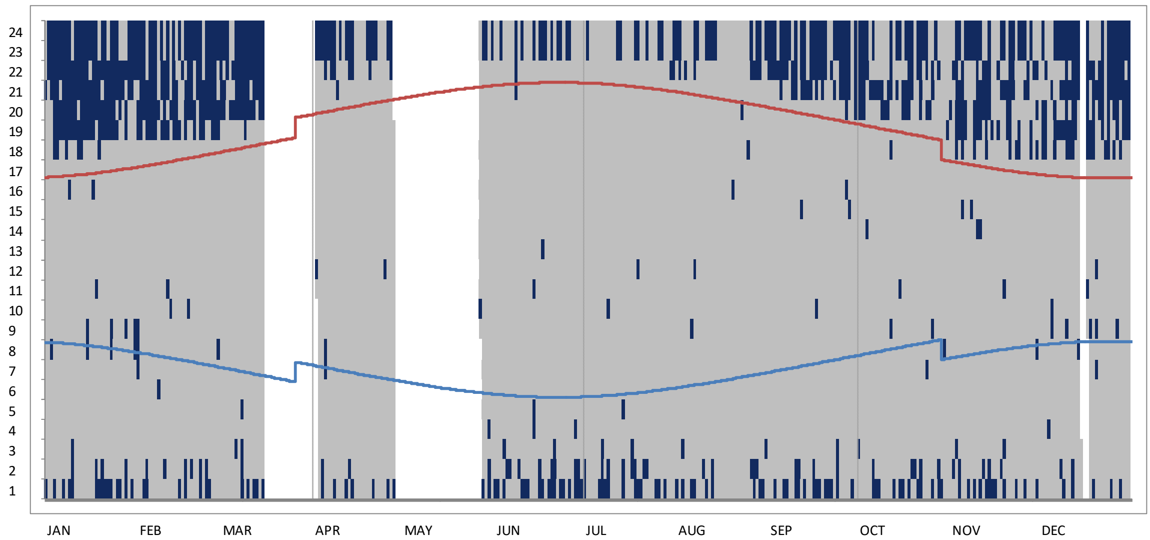

Figure 3. Temporal map of electric lighting use in the living room September 2012 – 13. The x-axis show the months of the year and the y-axis show the time of day. A dark blue colour indicate that electric lighting is switched on and a grey colour is the time when the light is switch off. The lower (light blue) and upper line (red) mark the sunrise and sunset, respectively, according to local time (Paris, France), including Daylight Saving Time (DST). The white area is missing data.

Figure 3 shows the electric lighting use in the living room and that good daylight provision can affect the way the residents switch on/off the electric lighting. The morning lights are rarely switched on, while the evening lighting use show a clear tendency of being switched on after sunset, which suggests that the daylight level affect the switching probability, while detailed data analysis shows outside weather, day of the week has less impact (e.g. family with small children). Interior daylight levels measured in the room, at the ceiling, show the light level is below 50 lux before the lights are turned on. Further analysis of lighting use indicate no distinct difference between summer and winter, general switching time is between 1 hour and 45 minutes to 3 hours after sunset, and when the residents need electric lights, they usually switch 'all' light on.

The outcome of the post occupancy evaluation (POE) shows that the residents rated the daylight levels in the demonstration house as "much higher" and state that they turn the electric lights on "less often" than in their former home. The family report high satisfaction with the daylight level and find it "appropriate" in the kitchen, the living room, and the bedrooms. Sunlight penetration is preferred all day in the kitchen and living room, while higher preference for morning sunlight in the bedrooms.

CONCLUSION

Daylight is vital to our health and wellbeing. Yet, our modern way of living challenges our daily access to daylight and connection to nature. What role is left for architects and planners when we are falling out of sync with the natural light cycles we evolved under? Throughout Europe, there are 110 million detached and semi-detached single-family homes and a great deal of them need renovation. Currently, about 35% of the EU's buildings are over 50 years old, and up to three out of four of these homes are not energy efficient [17]-[18]. With 40% of Europe's energy being consumed by buildings, and 36% of CO2 emissions being emitted by them, there is a clear need for more climate-friendly homes throughout Europe [18]. Increasing the renovation rate will also bring other benefits, such as having residential buildings with a good indoor environment that eventually can reduce healthcare costs and tackle the challenge of energy poverty.

The Healthy Homes Barometers show that improving home comfort and well-being, and reducing energy costs by energy efficient solutions, are both positive motivation factors and equally important for Europeans in their decision to improve their homes. It also shows that renovation solutions and mechanisms to increase public awareness need to underline the importance of energy efficient homes in the view of Europeans' daily lives, and more importantly the added value of improved indoor comfort parameters such as daylight.

It is evident that today's standards/guidelines for daylight in buildings need upgrading, as well as accepted and implemented amongst practitioners in their building design. The Model Home 2020 vision for climate neutral buildings with a high degree of liveability have proven that emphasis on indoor comfort and energy efficiency go well together.

ACKNOWLEDGEMENT

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Daylight Transmission Via Hollow Light Pipes With Fresnel (Directional) Reflection

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Abstract— **The light guide system is one of most attractive techniques for delivery the natural light into deep interior spaces. Such systems can help to save the energy otherwise expended for artificial illumination during daytime. Unlike other alternative light sources, the illumination below a hollow light pipe reflects the momentary exterior lighting conditions. The light pipe can be interpreted as an optical device that transform luminous energy entering the light pipe at its upper interface into an illumination at the workplane. The total length of a light pipe is typically large compared to the diameter of its circular interface. This is why the light beams undergo many reflections before they are detected at workplane. Reflection events may result in substantial intensity decay. We know from electromagnetic theories that reflection coefficient can change with angle of beam incidence, however, this effect still remains poorly quantified and thus deserves more attention. Among other methods, the Hollow Guide Interior Illumination Method (HOLIGILM) is a theoretically founded solution concept that can provide very accurate results in a reasonable time. We have incorporated Fresnel equations into HOLIGILM method and computed efficiency of light transmission for straight pipes under various conditions. The results are interpreted in terms light guide efficiency under different sky conditions and Sun's positions.**

Index Terms—**Hollow light guide, HOLIGILM, efficiency, Fresnel reflection.**

INTRODUCTION

Hollow light pipes are an inexpensive solution for guiding the light from the top of building to the deep and/or windowless interiors. The natural light enters the pipe at its upper interface and undergoes multiple reflections from the curved surface of a circular pipe before it is distributed in the interior space. The interior illuminance level depends on the illuminance outdoors that in turn alters with cloud coverage, daytime and season. Generally, it is difficult to predict interior illuminance levels under arbitrary conditions. Conventional flux-based methods such as e.g. [1]-[2] are to simplify the problem by e.g. introducing a mean number of reflections rather than computing the trajectory of every beam. We have developed a more accurate solution a few years ago that is based on ray-tracing approach. The method is known under acronym "HOLIGILM" (Hollow Guide Interior Illumination Method, [3]) and is to trace the original beams backwards from the point of interest in the interior to the sky element. Although the original HOLIGILM method uses mean reflection coefficient for the tube walls, the angle of incidence is exactly known for each reflection event. Here we extended the original method by implementing the Fresnel theory of the reflection with aim to see if the optical properties of a tube differ from those predicted by original HOLIGILM method.

REFLECTION MODEL

The typical light guide is made from high reflection foil with plastic and metallic layer. To simplify the interpretations we considered an ideally glassy metallic surface made from aluminium. The index of refraction of aluminium is a complex valued number $\widetilde{n} = n + ik$, where n and k are the real and imaginary parts of the refractive index. Generally, $\widetilde{n}$ is a function of wavelength, so we took the value of 0.965 + 6.4i at 550 nm [4] that is well representative for human vision during daytime.

The reflection coefficient R of a metallic surface for unpolarised light is given by the formulae [5]:

$$R = \frac{1}{2}\left(R_p + R_s\right),\ R_p = \left|-\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}\right|^2,\ R_S = \left|\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}\right|^2,\ \widetilde{n} = \frac{\sin\theta_i}{\sin\theta_t} \qquad (1)$$

where θ_i is the angle of incidence. Remember that for a metallic medium the index of refraction is complex valued function, meaning that the angle θ_t has no longer the obvious geometrical interpretation. Instead it is now a complex value.

For the angle of incidence of 90 degrees, Eq. (1) can be simplified as follows

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \tag{2}$$

For example, for aluminium and 550 nm wavelength (2) gives the reflectivity coefficient of 0.914.

Figure 1 shows the reflectivity coefficient of the unpolarised light at the interface of vacuum and aluminium as a function of the angle of incidence. It can be seen that the reflectivity is nearly constant for angles below 60° and it drops shortly before reaching 85°. The reflectivity approaches unity at 90°. Replacing Eq. (1) by a simplified model of Eq. (2) one can expect significant differences in optical effects at higher angles of incidence.

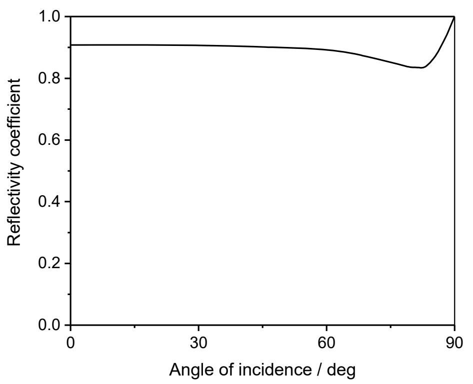

Figure 1. Reflectivity of the unpolarised light at the interface of vacuum and aluminium as a function of the angle of incidence.

RESULTS AND DISCUSSION

The trial tests have been made for a typical straight vertically oriented light tube with diameter of 0.56 m. The sky-conditions used were: CIE overcast, 1:3 (I.1. ISO 15469:2004) and CIE clear, country side (V.4. ISO 15469:2004). We varied the solar zenith angle and the vertical dimension of the tube. The light-guide efficiency was calculated for both full Fresnel model (1) and simplified model (2). In fact, the luminous flux at the bottom interface of the light pipe has been computed relative to that at the upper interface.

A. Overcast Sky Condition

The direct sunbeams are absent under overcast sky conditions, but exterior illuminance level still depends on solar altitude. We have made test computations for solar altitude of 70 degrees, which is a mean value in Mid-Europe region in summer time. The length of the tube was varied from 1 to 8 m.

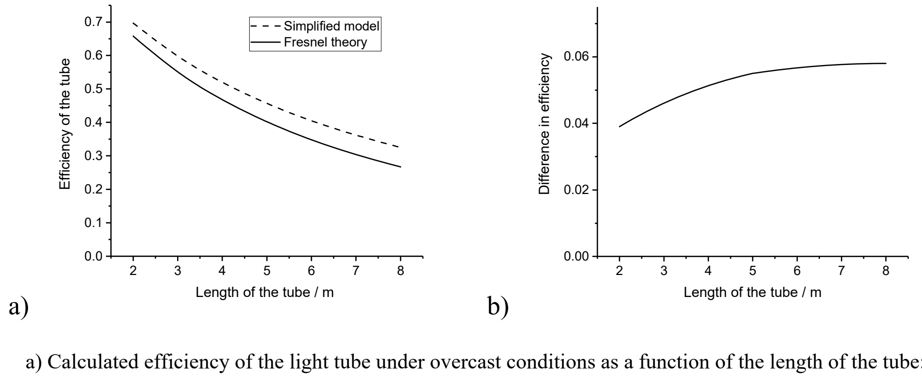

Figure 2. a) Calculated efficiency of the light tube under overcast conditions as a function of the length of the tube: simplified model (dashed-line) and Fresnel theory (full-line). b) Difference in the calculated effectivity between simplified and Fresnel model for the reflectivity coefficient.

Figure 2 is to show the calculated efficiency as a function of the light-pipe length. One of key findings is that the simplified model systematically overestimates the light-guide efficiency compared to what we obtained from accurate Fresnel computations. Nevertheless, the difference is as small as 6% for all tubes under evaluation. Taking into account multi-reflection model we conclude, that 6% difference in the tube efficiency requires the mean reflectivity coefficient in Eq. (2) to be 0.894 instead of 0.914.

B. Clear Sky Condition

The optical signatures of a straight pipe under clear sky conditions are largely determined by position of a sundisk. So, the mean value of the incidence angle strongly depends on the solar altitude. We have calculated the efficiency of a 4 m long light tube assuming the solar altitude varies from 20 to 85 degrees. Such interval is well representative for wide interval of geographical latitudes and for any time during a day.

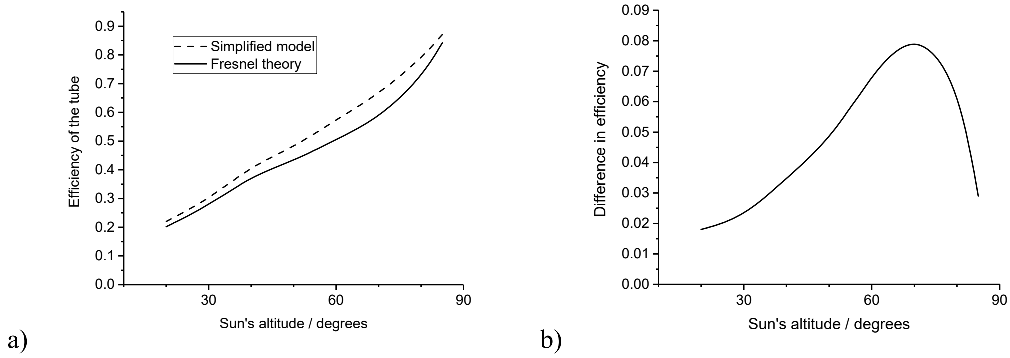

Figure 3. a) Light-tube efficiency calculated under clear sky conditions as a function of the solar altitude: simplified model (dashed-line) and Fresnel theory (full-line). b) Difference in the efficiencies determined from simplified and Fresnel model.

The main finding in Fig. 3 is consistent with that in Fig. 2: the simplified model (2) overestimates the light-guide efficiency. The difference between simplified and Fresnel models depends on the solar altitude: in fact it remains small at high solar altitudes when the angle of the beam incidence is close to 90 degrees and reflectivity coefficient is high (see Fig.1). The difference and also the efficiency are both small for low sun. This is because the angle of incidence for most of rays is close to 0° and the difference between models (1) and (2) is small. The peak difference of about 7 - 8% is found for solar altitude 60 - 75°.

Conclusions

The difference in the calculated efficiency for simplified model (i.e. for constant reflectivity coefficient) and more exact Fresnel theory of reflection was analysed for an aluminium-covered circular light tube with the diameter of 0.52 m. We have found that simplified model overestimates the efficiency of the tube, and depending on the sky conditions the peak difference can be as high as 6 - 8%. As rays undergo multiple reflections in the tube, the mean reflectivity coefficient should be ca 2% lower than the reflectivity coefficient for normal reflection. Under clear sky conditions the difference between both approximate and exact models is largest at solar altitudes of 60–75°. The results found indicate that the efficiency of the light tube should corrected if computed from simplified models like that in Eq. (2).

Acknowledgement

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Electrochromic Glazings: Integrated Dynamic Simulation with Dial+

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***Abstract*— Electronically tintable glazings have now reached maturity and are part of the options to be considered in the design of energy-efficient dynamic facades, both in renovation and for new buildings. However, to assess concretely the daylighting performance of such solutions, it is necessary to carry out dynamic simulations in order to take into account the different states of the glazing according to the control strategy.**

This approach, which until now required the use of specialized tools, is now available with an intuitive software and can be initiated at the earliest stages of design. This paper presents the new simulation possibilities offered in the last release of the DIAL+ software, and show how the tool provides a new effective way to quickly quantify the potential of electrochromic glazings regarding daylight and comfort targets.

***Index Terms*—Daylighting, Dynamic simulations, Early design, Electronically tintable glazings**

INTRODUCTION

The constant evolution of energy performance requirements over the last few decades has led to the design of buildings that are increasingly energy-efficient in terms of heating requirements. One of the consequences of this trend is that buildings are more and more sensitive to the risks of overheating, including in mid-season. In addition, taking into account the visual comfort of the occupants and, in particular, the control of glare in the workplace, places solar protection at the heart of designers' concerns. At the same time, daylighting and views have been shown to be beneficial for people's health and well-being in most building types [1]. In this context, the maturing of electronically tintable glazings (electrochromic or EC glazings), which visual and solar properties can adapt to external changing conditions while being always transparent, offers new and exciting opportunities, both in renovation and new buildings. The assessment of the contribution of this new technology is complex, however, insofar as it requires a dynamic evaluation of the thermal and light effects associated with this technology.

DIAL+ software deals with the optimization of the building envelope, on the basis of room scale analysis [2]. Until now, the daylighting analysis was focused on Daylight Factor calculation and Diffuse Daylight Autonomy (Radiance [3] simulations). Three-Phase method calculation [4] has been implemented in the last release (v2.5) in order to take into account the dynamic properties of EC glazings as well as automated blinds. Although the DIAL+ software is also able to simulate the thermal behavior of a room equipped with EC glazings, we decided to focus this study on daylighting aspects.

INPUT PROCESS

EC glazing is a novelty in the pallet of sun shading devices insofar as the glazing and the mobile protection are only one. During the current input process, the user has to select between the following glazings types: *Reflecting*, *Tinted*, *Clear*, *Diffusing* and *Electrochromic (EC).* In the event that EC is selected, no other mobile sunscreen will be considered in the next steps of the input process.

A. *Number Of Control Zones*

Some of the existing products available on the market are proposing a multi-zone control of a given glass pane [5]. Thanks to the DIAL+ interface, the user can easily choose the most suitable configuration (one, two or three independent zones) and adapt the dimensions of the corresponding areas.

B. *Switching Thresholds*

EC glazings offer several intermediate states (up to 3) between “Clear” and “Fully Dark” states. For each state, the software proposes default sets of values for both visible transmission and g-value. In addition, threshold values are proposed to switch from one state to the other. These values are based on the incident flux on the façade and are expressed in illuminance (lux).

C. *Control Strategy*

There are two main modes of control of the EC glazings:

- The "Daylight" mode is used to activate intermediate tinted states. This mode is useful to accompany the slow variations of the daylight and makes it possible to limit the risks of glare related to intermediate skies. It is only controled with the incident illuminance on the façade.
- The "Glare" mode is dedicated to preventing the risk of glare in particular due to direct sun and reflections, and uses the darkest state of the glazing. When activating this mode, the user has to describe a specific area where sunrays are prohibited during the defined hours.

CASE STUDY

To illustrate the performance analysis related to the implementation of EC glazings, we described a medium-sized landscape office located in Lausanne (width: 18.3m; depth: 7.75m; height: 2.88m) with one external west-oriented glazed façade (the other walls are internal). The window to floor ratio is 16% (glazed area). The reflection coefficients of the room are as follows: floor: 0.30, vertical walls: 0.50, ceiling: 0.70. The simulations were run with climatic data of the city of Lausanne [6].

The tint of the EC glazing is controlled in a single zone (i.e. the same setting is applied simultaneously to the entire surface of the glass). The visible transmission coefficient (Tv) and g-values of EC glazing for each state are as follows:

- Clear state: Tv = 0.59 g-value = 0.40
- Intermediate state 1: Tv = 0.17 g-value = 0.12
- Intermediate state 2: Tv = 0.06 g-value = 0.07
- Maximum tinted state: Tv = 0.01 g-value = 0.05

SIMULATION PROCESS

To evaluate the daylight potential of EC glazing, it is necessary to carry out a simulation for each hour of the year, in order to take into account the adaptation of the glass transmission characteristics according to the meteorological data. To this end, we implemented in DIAL + the Three-Phase method resolution model [4]. The process is as follows:

- Determination of sun protection status: for each hour, the software determines if there is sun and what is the outdoor illuminance on the façade. According to the thresholds described before, the status of the EC glazing is then pre-calculated.
- To speed up the simulation process, the flux transfer is then calculated into the following three phases for independent simulation:

  1. Sky to exterior of fenestration,

  2. Transmission through fenestration (BSDF),

  3. Interior of fenestration into the simulated space.
- Hourly calculation: For each hour a simulation is performed to calculate the direct and diffuse components entering the room.

RESULTS

A. *Illuminances*

As first result of the daylighting simulation, DIAL+ displays a map of the average annual daylight illuminances on the workplane (see Figure 43). As such, this information is not easy to interpret, but it represents a sort of summary of all the information from dynamic simulation. It is observed here that the maximum average value is relatively reasonable (1671 lux), which reflects the continuous control provided by the EC glazing**.**

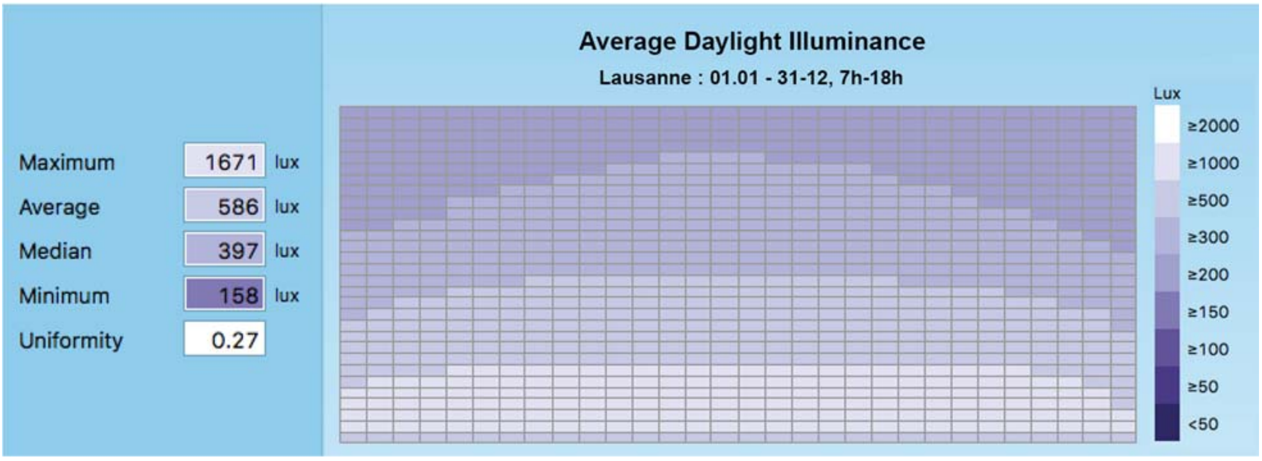


Figure 43: Annual average illuminance on the work plane (h = 0.80) West oriented room equipped with EC glazings (1 zone / daylight mode**)**

It is also possible to display the illuminance values for specific hours (see Figure **44**). In this example, we see that at 12:30 there is only diffuse light on the facade and the glazing is in clear phase. At 13:30, the sun hits the façade and the EC pane is tinted to limit glare, which ends up with some reduction of daylight availability.

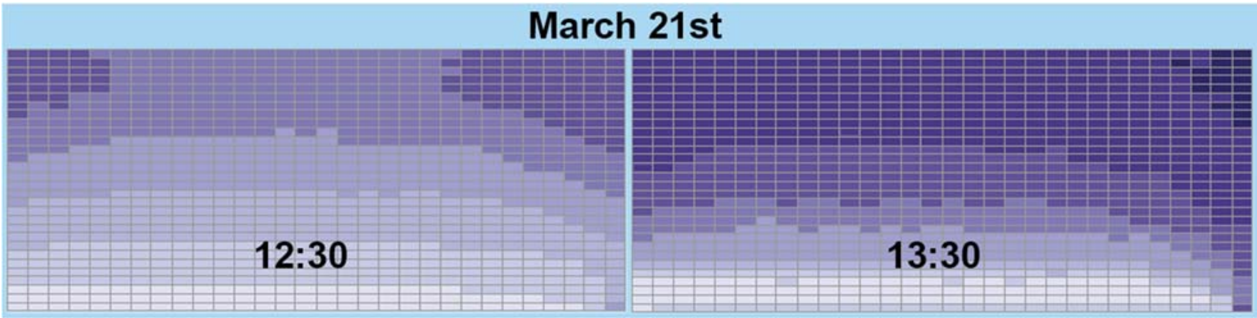


Figure 44: Illuminance values on the work plane (h= 0.80 m) for 2 consecutives hours on the 21st of March. West oriented room equipped with EC glazings (1 zone / daylight mode)

B. Temporal maps

Temporal maps of the different tint states can be displayed (see Figure **45**). They are useful for checking the functioning of the system and make it possible to better analyze the results of the simulations. Daylight and Glare modes can be activated separately (left part of Figure **45**) or jointly (right part of Figure **45**).

In this example, we can see that when the "glare mode" control is ON, the "fully dark" state is activated as soon as the sun hits the façade, which prevents any glare risk. The same type of temporal maps can also be displayed to control the status of "classic" shading devices as venetian blinds or fabric devices.

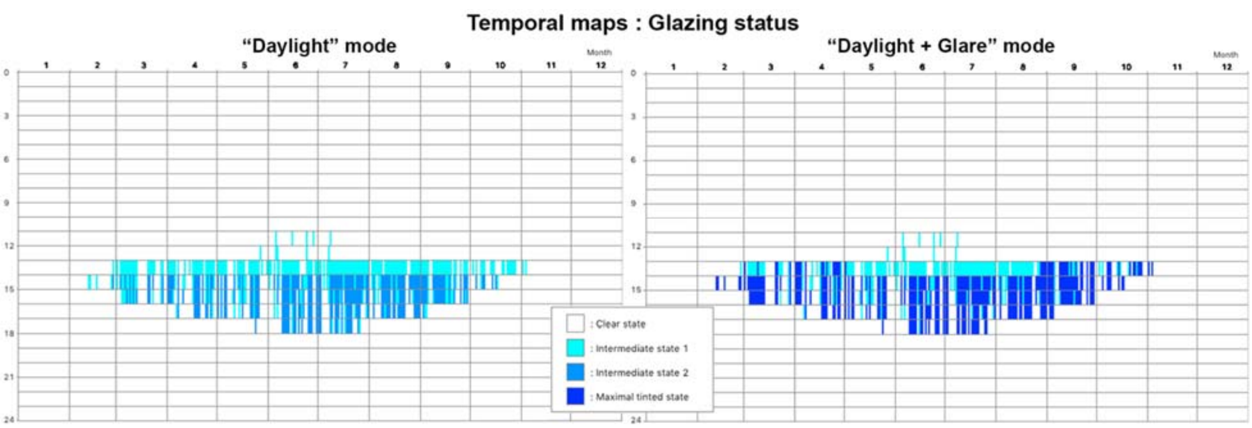


Figure 45: Temporal map showing the glazing status during the year according to the control strategy (one zone). (Left = "Daylight" mode / Right = "Daylight + Glare" mode,).

Temporal maps also allow the user to have an overview of the annual average illuminance in the analyzed room, as shown in Figure **46**. On the right part of this figure (Glare mode = ON), it is possible here to easily identify the moment when the glazing is in the "Fully dark" mode.

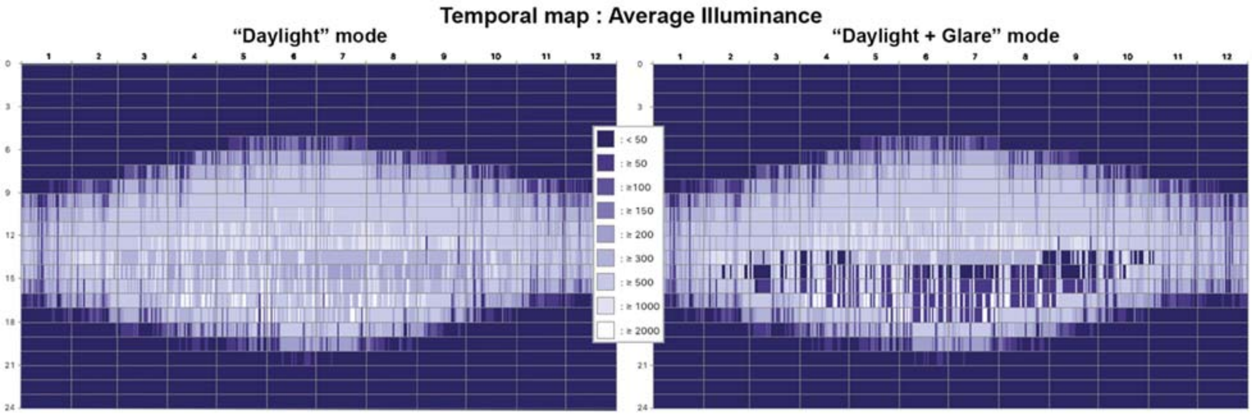


Figure 46: Temporal maps showing the average illuminance during the year according to the control strategy (Left = Daylight mode / Right = "Daylight + Glare" mode).

C. Dynamic Daylight Autonomy

Since the simulation is performed on an hourly basis, it is also possible to calculate the Dynamic Daylight Autonomy, as shown in Figure 47. Results can be adjusted as a function of the occupancy schedule, and the illuminance requirements. Other results, such as Spatial Daylight Autonomy (sDA) or Useful Daylight Illuminance (UDI), are available and can help positionning the room performance with regards to environmental labels [7].

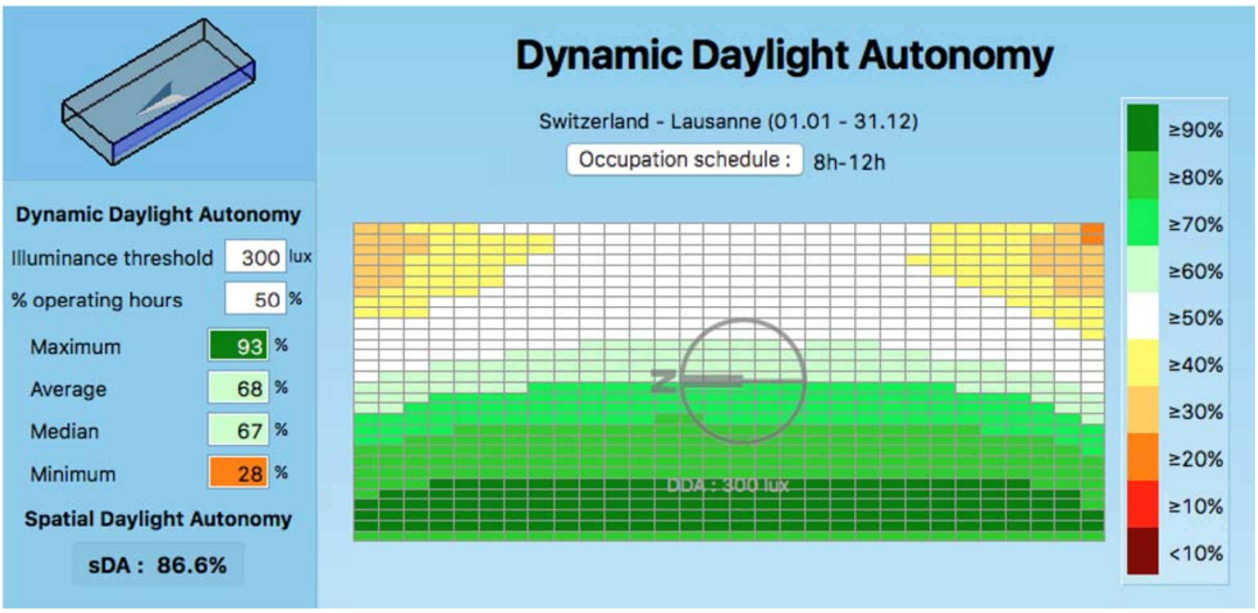


Figure 47: Dynamic Daylight Autonomy and Spatial Daylight Autonomy on the work plane of a west oriented room equipped with EC glazings (workplane height = 0.80m, 1 control zone / daylight + glare mode**).**

D. Useful Daylight Illuminance

Figure **48** shows the useful daylight illuminance ($UDI_{100\text{-}2000}$). This metric is defined as the annual occurrence of daylighting levels that are within a range considered "useful" by occupants. It is found that the median value is equal to 88%, which means that the illumination is between 100 and 2000 lux during 88% of the opening hours on half the surface of the room. This, once again illustrates the capacity of EC glazing to control the incoming daylight and block excessive sun to limit glare risks, while allowing sufficient daylight when needed.

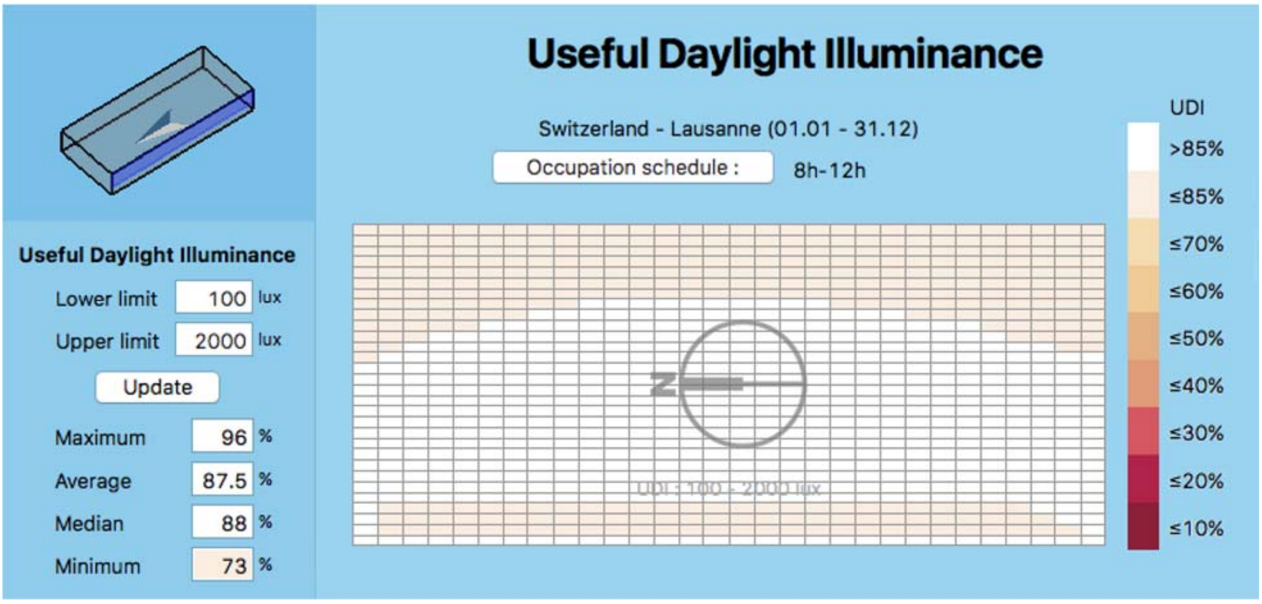
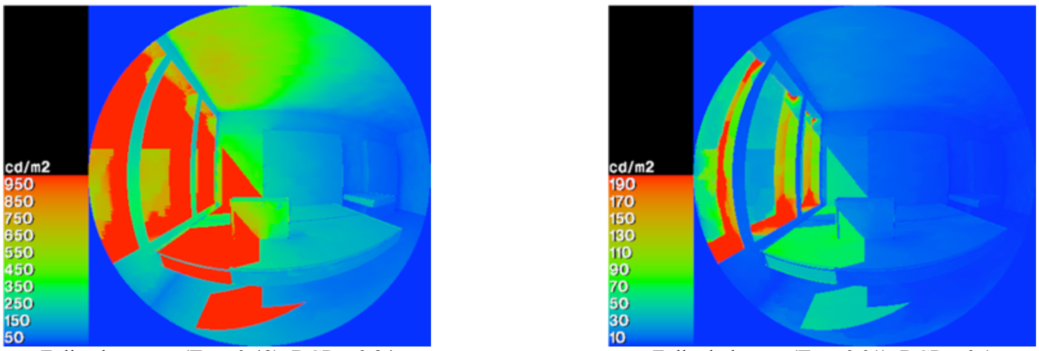


Figure 48: Useful Daylight Illuminance ($UDI_{100-2000}$) on the work plane of a west oriented room equipped with EC glazings (workplane height = 0.80m, 1 control zone / daylight + glare mode).

E. Glare Analysis

One of the next steps concerning the integration of EC glazings within DIAL+ deals with the glare analysis. The actual beta version allows us to evaluate the visual comfort condition for a given situation (specific time and weather condition) by using the Radiance evalglare command [8], see Figure 49. In the future, we plan to give the user the possibility to make a dynamic analysis in order to characterize the annual performance of rooms regarding glare occurrence.



Fully clear state (Tv = 0.49): DGP = 0.34　　Fully dark state (Tv = 0.01): DGP = 0.1

Figure 49: Glare analysis : Luminance comparison between the two extreme states of the EC glazing. The simulations are mare with the same climatic conditions (Lausanne, August 10th, 10 AM, clear sky) with a triple glazing configuration.

Conclusions

This quick overview of the new functionalities of DIAL+ shows that it is possible to evaluate from the early design phase the performance of dynamic systems such as EC glazings. The opportunity to perform a simultaneous analysis of the daylighting performance and the thermal behavior of a given room allows the designers to make an informed decision. We believe this offers new insights into the use of this emerging technology and will facilitate its implementation in projects where it is particularly suited.

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Ledification: Revisiting Quality of Light

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***Abstract*—Nowadays, light quality is prominently positioned as a key differentiator in lighting. Lighting professionals often refer to quality of light when describing the lighting effect of a specific luminaire or lighting design without considering the bigger picture. In general, quality of light refers to the visual aspects of light and its dependencies on and interaction with people and the environment. Ledification gives us endless possibilities to differentiate in quality of light, but the advantages of LED lighting like a fast temporal response, multi-primary control, and a small form factor also introduce some challenges. It forces us to revise our traditional way of evaluating light quality. Current established measures and models to describe light quality need change or extension. The current paper discusses some of these challenges.**

***Index Terms*—light quality, framework, spatial quality, spectral quality, temporal quality, measures**

Introduction

Lighting professionals often refer to quality of light (QoL) when describing the lighting effect of a specific luminaire without considering the bigger picture. Broadly speaking, quality of light refers to the visual aspects of light and its dependencies on and interaction with people and the environment. Because quality of light is such a broad term, and because it includes so many different aspects, precisely defining it is difficult. It's like asking what the definition of "quality of food" is. Quality of food could refer to the quality of the ingredients used for preparing the meal, and to the chefs mastery with which they're combined—the proportions, the spices, the cooking techniques and timing, and so on. The perception of food quality could also relate to the experience of having your meal in a restaurant—an experience that includes presentation, taste, accompanying wine, price, and how it makes you feel. Lastly, it can strongly differ between people.

Quality of light is in a way very similar. It refers on the one hand to the ingredients of light—the different measurable aspects of luminaires and the light they produce. And it refers on the other hand to the perception of light—how light influences the environment and objects in different applications, and how it affects the people present in those spaces. The framework in Figure 1 is a systematic approach to evaluate light quality and addresses the elements described above [1].

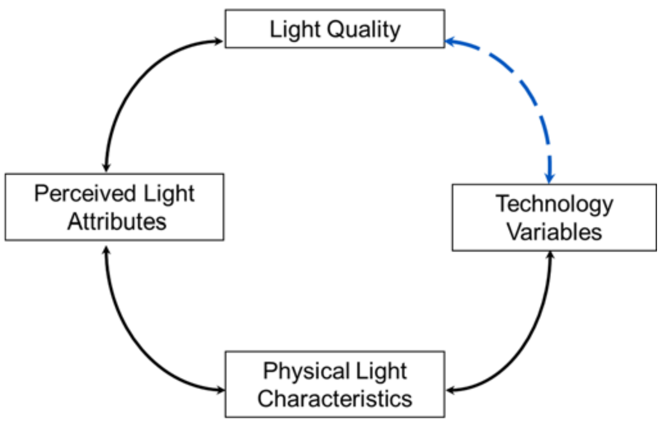

Figure 1: Light Quality circle adapted from Engeldrum [1].

The direct link between overall light quality and lighting technology variables (such as led pitch, reflector type, led phosphor) is not straightforward since complex interactions between these variables impact overall quality of light. The model breaks down this link in intermediate steps to come to a better understanding and better quantification of lighting quality.

A lighting system can be characterized with a set of physical light parameters (such as the spectral composition or the light distribution). Different choices in your technology variables will directly influence these physical light characteristics. The physical light characteristics can be linked to the perceived light attributes (such as colourfulness, flicker, and brightness). A good understanding of the individual strengths of these perceptual attributes in combination with thorough application knowledge makes it possible to make the link to overall light quality. This application knowledge is crucial because the weighting of the perceptual attributes differs per application. This approach makes it possible to systematically optimize your lighting quality.

A. *The Ingredients Of Light*

There are several well-known measures (e.g. colour rendering, UGR, CCT) which quantify the physical characteristics of light. These measures are calculated from the photometric measurements and are typically published as part of a luminaire's technical specifications. The left part of Table 1 shows examples of physical light characteristics of light, the things we can measure, or in other words the ingredients of light.

TABLE I. INGREDIENTS OF LIGHT (LEFT) AND VOCABULARY OF LIGHT (RIGHT)

Ingredients of light			**Vocabulary**		
Spatial	***Spectral***	***Temporal***	***Spatial***	***Spectral***	***Temporal***
Illuminance (lx) Beam angle Contrast UGR	Chromaticity (xy) CCT (K) Colour difference (dE) Colour rendering (CRI) Colour saturation	Frequency Modulation depth Waveform Duty cycle	Brightness Uniformity Sparkle	Whiteness Colour Colourfulness Vividness	Flicker Strobo Smoothness

B. *The Vocabulary Of Light*

The physical light characteristics influence the appearance of the environment, the objects, and the light sources. The vocabulary people use to describe this appearance we call perceived light attributes. In the right part of Table 1, some examples of this vocabulary are shown.

C. *The Perception Of Light*

Being able to fully describe the link between the perceived light attributes, physical light characteristics, and technology variables is still insufficient to describe the overall light quality because critical application knowledge is missing. How we perceive e.g. colours and whites depends on the application and the observer. The goals and requirements for illuminating an office space, for example, differ significantly from the goals and requirements of illuminating a fashion store. Hence, even between fashion stores these can differ strongly. Also the observers' preference and adaptation state will play an important role. A lighting designer or specifier will always choose high-quality lighting components, but the designer's artistry and expertise to create a lighting solution that is appropriate for the space being illuminated is equally important for a successful design. This gives the users and managers of the space the high-quality experience that they expect and desire.

D. *Challenges In Light Characterization*

As with any new technology, solid-state lighting gives use endless possibilities to differentiate in quality of light like fast temporal response, multi-primary control, and small form factor, but also introduces some unwanted visual effects that were absent or less dominant for the conventional, well-established, lighting technologies. In the following chapters we discuss challenges and solution directions for quantifying spatial, spectral, and temporal light quality.

SPATIAL QUALITY OF LIGHT

A. *Colour Uniformity*

Visibility of spatial chromaticity contrast has been topic of considerable research for more than half a century in relation to lighting. Already in 1942, MacAdam [2], performed colour matching experiments to describe ellipses in a chromaticity space in which all colours are indistinguishable from its center colour by the human eye. The current standards for colour consistency in the lighting industry set by ANSI, NEMA, and Energystar, the SDCM and Δu'v', as well as other colour difference measures (Δxy, ΔE^*_{uv} , ΔE^*_{ab}) are all based on these ellipses and thus on the MacAdam stimulus (Figure 2, left).

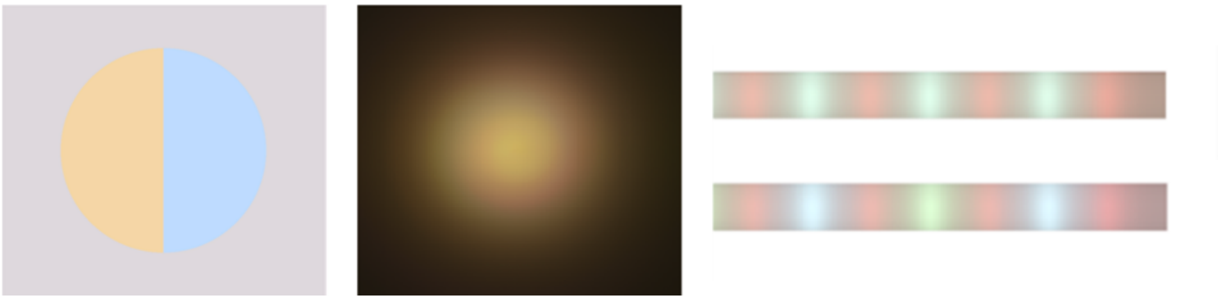

Figure 2: Examples of spatial chromaticity differences. Left: a MacAdam stimulus, Middle: spot with colour over angle, Right: led strip with multiple coloured leds.

Figure 2 also shows two spatial colour non-uniformities for real spot and linear applications. In contrast to the MacAdam stimulus shown on the left, it is impossible to predict a spatial chromaticity contrast of these realistic examples since the existing standards do not take the visual complexity into account. There are many more parameters that determine the visibility of colour differences; physical light characteristics (e.g., base colour, luminance level, size & shape, gradient steepness, spatial frequency), observer state (adaptation) and application (viewing distance, within vs between fixtures and fixture in isolation vs in application). Next to that it is important not to focus on these parameters in isolation, since they all interact. To predict the visibility of colour difference in lighting applications, a comprehensive and generic human visual system (HVS) model, e.g., based on the spatial sensitivity of individual receptive fields, is required taking into account all these different parameters [3].

B. *Glare*

In the general lighting area many new luminaire architypes are available some of which having a non-uniform or pixelated exit window. Where in accent lighting the small size and high peak brightness characteristics of LEDs can have big advantages, in general lighting like e.g. office lighting, this can lead to discomfort glare. Figure 3 shows an example of a uniform and non-uniform exit window.

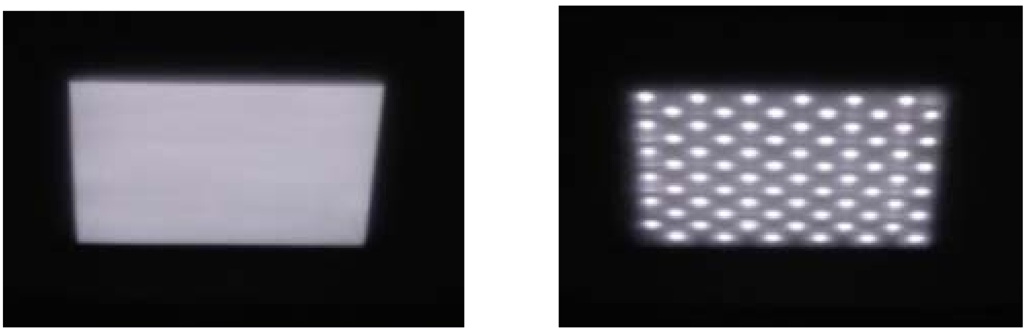

Figure 3: On the left a luminaire with a uniform exit window and on the right a luminaire with a pixelated exit window.

These high luminance contrasts in non-uniform exit windows are not taken into account in most common used glare indices (like UGR) that are based on uniform exit windows. Studies show indeed that pixelated exit windows having the same average luminance as uniform exit windows and thus the same UGR, yet result in higher discomfort glare [4]. Hence, also here support is needed for the lighting industry to come up with new alternatives which better predict glare and are easy to implement.
Investigating the applicability or improvement of the current UGR and exploring alternative ways to predict discomfort glare is a considerable topic of research. Improvement to the current UGR are mainly aimed at correction of the position index in the UGR formula to take the viewing-angle-dependency into account, correction of the average luminance, a correction of the observed luminous surface, and general correction by adding an additional intercept to express the luminance contrast within the glare source [5,6,7,8,9,10,11,12,13,14,15]. Suggestions for alternative methods of describing glare are based on modeling the retinal receptive fields of the HVS and applying this model on luminance maps of the room to assess discomfort glare [16,17,18].
To reach agreement on a new or modified measure both the reliability of the glare prediction and the practical implications of the new proposal should be carefully balanced. After all, the outcome should provide the lighting industry and designers with a useful quality measure for their products and design.

SPECTRAL QUALITY OF LIGHT

Whereas the configurable form factor of LEDs necessitated the revision of measures for spatial light quality, the availability of multi-primary light sources, enabling almost any arbitrary spectral power distribution (SPD), required revision of spectral light quality measures. Traditionally, spectral properties of light sources are characterized with correlated colour temperature (CCT), distance to the blackbody locus (Δuv), and colour rendering index (CRI-R_a). These measures were developed decades ago and based on 2-degree colour matching functions (CIE1931). From a lighting application point of view, one can wonder whether 2-degree functions are predictive for how people perceive a lit environment with a much wider field of view. Although 10-degree colour matching functions (CIE1964) might be more appropriate in this respect, they are not common practise for specifying a light source.

The CCT alone is not sufficient to describe the appearance of “white” light. Two light sources can have identical CCT but in appearance look completely different. In Figure 4 the two light boxes on the left have equal CCT (4000K) but differ in the distance to the blackbody locus (BBL). The chromaticity of the light on the left is above BBL and appears a bit greenish, whereas on the right the chromaticity of the light is below BBL and appears a bit purplish. Adding Δuv, together with its sign (+ above BBL, - below BBL), to CCT quantifies these differences.

Figure 4: Boxes on the left have equal CCT but differ in the distance to the BBL. Boxes on the right have equal CCT, Δuv, and CRI values but differ in colour saturation.

Figure 4 (boxes on the right) clearly demonstrates that CRI alone is not sufficient to describe the colour rendition qualities of white light sources. Although the two spectra on the right have identical CCT, Δuv, and CRI values, the appearance of objects is different in terms of colour saturation which also impacts the user appreciation. This difference in appearance is not revealed by CRI, because the fidelity index only represents a colour difference, without indicating the direction of the colour shift. Several new characterization methods have been proposed in journal publications (e.g. GAI, CQS, FCI, MCRI) and technical memoranda (e.g. IES TM-30-15), but none of them have been accepted as an international standard. The use of a 2-dimensional system, where the fidelity index is supplemented with a saturation-based index, is commonly recommended to better describe the colour rendition properties of white light sources [19,20,21,22,23,24]. The CIE is preparing, with Reportership R1-68, a Technical Note and an accompanying calculation tool that includes a colour gamut index that can be used in conjunction with the well-established CRI-R_a. It shows if the 8 test-colour samples, used to compute CRI, will appear on average more or less saturated under the test source in comparison to their appearance under a reference illuminant. Additionally, the missing information on the direction of the colour shifts, for all 14 CRI test-colour samples, will be made available through the technical note for providing a more complete description of the colour rendition properties of white-light sources.

TEMPORAL QUALITY OF LIGHT

A unique capability of LEDs is their fast response to changes in the driving current. This characteristic can be used to control the light output in an easy way (i.e. dimming), for instance by rapidly switching the digital signal on and off to simulate a varying voltage. However, visible temporal light artifacts (TLA) such as flicker and stroboscopic effects, can occur due to improper selection of the driving parameters (i.e. frequency, modulation depth, duty cycle, wave shape). Several solutions can reduce or eliminate the occurrence of TLAs but in general it comes with increased driver cost and size. Therefor it is important to better understand the effect of driver parameters on the visibility of TLAs. The currently applied measures (modulation depth and flicker index) do not quantify TLA correctly because effects of frequency, duty cycle, and wave shape are not fully account for. For example, two waveforms with the same frequency but with different duty cycle (30% and 95%) will look the same according to these current measures, but in reality will look completely different with respect to TLA. A better alternative to quantify flicker is the short-term Pst measure which has been used in IEC electromagnetic compatibility standards. For the stroboscopic effect the SVM measure is developed accounting for different wave characteristics and has good correlation with perception [25]. The visibility thresholds for both metrics are at 1, but acceptance limits however may differ for specific applications. The introduction and promotion of SVM as the best metric for stroboscopic effects is initiated through the appropriate CIE committees.

CONCLUSIONS

Quality of light isn't one specific easy-to-define thing, but rather a coordination of several different but related considerations. The technical measurements of light is only one consideration: quality of light also entails the perception of people and goals and requirements of specific applications, and may even take into account the health of people in the lit environment. New approaches to connected lighting are adding further challenges to quality of light. By bringing digital lighting and information technology together, connected lighting systems can gather and share in-context information, creating a platform for Internet of Things applications. The flow of data enabled by a connected lighting system delivers new insights, benefits, and experiences to both the users and managers of illuminated spaces. Quality of light becomes more personalized and situational, changing depending on who is present and what their needs are —whether it's directions to a specific item on the shelf of a supermarket, the ability to adjust the lighting over a desk in an open-plan office, or a way of continuously monitoring the noise level on the streets of a city. Quality of light should be considered at system and service level and not solely on a product level. New directions with interesting challenges ahead.

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Study of Overhead Glare Discomfort from Downlight Luminaires

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Abstract— **The sensation of discomfort and annoyance, experienced by many office workers seated directly underneath downlight luminaires and normally looking forward, has been reported during the last twenty or so years. This paper reports on three studies made in the last three years to seek clarity on the cause of discomfort from overhead luminaires and recommends the introduction of an illuminance limit for work places employing sedentary workers.**

Index Terms—**discomfort, glare, overhead**

INTRODUCTION

The sensation of discomfort and annoyance, experienced by many office workers seated directly underneath downlight luminaires and normally looking forward, has been reported during the last twenty or so years. The complainants predominately tended to be office workers operating desk top computers and display screens having primarily forward and downward viewing directions. In most cases the offending luminaires were outside the field of view but a sensation of "visual discomfort" has been reported by early researchers who described the experience as "overhead glare" [1]. This overhead glare was judged to be caused by downward concentrating reflector type luminaires with high downward luminance and located directly above the seated worker. The effect from these overhead luminaires was somehow being seen by the workers. Initial investigations by researchers to seek limits had linked the experience to discomfort glare and one proposal was to cap the downward luminaire luminance [2] in the lower hemisphere to about 9000 cd/m^2 whilst another proposal was to extend the UGR model to cover the condition [3]. Clearly extending UGR beyond the field of view would invalidate the UGR equation and the Position Index table that requires the luminaire to be in the field of view. Luminance limits are also questionable as this is not only dependant on the luminaire downward intensity but also the luminaire luminous area. We suspected that it is illuminance on the top of head that may be the cause of discomfort so in the last three years we made three subjective controlled studies. The objective of each study was to confirm the occurrence of discomfort from illuminance from overhead luminaires. Also to indicate whether overhead glare was a visual discomfort from high luminance or was a form of "lumen pressure", manifested as illuminance and detected by the head.

FIRST STUDY

The aim of this study was to ascertain if illuminance from different type and size of overhead luminaires will cause significantly different discomfort sensations.

The study was made in a test area as shown in Figure 1. 15 subjects were invited and seated to perform two types of tasks under three different dimmable luminaires, having different light source, size and light distribution (T16 lamp reflector troffer, LED downlight and TH lamp downlight). Each luminaire in turn was mounted on an adjustable height platform centred directly above the subjects head. The task areas, see Figure 2, were illuminated by a separate system to the required standard. With the subject performing task 1, to assemble a jigsaw puzzle placed on the table in front and the test luminaire at maximum height, the downward light output was adjusted from zero until the subject reported just noticeable light from above. With the light output held at this level the luminaire was lowered and the subject was asked to indicate when the light from above became just uncomfortable and then when it became just intolerable. At each report the height of the luminaire and the illuminance at head height and on task area were measured. The procedure was repeated but with the subject performing a word search task displayed upon an inclined computer screen on the desk situated in front of the subject. Each test run was continuous and lasted approximately 15 minutes, giving minimum time to adapt to the changing lighting conditions. At the end of the test runs the subjects were invited to give feedback on the experience.

RESULTS

A summary of the measured head level illuminances when a report was made by the subjects is shown in Table I. A follow up test run with the LED luminaire to check practice effects yielded no significant change in the subjects reaction. Only a few subjects volunteered feedback although this was of no significance.

Figure

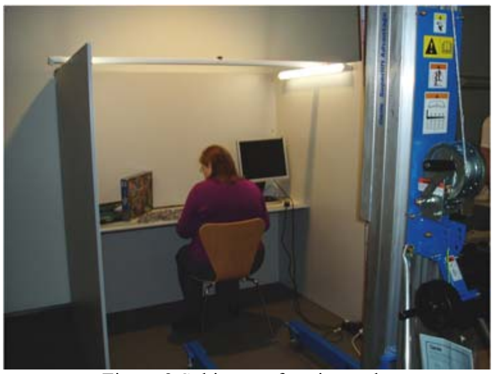


Figure 2 Subject performing tasks

TABLE I SUMMARY RESULTS STUDY 1 – ILLUMINANCE (LX) ON SUBJECTS HEAD

Subject	LED – 3000 lm L830			TH – 1x50W QPAR			MCF/E – 4x14WT16		
m male f female	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE	Jigsaw/ DSE
Status	1	2	3	1	2	3	1	2	3
JA m	160/161	381/200	4709/394	97/69	-/-	-/-	47/115	180/289	776/754
LB m	80/130	761/217	2870/391	90/120	820/740	-/-	108/119	518/892	1197/1857
EB f	304/161	1279/651	6534/1176	263/800	-/-	-/-	135/832	739/2709	-/-
JG f	161/419	813/537	1950/979	x	x	x	112/308	341/409	494/636
BH m	162/163	314/235	562/411	380/140	1100/270	10140/-	93/43	368/97	762/407
SJ m	74/107	1233/622	2575/-	100/80	2960/805	-/-	77/107	438/315	-/489
NK m	161/136	724/297	9240/-	-/-	-/-	-/-	53/68	642/2480	1690/1456
JK f	1088/320	9620/1446	-/1903	115/213	175/817	722/16200	47/271	89/504	174/1103
JM m	77/104	-/-	-/-	63/27	2280/-	-/-	58/56	-/621	-/1282
SRW f	107/161	2792/516	3215/2060	100/-	-/-	-/-	134/619	761/1278	1514/3141
CS f	112/77	442/200	5055/360	20/90	30/120	60/170	24/92	49/266	100/51
KS f	140/162	640/694	4018/9152	70/150	-/2290	-/-	44/806	-/4197	-/-
JT m	161/635	-/3372	-/-	60/60	-/-	-/-	88/132	-/440	-/1733
PT m	125/161	6330/669	-/8960	100/104	-/350	-/2138	53/110	451/179	1815/755
MW m	130/194	1174/210	-/465	90/90	-/150	-/440	86/53	776/131	66/265

Note, Status row indicates 1: Noticeable, 2: Uncomfortable, 3: Unacceptable lx levels

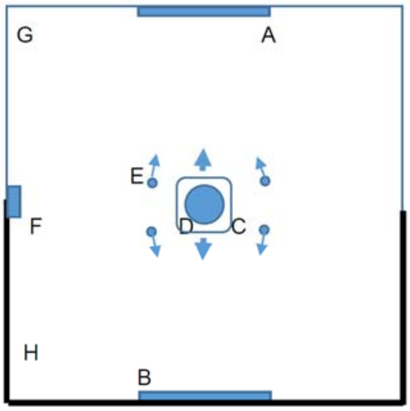
COMMENTS

The results indicate that all subjects became aware of the light from the three types of overhead luminaires and most experienced discomfort when the light level increased. The tungsten halogen luminaires produced the least discomfort. There was no significant difference in experience when tackling the jigsaw or display screen based tasks by male or female subjects. The reported experience may have been influenced by the increased reflected light from the task area. The random nature of the results required further studies under fixed mounted variable output overhead luminaire.

SECOND STUDY

The first study indicated that subjects located directly under luminaires do experience discomfort from illuminance falling on their head. The aim of the second study was to evaluate at what value of illuminance on the subjects head it will become noticeable and may cause discomfort to subjects from the overhead lights.

This study used a high output narrow beam dimmable LED downlight luminaire of 6600 lm output mounted at 2.5m above the floor in the centre of the 2.9m high ceiling of the test room. One half of the wall surfaces of the test room (2.9m long and 2.4m wide) was finished in light grey (reflectance 45%) and the other half in black (reflectance 4%). The ceiling was white (reflectance 79%) whilst the floor was covered with black carpet (reflectance 2%). Two white paper task areas of 600mm x 300mm containing rows of numbers were placed at eye and floor level in the centre area of both grey and black 2.4m wide walls. Spot lights were used to illuminate these task areas to about 500 lx and an uplight was placed at the centre of the long wall to provide some 50lx background illuminance. A chair was placed in the centre of the room facing the task areas, see Figure 3. 24 subjects with age range of 18 to 68 years consisting of 16 males and 8 females of which 5 males and 3 females wore spectacles were invited to participate in the study. Some of the subjects also participated in study 1. On arrival each subject was briefed on the study aims and asked to sit in the test room directly below the luminaire facing either the grey or black wall , Figure 4. The distance between top of head and floor was measured. At the start of the test run the subjects were asked to read the rows of numbers on task area 1 (at eye level) and were asked to count how many rows had identical numbers whilst the downlight output was increased from zero to maximum. The downlight was able to deliver more than 23000 lx at head height. As the output of the downlight increased the subjects were asked to report when they just became aware of the additional light from the downlight, when the light just became uncomfortable and when the light became just intolerable. At each report the setting on the dimmer was noted and the light level at head height was measured, Figure 5. Each test run lasted about 5 minutes. The test run was repeated with each subject having to search the numbers on the task are located by the floor (below the line of sight). The whole procedure was repeated with the chair and subject turned to face the alternate wall finish. Each subject was exposed to two different contrasting finish of room surface surrounding the task area. On completion of the test runs the subjects age, gender and use of spectacles was recorded.



Where
A – Task areas 1 and 2
B – Task areas 3 and 4
C – Chair
D – Downlight
E – 4 off spotlights
F – Uplight
G – Grey walls
H – Black walls

Figure 3 Test room set up

Figure 4 Set up to face tasks 3 and 4

Figure 5 Subject in seat for height measure

TABLE II SUMMARY RESULTS STUDY 2 – ILLUMINANCE (LX) ON SUBJECTS HEAD

Subject	Age (years)	Height (cm)	Glasses	Grey			Black		
				Upper : Lower			Upper : Lower		
				Noticeable	Uncomfortable	Unacceptable	Noticeable	Uncomfortable	Unacceptable
M3	52	138	No	433:433	4040:20970	20970:-	433:4040	20970:20970	-:-
M4	50	138	Yes	923 : 923	4040:4040	20970:20970	4040:923	20970:4040	-:20970
M11	68	134	No	415 : 415	3800:19700	19700:-	3800:415	19700:19700	-:-
F4	26	132	No	858 : 3700	3700:19200	19200:-	3700:19200	19200:-	-:-
F5	48	132	No	3700 : 700	19200:19200	-:-	858:19200	19200:-	-:-
M15	52	130	Yes	3620 : 620	18700:1870	-:-	839:3620	3620:18700	18700:-
F7	49	128	No	394 : 3530	820:18220	3530:-	394:820	3530:3530	18220:18220
M1	42	140	No	950:442	21740:21740	-:-	21740:4170	-:-	-:-
M2	21	140	No	4170:4170	21740:21740	-:-	21740:4170	-:21740	-:-
F1	31	138	No	-:4040	-:-	-:-	-:-	-:-	-:-
M5	19	138	No	4040:4040	20970:20970	-:-	923:4040	20970:20970	-:-
M6	19	138	No	923:923	4040:4040	20970:20970	4040:923	20970:4040	-:20970
M7	54	138	No	4040:923	-:4040	-:20970	20970:4040	-:-	-:-
F2	39	136	No	424:900	900:3920	3920:20370	424:900	3920:3920	20370:20370
M8	34	136	No	900:424	3920:20370	20370:-	900:900	3920:3920	20370:20370
M9	61	135	Yes	3870:3870	20100:20100	-:-	420:3870	3870:20100	20100:-
M10	43	135	Yes	890:890	-:-	-:-	3870:3870	-:-	-:-
M12	46	134	No	876:876	19700:19700	-:-	415:3800	19700:19700	-:-
F3	56	134	Yes	3800:3800	19700:19700	-:-	3800:3800	19700:19700	-:-
M13	60	132	Yes	858:408	3700:3700	19200:19200	408:408	-:-	-:-
F6	23	132	Yes	858:3700	3700:19200	19200:-	3700:3700	19200:19200	-:-
M14	18	130	No	3620:402	18700:839	-:3620	3620:3620	18700:18700	-:-
M16	51	130	Yes	3620:3620	18700:18700	-:-	402:402	3620:830	18700:3620
F8	20	126	Yes	800:3430	3430:17710	17710:-	800:3430	3430:17710	17710:-

COMMENTS

The summary results in Table II, show that only two subjects reported no discomfort from the illuminance on the head from the overhead downlight luminaire. The other subjects reported discomfort but were slightly less sensitive to the illuminance on the head when viewing the task located below the horizontal line of sight. Two subjects experienced discomfort from an illuminance below 1000 lx and nine below 5000 lux. There was no clear difference in the detection dependency when considering age, head height, gender and wearing glasses by the subjects. Also although not recorded we observed that the density and colour of hair on the subjects head had insignificant impact on the illuminance at which discomfort was reported. The grey and black finish on the walls also showed minor differences in the impact on the offending illumination levels.

THIRD STUDY

The aim of this study was to explore if the light sensation is via the eye or the head surface. The study was conducted in the same test room as used for study 2. Eight subjects were invited to participate where some also participated in study 2. On arrival at the test area each subject was briefed and then blindfolded. The blindfold effectiveness was tested by exposing each subject to a 30000 lx light wall. No light leaks were reported. The subject was led into the test room and guided to sit on the chair located directly under the downlight. When ready the downlight output was increased from zero to maximum and the subject was asked to report when they just noticed the light, when they found it just uncomfortable and when it became just unacceptable. At each report the dimmer setting and light level at head height was measured. The results are summarised in Table III. The – in the table indicates that no report was made when the light output of the luminaire reached its maximum value with an illuminance at head height of 23000 lx.

TABLE III SUMMARY RESULTS STUDY 3 – ILLUMINANCE (LX) ON SUBJECTS HEAD

Subject M(Male) F(Female)	Age Years	Head Height cm	Illuminance lx Noticeable	Illuminance lx Uncomfortable	Illuminance lx Unacceptable
1M	53	136	21220	-	-
2M	58	139	-	-	-
3M	60	131	-	-	-
4F	45	130	-	-	-
5M	43	131	21220	-	-
6F	25	128	215	20210	-
7M	68	133	20930	-	-
8M	75	128	3710	20210	-

COMMENTS

The results show that five (62.5 %) out of the eight blindfolded subjects detected the light delivered from the overhead downlight onto their heads. This indicates that high levels of unseen light from overhead luminaires can be detected by some seated people. The differences in age, head heights and gender yielded no significant differentiation in the detection of the light.

DISCUSSION OF RESULTS

The studies show that people can suffer discomfort from downlight luminaires outside the field of view. The subjects experience of discomfort when exposed to high illuminance, over 1000 lx, on their head can manifest very quickly and whilst not explored this discomfort may increase if exposure continues over long time. The cause of discomfort is due to high illuminance or light pressure, is not overhead glare and is not dependant on the luminance of the source. The phenomena can best be described as "Lumen pressure" on the head. Most people will not suffer discomfort if the illuminance at head height (the "Lumen Pressure") does not exceed 5000 lx. There are valid reasons for introducing such a limit into the specification of lighting design criteria. There is likely to be much benefit in eliminating such discomfort in work places employing predominantly sedentary workers.

CONCLUSIONS

There is no such thing as overhead glare but people can suffer discomfort from unseen light. Discomfort from overhead lighting can be experienced if the illuminance at head height exceeds 5000 lx. The discomfort is not related to luminaire luminance and cannot be estimated by the UGR system. The experience felt by people is akin to "lumen pressure" a term well worth adopting for this phenomena.

RECOMMENDATIONS

Introduce an illuminance limit of 5000 lx on a horizontal plane 1.5m above floor level for work places employing sedentary workers

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Receptive Field Mechanism and Pupillary Light Reflex for the Assessment of Visual Discomfort

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***Abstract*—Discomfort glare is caused by high luminance levels relative to the average luminance level in the field of view. Traditional glare metrics fail for non-uniform luminaires. As an alternative, visual discomfort is determined by a physiological model incorporating the centre-surround receptive field mechanism and the pupillary light reflex. The pupil area, controlled by the pupillary light reflex, regulates the retinal illuminance. A centre-surround receptive field, described by a difference of Gaussians, represents the visual signal. The centre excites the signal whereas the surround controls the inhibition. A forced choice paired comparison experiment involves 7 non-uniform rear projected stimuli with different spatial frequencies. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.**

***Index Terms*—Discomfort Glare, Luminance Map, Receptive Fields**

INTRODUCTION

Discomfort glare is the sensation of discomfort caused by high luminance levels relative to the average luminance level in the field of view [1]. Ever since the beginning of the previous century, researchers have been attempting to quantify the amount of visual discomfort [2]. A multitude of glare indices have been developed. The Unified Glare Rating (UGR) is proposed by the CIE for the assessment of discomfort glare for interior lighting and is included in the European standard for indoor workplace environment EN 12464-1 [3, 4]. The International Engineering Society of North America (IES) proposed the VCP for the assessment of discomfort glare [1].

Traditional glare metrics often include an average luminance level calculated from the far field luminous intensity distribution [1, 3]. Any non-uniformity in luminance distribution is ignored. Since a non-uniform luminaire produces more discomfort glare than a uniform one of equal average luminance, the applicability of traditional glare metrics for non-uniform light sources is under discussion [5-11]. The non-uniformities of a luminance distribution are accurately described by a luminance map [12]. With a growing market share of highly non-uniform LED luminaires for interior and exterior lighting, a valid assessment of visual discomfort based on luminance maps becomes essential.

Although some mechanisms involved in glare perception are known, sometimes already for decades, traditional glare formula are merely phenomenological and lack any physiological or psychological justification. In the model presented in this paper, the receptive field concept is extended with the pupillary reflex for the calculation of visual discomfort.

The pupillary light reflex controls the retinal illuminance as part of the adaptation process. Different formulas for the pupil size are developed [13]. Early formulas only include the luminance level of the stimulus [14-17]. Next to the luminance level, also the stimulus size is a determining factor [18, 19].

The receptive field neural pathways have been studied already from the 1930's on [20, 21]. By physically stimulating the retina of mammals and other animals, the neuron response is directly recorded [22, 23]. Patterns with different spatial frequencies invoke a neural stimulation [24, 25]. The computation of the neural stimulation forms a physiological basis for visual discomfort and is recently applied in lighting design [26].

In the present study, visual discomfort is calculated from a luminance distribution by applying a model including the receptive field mechanism and pupillary light reflex. The model is analysed with a forced choice paired comparison (PC) experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies.

METHOD

A. Human Visual System

The human visual system includes several mechanisms (Fig. 1). The eye images an object plane characterized by a luminance distribution on the retina. The retinal illuminance is proportional to the pupil area, controlled by the pupillary light reflex, and the object luminance. In lit environments, a constriction of the iris reduces the pupil area and limits the incident light. In dimmed settings, an iris dilation increases the pupil aperture maximizing the retinal illuminance. The pupil size ranges approximately between 2 mm and 8 mm. In this paper, the pupil diameter is obtained from the average stimulus luminance level and the stimulus field size [18]:

$$D = 5 - 3\, tanh\left(0.4 log\, \frac{L_s a}{40^2}\right) \tag{1}$$

where

- D pupil diameter (mm)
- L_s the average stimulus luminance level (cd/m²)
- a the stimulus field size (deg²)

The pupil area controls the retinal illuminance (E_{ret}) by scaling the luminance distribution (L, cd/m²). For direct view, the retinal illuminance can be approximated as:

$$E_{ret} \sim L \,.\left(\frac{D}{2}\right)^2 .\, \pi \tag{2}$$

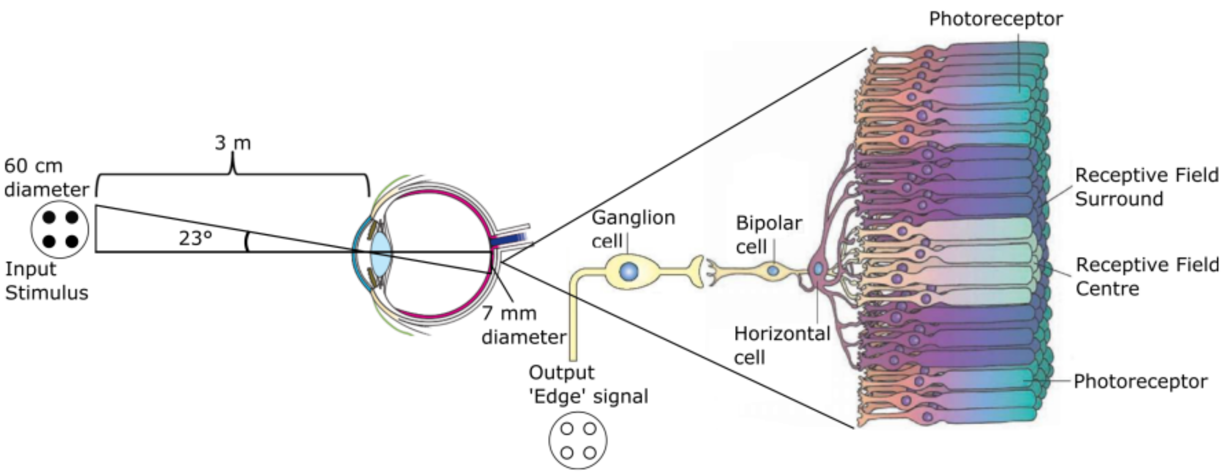

Figure 1. The human visual system includes the pupillary light reflex and receptive field mechanism

Seen from the back of the eye to the front, three retinal layers can be distinguished: the photoreceptors, the layers with the bipolar and horizontal cells and the ganglion cell layer. Under photopic conditions (Hunt, 1998), the cone photoreceptors convert the incident light into an electrical signal. Since photoreceptors are situated in the deepest retinal cell layer, nerve cells in other layers must be transparent. Centre photoreceptors link directly to a bipolar cell. A horizontal cell parallel to the retina connects several surround photoreceptors and also relay the signal to the bipolar cell in an indirect path. A bipolar cell in turn transfers the direct and indirect photoreceptor signal to a ganglion cell. The ganglion cell sends a pulsed signal train to the brain.

Combining the direct and indirect signals results in centre-surround receptive fields. In an ON-centre OFF-surround receptive field, the ganglion signal is excited by the centre but inhibited by the surround signal and vice versa for an OFF-centre ON-surround receptive field. Photoreceptors can be part of multiple centre and/or surround fields [21]. A receptive field is modelled by a difference of 2-dimensional Gaussian distributions. Subtracting a surround Gaussian from a centre Gaussian results in the total difference of Gaussians (DoG) receptive field pattern. When a single receptive field is uniformly illuminated, the net signal will be marginal. At a sharp dark-light edge where the surround is not entirely illuminated, the centre is not maximally supressed. A receptive field consequently acts as an edge filter (Fig. 2).

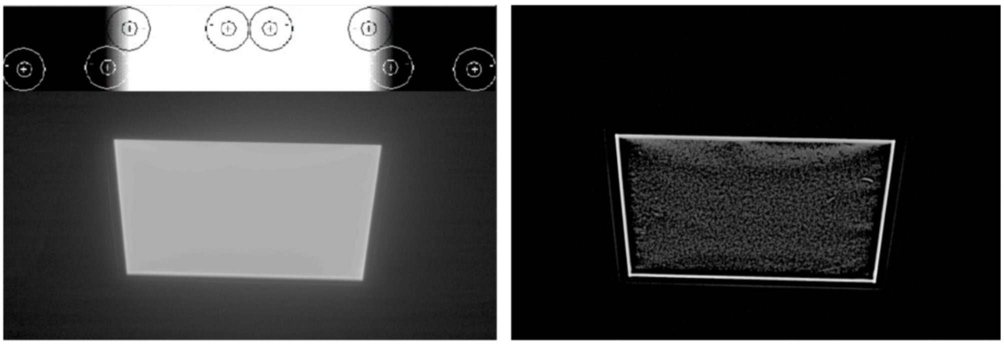

Figure 2. When a single receptive field is uniformly illuminated, the net signal will be marginal. At a sharp dark-light edge where the surround is not entirely illuminated, the centre is not maximally supressed. A receptive field consequently acts as an edge filter.

A luminaire can be represented by a luminance map. To each pixel of a high definition luminance map, a luminance value and spatial coordinate in the luminaire can be attributed. A centre-surround receptive field is modelled by a Mexican hat shaped difference of Gaussians (DoG). The difference between the maximum centre signal and maximum surround signal is reflected in the weighing factor (WF). The DoG kernel is scaled and discretised to correspond to the retinal illuminance map resolution. A single ganglion cell receptive field signal is calculated by overlaying the DoG kernel on one specific area of the luminance map, pointwise multiplying the overlapping matrices and adding all obtained products. The response of all ganglion receptive field signals in the eye is modelled by the convolution of the luminance map with the DoG kernel. The convoluted luminance map represents a measure for the transmitted signal to the brain for each pixel. To count both the ON- and OFF-centre receptive field contributions, the absolute signal value of the convoluted luminance map is considered. The sum of all pixel signals is a measure for the total visual signal of the luminaire. The total number of pixels is dependent on the luminance camera field of view and the luminance map resolution. To normalise for the difference in number of pixels for different resolution luminance maps, the pixel signal is weighed with the pixel visual solid angle. A natural logarithm accounts for the compression mechanisms, as can be found in multiple perception formulae [1, 3]. A centre and surround field width have previously been reported [10]. The natural logarithm is arbitrarily chosen in this paper. The total calculation procedure used in this paper is summarized below:

$$\text{Visual Discomfort Model} = ln\sum_{pix}\omega_{pix}.\left|(C - WF.S) * E_{ret}\right| \tag{3}$$

where

- ln is the natural logarithm;
- ω_{pix} is the pixel solid angle;
- C is the centre kernel;
- S is the surround kernel;
- WF is the Surround-to-Centre Weighing Factor;
- E_{ret} is the retinal illuminance map;
- * is the convolution operator.

B. Paired Comparison Visual Experiment

Seven non-uniform stimuli were rear projected on a diffusor screen creating Lambertian light distributions (Fig. 3). Light patches with a luminance level of 1500 cd/m² were arranged in a 33.5 cm by 34.0 cm matrix observed from a fixed 3 m distance. While increasing the number of squares, the luminous surface per square and spatial separation between squares was decreased maintaining an average luminance level of 350 cd/m² and a total light emitting surface of 0.0042 m^2. The matrix consisted of 2 by 2, 6 by 6, 26 by 26, 60 by 60, 179 by 179 and 360 by 360 light patches complemented with a uniform stimulus.

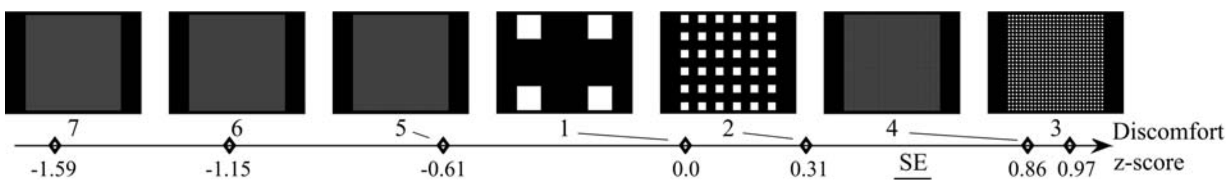

Figure 3. The 7 rear projected stimuli and subjective PC results with standard error.

DALI controlled wall washers produced a uniform background luminance ranging from 40 cd/m² to 50 cd/m² with an average luminance level of 45 cd/m². In a full forced choice PC experiment, all 20 observers were shown 42 pairs and were asked to indicate the most visual discomforting stimulus per pair. The observers were between 20 and 38 years old with an average of 26 years. The experiment took about half an hour and observers could ask for a break whenever they wanted. A generalised linear model produced a z-score on an interval scale for each stimulus and a standard error for visual discomfort (Fig. 3) [27, 28]. Luminance maps were measured with a LMK Labsoft luminance camera with a total reported uncertainty of 2.8 %.

RESULTS AND DISCUSSION

The subjective assessment with error bars is plotted against the modelled value in Fig. 4. The numbers in Fig. 4 correspond to the numbers in Fig. 3. A high coefficient of determination of 0.90 is found. The impact of the spatial luminance frequency on discomfort glare has been studied and recently applied in lighting design using a Fourier transformation [24, 26]. In this paper, this relation is explained by the model including the receptive field mechanism and pupillary light reflex. Visual discomfort initially increases with increasing frequency (stimuli 1 to 3). An increase in the number of light patches results in an increasing amount of edges while the spatial separation decreases. In agreement with the subjective assessment, a higher amount of edges initially results in a higher modelled value since the model acts as an edge filter. When the spatial separation of the light patches reaches the spatial eye resolving power, the light-dark edges become less clear. At a certain frequency, the human eye will not clearly resolve the edges and the visual discomfort saturates at a maximum. In the model, the spatial separation of the stimuli reaches the dimensions of the centre-surround receptive field kernel. The excitation from one light patch on the centre starts to be supressed by another light patch on the surround of a receptive field. If the spatial separation of the light patches further decreases (increasing amount of patches), the edges will progressively appear less clear and the stimuli will steadily be seen as more uniform. The observed visual discomfort starts to decrease (stimuli 4 to 7). Stimulus 3 produces the maximum visual discomfort corresponding to a frequency of 4.0 cycles per degree. Conservatively, any stimulus in the range between 1.0 and 9.3 cycles per degree will produce the maximum discomfort. A quadratic fit predicts a stimulus with maximum discomfort within the range to 4.0 to 9.3 cycles per degree. From the contrast sensitivity function (CSF) [29], a maximum frequency sensitivity between 6 and 11 cycles per degree for direct view is observed. A satisfactory agreement in the range of 6 to 9.3 cycles per degree is noted.

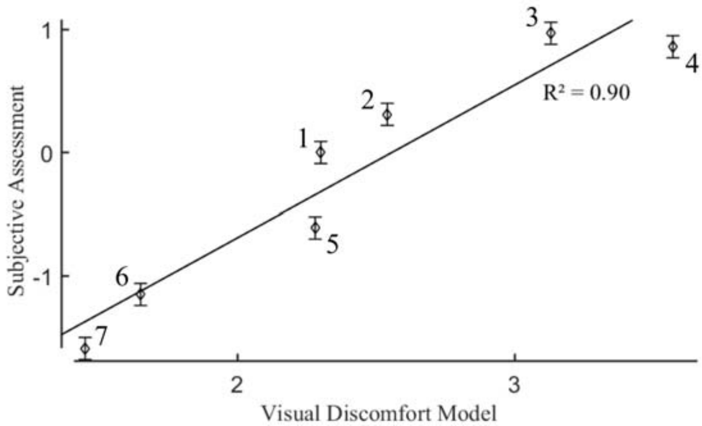

Figure 4. The paired comparison subjective assessment against the modelled value.

In the formula for the pupillary light reflex (1), only the product of luminance level and stimulus field size is considered. Also age can be included in the pupil diameter calculation, but proves to be tedious [30]. In this study, the age effect is ignored. The maximum deviation in pupil diameter from age differences is 7 % relative to the pupil diameter of the average observer.

The luminance level of some projected pixels at the edge is 50% lower than the maximum pixel luminance at the centre. None of the observers reported a drop in luminance level at the edges, even when this was explicitly mentioned. The measured luminance maps were used for the analysis. To test the robustness of the model, the light emitting patches were equalised in theoretical luminance maps. The light emitting surface was defined as all pixels with a luminance level above 50% of the maximum luminance to include all pixels at the edge. The luminance level of all light emitting pixels was fixed at the average luminance level of the light emitting surface. The modelled value for the actual measured luminance maps was compared with the value for the theoretical maps resulting in a difference of only 4%. In agreement with visual perception, the model is robust to gradual changes in luminance level.

Donners et al. proposed a similar receptive field model including the pupillary light reflex to assess the discomfort glare for both office and road lighting luminaires [31]. An additional local normalisation mechanism for the dark outdoor environment had to be included since luminance contrast and range is larger in a road lighting setting than in an indoor environment. The normalisation mechanism is not included in this paper.

CONCLUSION

A model including the receptive field mechanism and pupillary light reflex has been developed for the assessment of visual discomfort. The pupillary light reflex regulates the retinal illuminance were a centre-surround receptive field describes the visual signal. The model has been analysed with a paired comparison experiment involving 7 non-uniform rear projected stimuli with different spatial frequencies. A spatial luminance frequency in the range of 4.0 to 9.3 cycles per degree will produce the maximum visual discomfort. Inspired by a promising coefficient of determination of 0.90, the model is a candidate to replace current glare metrics as UGR or VCP, especially when non-uniform luminaires are to be evaluated.

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Testing Colour-Matching Functions - Perception of Luminous Colour Differences of white LEDs in Relation to Ambient Luminous Colour and Age of Observers

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***Abstract*— Studies have revealed inconsistencies in metamerism in that colour differences between LEDs are perceived even though the chromaticity coordinates are identical when the CIE colour-matching functions (CMFs) are used for the calculation. The present investigation used LEDs illuminating light boxes in order to find out which CMFs model human perception best and to determine the influence of the ambient luminous colour and the observer's age. Without age differentiation no correlation could be found between the calculated chromaticity differences and the perceived luminous colour differences by the subjects. However, for young people, CMFs recommended by POLSTER were found to model colour perception better than the hitherto standard procedure. For elderly persons the CMFs of the CIE 1931 and those recommended by POLSTER (2006 TUIL-10°A70) and by the CIE 2006-10°A70 (the latter corrected for age) model colour perception best. No effect of the ambient luminous colour was found.**

***Index Terms*-- age-related effects, Colour-matching functions, luminous colour perception, LED.**

Introduction and State of the Art

Currently, the colour-matching functions (CMFs) for the CIE standard observer of 1931 are the standard in general colorimetry and the binning of white LEDs. Studies have revealed inconsistency in metamerism [1], [2]. Colour differences are perceived between LEDs even though the chromaticity coordinates are identical when the CIE colour-matching functions are used for the calculations. Polster found chromaticity differences between visually matched LED spectra and the results of calculations based on the CIE 1931 CMFs up to $\Delta u'v' = 0.0165$ [3]. Kramer investigated which differences in chromaticity are just noticeable. The threshold values he found are in the range between $\Delta u'v' = 0.0004$ and $\Delta u'v' = 0.0018$ [4]. In some cases, the visible differences in luminous colour are so clearly perceptible that users find them unacceptable. Polster and Kramer have investigated young subjects (30±6 and 28±7 years respectively), each using the same chromaticities for LED light source and surroundings. New CMFs (CIE 2006-2° and CIE 2006-10°) were published by CIE in 2006 on the basis of physiological data. This technical report also established age-related CMFs [5]. After making numerous colour-matching experiments, Polster has suggested new CMFs (2006 TUIL-2° and 2006 TUIL-10°) [3]. Early exploration of these suggestions showed a good correlation between the calculated chromaticity differences and the perceived luminous colour differences based on the CMFs recommended by Polster [3], [6]. These investigations were limited to young subjects. Colour perception is affected by many factors: the properties of the visual object, the viewing conditions and the characteristics of the observer. The effect of combinations of different luminous colours for the LED light source and the surroundings has not so far been considered.

Research Issues & Hypotheses

The aim of the present investigation was to test a variety of CMFs for their capacity to model colour perception. Younger and older people were included in the investigations. Comparing subject's ratings with the calculated chromaticity differences $\Delta u'v'$ show how suitable the CMFs are in this respect. "Good" CMFs will deliver a high correlation between observed luminous colour differences and calculated chromaticity differences.

From the early investigations, it can be hypothesised that the colour-matching functions recommended by Polster will be more successful than those of the standard in modelling the perception of luminous colours of white LEDs.

Because of aging in the human eye, older people perceive luminous colours differently from younger people, which means that age-related changes must be taken into account for modelling the perception of luminous colours of light sources. CIE 170-1: 2006 addresses this issue and its performance requires verification [5].

The luminous colour of the surroundings will determine the chromatic adaptation of the eye. If the luminous colour of the surroundings is changed, the retinal cones can be expected to adapt, which will influence the colour perception. It is desirable to investigate the influence of the ambient luminous colour on the perception of luminous colour differences between LED light sources.

Experimental Setup and Methodology

Using simulation to establish the possibility of variation in the spectral distribution due to the manufacturing procedure, we selected 10 types of LED with $CCT = 4000$K which were likely to be relevant in a study of inconsistency of metamerism, then manufactured them and characterised them colorimetrically. We fitted them into boxes with diffusors for which the luminous surface was 30 cm by 30 cm. The mean luminance L was 800 cd/m² with a CCT of 3500 K. Two adjacent boxes were presented to the subjects at eye level in a room ($l = 6.6$ m, $b = 4.2$ m, $h = 2.8$ m) at a viewing distance of 1.7 m (i.e. at a viewing angle of 10°). At the sides of the room, there were two luminaires with fluorescent lamps with different luminous colours which serve to illuminate the background at a projection screen (2 m by 2 m, viewing angle of ~40°) at a mean luminance of 200 cd/m². The experiments were carried out with a variety of luminous colours in the surroundings (CCT: 2700 K, 4000 K, 6500 K) and also without any additional lighting there. Figure 1 shows the experimental setup. Figures 2 and 3 give an overview about the construction of the light boxes and the spectral distributions of them.

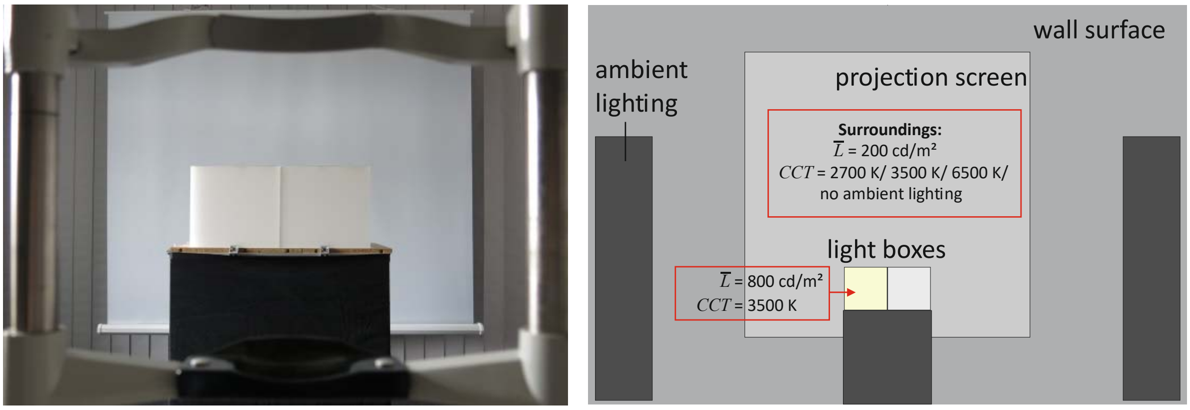

Figure 1. Left: Experimental setup photographed from the viewing position of the observer. Chin rest appears in the foreground, Right: Experimental setup, schematic drawing.

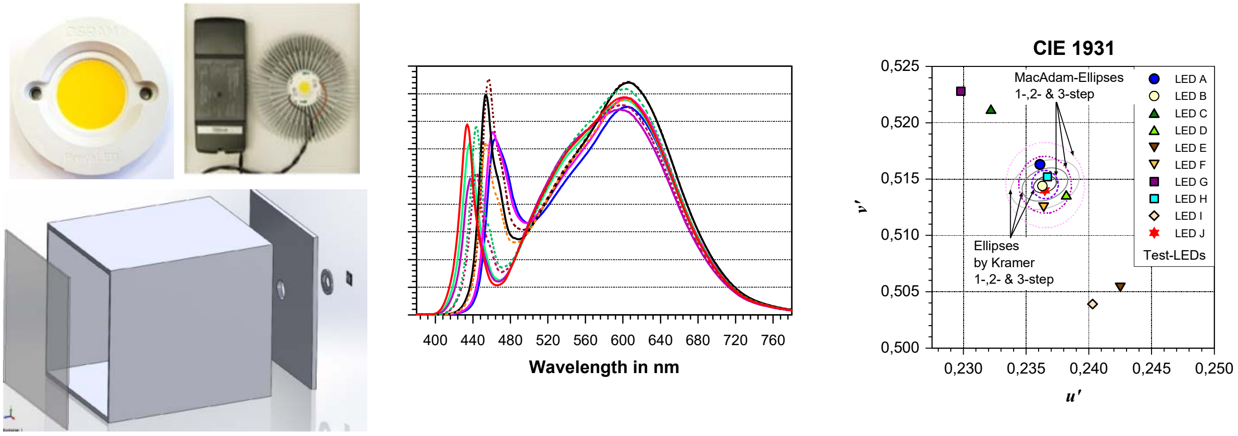

Figure 2. Top left: example of COB (chip on board) pc (phosphor converted) LED fitted onto a cooling unit. Below left: construction of light box with diffusor. Centre: spectra of the ten types of LED. Right: chromaticity coordinates using CIE 1931 CMFs.

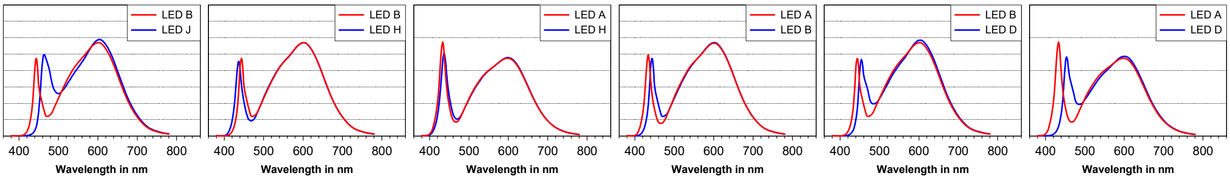

Figure 3. Samples of spectral distributions of different LED-combinations with small chromaticity differences Δ*u'v'* in CIE 1931.

The light boxes were evaluated by 41 young people (< 35 years, avg 24 ± 4 years) and 39 older people (> 60 years, avg 71 ± 6 years), who rated the luminous colour differences they perceived in the 23 LED-combinations tested. Among the subjects were 38 men and 42 women. The semantic scale shown in Figure 4 was used for the ratings by the subjects.

Figure 4.Scale for the rating by the observers.

The CMFs included in the investigation were the standard CMFs CIE 1931 (2°) and CIE 1964 (10°) [7], plus the CMFs CIE 2006-2° and CIE 2006-10° [5] and the CMFs 2006 TUIL-2° and 2006 TUIL-10° recommended by Polster [3]. An additional calculation was carried out using the CIE 170-1: 2006 recommendation in respect of older people. These are the CMFs shown in Figure 5.

For each LED the chromaticity coordinates were determined from its spectra and the different CMFs. From these data the chromaticity difference Δ*u'v'* for each combination of LEDs was calculated [8]. Besides comparing these calculated differences with the subjective ratings of the participants in the experiment, we also focussed on the changes in colour perception attributable to ageing. The methodology we used is shown in Figure 6.

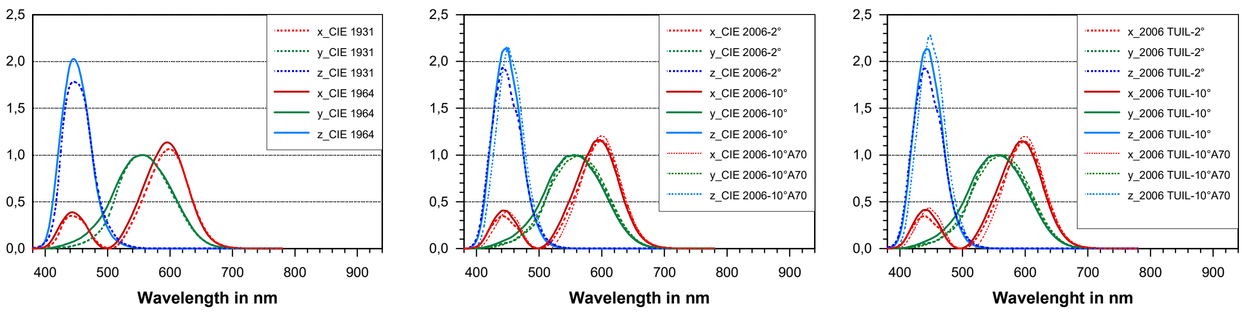

Figure 5.CMFs tested in the investigation.

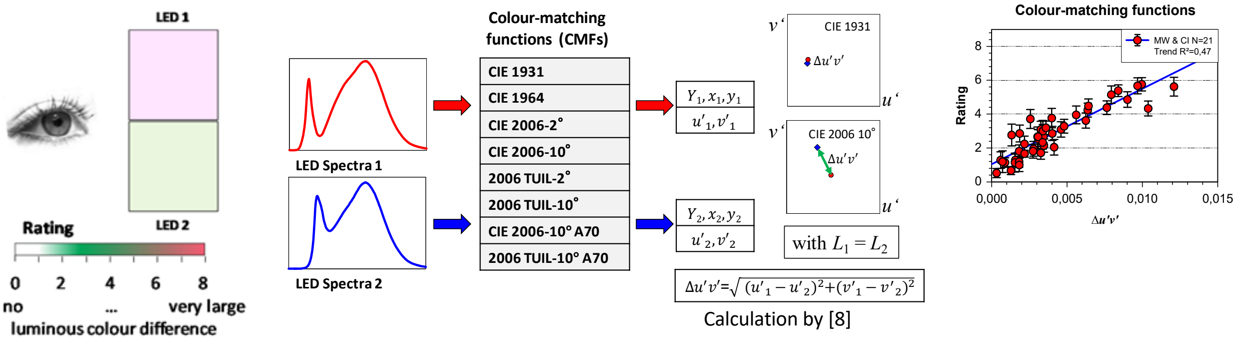

Figure 6. Method of investigation.

We analysed the data by linear regression of the subjective ratings versus calculated chromaticity differences $\Delta u'v'$ for each CMFs. High correlation in the data is associated with high coefficient of determination R^2 and a high goodness of fit (TABLE I). The coefficient of determination is a value between 0 and 1. Additionally, the statistical significance of the results was analysed.

TABLE I. INTERPRETATION OF COEFFICIENT OF CORRELATION R^2

R^2	Values up to 0.05	Values up to 0.2	Values up to 0.4	Values up to 0.8	Values over 0.8
Interpretation	No or low correlation	Low correlation	Moderate correlation	Highly correlated	Very highly correlated

RESULTS

TABLE II summarises the mean ratings (Mean) and the intervals of confidence 95% (CI) for the LED-combinations presented in Figure 3. There are clear inconsistences using the standard CMFs. Where the chromaticity difference is small it is not perceived as such by the observers and ditto for larger differences. It is also clearly age-related. Figure 7 shows relevant results diagrammatically. There is a summary of coefficients of determination in TABLE III.

TABLE II. MEAN SUBJECTIVE RATINGS (MEAN ± CI) OF N SUBJECTS FOR SELECTED LED-COMBINATIONS REPRESENTED IN FIGURE 3

LED-combination →	BJ	BH	AH	AB	BD	AD
CIE 1931	$\Delta u'v'$=0.0008	$\Delta u'v'$=0.0012	$\Delta u'v'$=0.0019	$\Delta u'v'$=0.0019	$\Delta u'v'$=0.0020	$\Delta u'v'$=0.0034
CIE 1964	$\Delta u'v'$=0.0046	$\Delta u'v'$=0.0051	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0011	$\Delta u'v'$=0.0009	$\Delta u'v'$=0.0002
CIE 2006-10°	$\Delta u'v'$=0.0057	$\Delta u'v'$=0.0061	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0012	$\Delta u'v'$=0.0014	$\Delta u'v'$=0.0004
2006 TUIL-10°	$\Delta u'v'$=0.0084	$\Delta u'v'$=0.0100	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0034	$\Delta u'v'$=0.0046
2006 TUIL-2°	$\Delta u'v'$=0.0052	$\Delta u'v'$=0.0019	$\Delta u'v'$=0.0005	$\Delta u'v'$=0.0020	$\Delta u'v'$=0.0034	$\Delta u'v'$=0.0053
Younger subjects' rating (N = 41)	5.4± 0.4	1.3 ± 0.2	0.7 ± 0.2	0.7 ± 0.2	2.8 ± 0.3	3.0 ± 0.3
Older subjects' rating (N = 39)	2.1 ± 0.3	2.2 ± 0.3	2.1 ± 0.2	3.3 ± 0.4	2.4 ± 0.4	4.1 ± 0.4
All subjects' rating (N = 80)	3.2 ± 0.4	1.9 ± 0.2	1.6 ± 0.2	2.4 ± 0.3	2.6 ± 0.2	3.6 ± 0.3

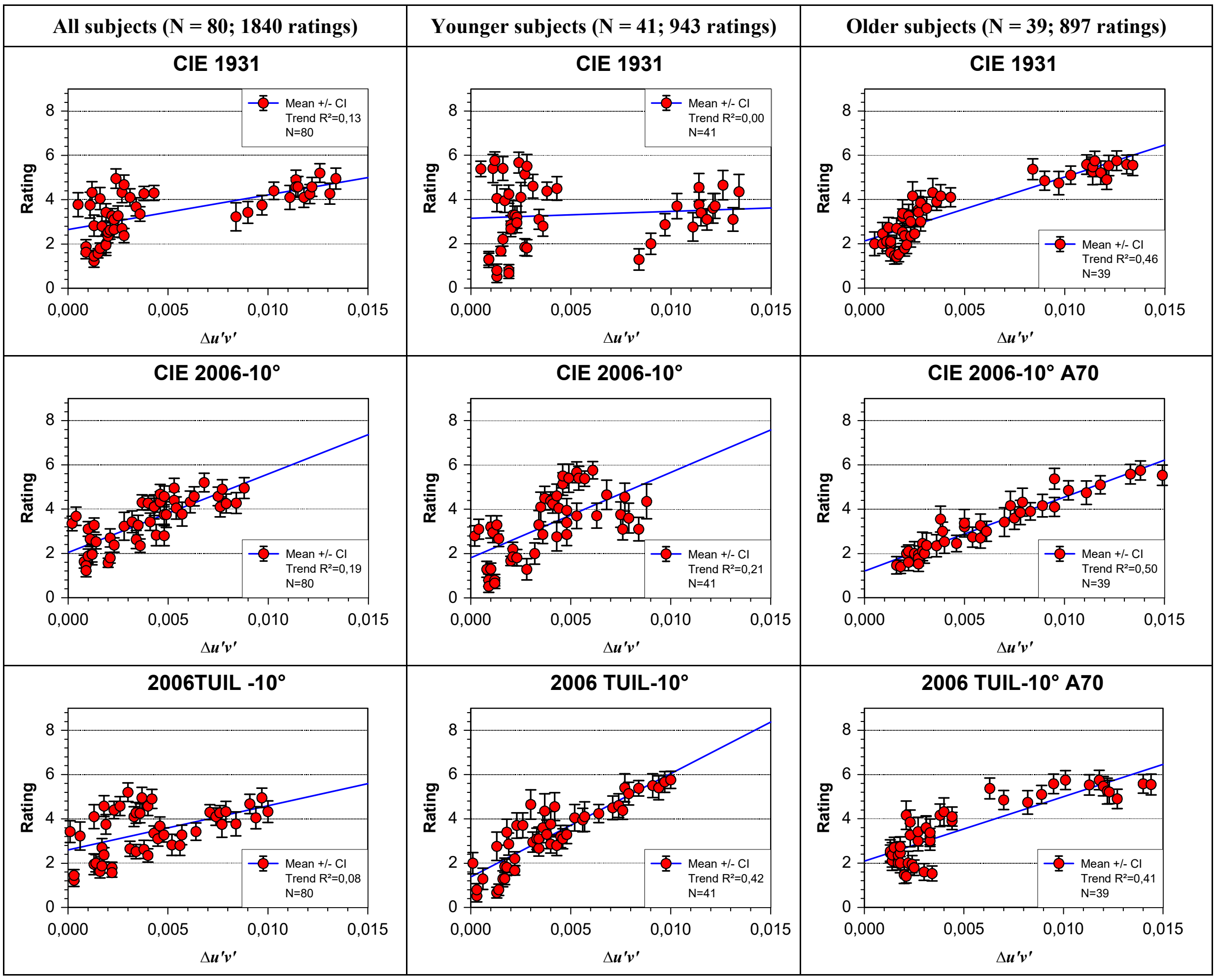

Figure 7. Results of the investigations: Mean and confidence intervals (CI 95%), linear regression function, coefficient of determination R^2: results of the ratings of N subjects.

For the subjects as a group, without age differentiation, no correlation was found between the calculated chromaticity differences and the luminous colour differences perceived, for any of the CMFs tested. The best compromise is achieved by the 2006 TUIL-2° proposal. There are significant differences between the two age groups. For younger people, the CMFs recommended by POLSTER model colour perception better than the standard procedure used to date. For older people, the colour-matching functions of CIE 1931 and those recommended by POLSTER (2006 TUIL-10°A70) and by the CIE (CIE 2006-10°A70) model colour perception best (A70 denotes the age correction in the respective CMFs).

TABLE III. COEFFICIENT OF DETERMINATION R^2

CMFs/ Subjects	All Subjects N = 80; 1840 ratings	Young Subjects (< 35 y.), N = 41; 943 ratings	Old Subjects (> 60 y.), N = 39; 897 ratings
CIE 1931	0.13	0.00	0.46
CIE 2006-2°	0.16	0.04	0.39
2006 TUIL-2°	0.26	0.34	0.19
CIE 1964	0.18	0.12	0.25
CIE 2006-10°	0.19	0.21	0.17
2006 TUIL-10°	0.08	0.42	0.02
CIE 2006-10° A70	0.18	0.03	0.50
2006 TUIL-10° A70	0.11	0.00	0.41

As regards the influence of the luminous colour of the ambient lighting on colour difference perception, the data analysis revealed nothing of significance. Samples of the results are shown in Figure 8. However, the perception of LED luminous colour itself was found to vary in relation not only to age but also to the luminous colour of the surroundings.

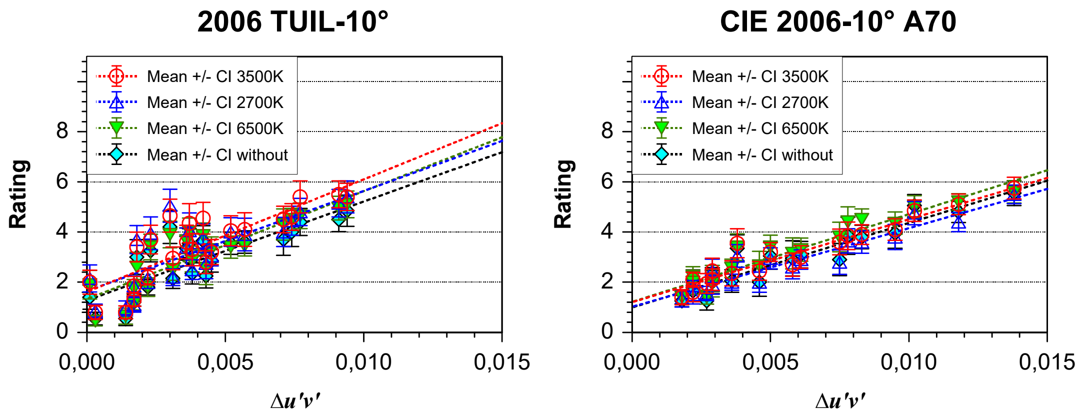

Figure 8. Ratings of chromaticity differences (mean and confidence intervals 95% (CI) and linear regression functions for different ambient luminous colours and without any ambient lighting for younger people N = 20 (left) and older people N = 20 (right).

CONCLUSION

It is here shown that the binning of LEDs on the basis of the standard CIE 1931 CMFs fails to prevent users from perceiving marked differences in luminous colours despite the fact that the chromaticity coordinates are similar. It may be useful to classify the LEDs on the basis of different CMFs. There may also be useful in checking the age-related effects of particular combinations of LED. As the ambient lighting as tested seems to be of no relevance, generalisation to practical applications is acceptable.

ACKNOWLEDGEMENT

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Office Lighting Characteristics Determining Occupant's Satisfaction and Health

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***Abstract*—Light beneficially influences human health directly, but moreover, indirectly via occupant's satisfaction with lighting. This study identified parameters influencing occupant's satisfaction with lighting. During a five-day study, 46 office workers evaluated their office lighting conditions once a day using the Office Lighting Survey. The significant correlations between satisfaction with lighting and the lighting statements in the OLS indicated that the aspects 'brightness', 'distribution', and 'reflections' are of importance. These aspects relate to the lighting parameters 'illuminance', 'uniformity', 'luminance distribution', 'glare', and 'luminance'. The significant correlations between general health and the lighting descriptors became not significant when the correlation was controlled for satisfaction with lighting. This research shows the relevance of investigating satisfaction with lighting and its possible (beneficial) aftereffects. Including this knowledge in the lighting design process is important as office workers' satisfaction with lighting and their health will clearly be determined by the overall lighting situation provided at their workplace.**

***Index Terms*— Field study, Occupational Health, Office landscape, Office Lighting Survey (OLS), Visual comfort**

INTRODUCTION

Office environments have recently evolved from individual offices to shared office landscapes. A general lighting design in combination with central lighting control reduces the office workers' ability to set the lighting conditions in accordance with their individual needs, desires, and preferences. In order to apply the preferred lighting conditions per individual office worker, it is necessary to control lighting conditions per individual. Moreover, it is essential to know which aspects influence these individual needs and preferences as well as the impact of light on their satisfaction with lighting and their general health in order to design and control the lighting conditions.

Light influences human health via the circadian timing system [1] and via environmental satisfaction [2]. In order to assess occupant's satisfaction with lighting, Boyce and Eklund developed an Office Lighting Survey (OLS) in 1995 [3]. This questionnaire is often used in light effect studies to determine people's experiences and evaluations regarding office lighting [4],[5],[6].

The objective of this study was to identify parameters which relate to the overall satisfaction with lighting of office workers within office landscapes. These parameters are expected to contain several office lighting characteristics, but other environmental or personal aspects may also play a role in determining office workers' satisfaction with lighting.

METHOD

The five-day study was performed in May 2016 in an office building in the Netherlands. This office building consisted of two floors mainly designed as office landscapes. The office featured in total 83 workplaces equipped with computers and all had a view to the outside.

A. Lighting Conditions

The weather conditions varied throughout the study period from overcast sky on Monday to clear sky on Friday. The windows on the ground floor did not contain a blind system, whereas at the first floor an automatic blind system was installed. The office landscapes were lit by dimmable suspended luminaires (Prolicht, Glorius, Ø1400 7x14//24W DALI) and dimmable LED spots (Quadro LED reflector 31W 2100lm 3000K or Quadro LED Reflector 53W 2400lm), see Fig. 1 and Fig. 2.

Figure 50: Suspended luminaires (Prolicht, Glorius)

Figure 51. LED spots (Quadro led reflectors)

B. Participants

Forty-six office workers (22 male and 24 female) participated in this research. The participants all voluntary participated and signed an informed consent form. The majority of the participants fell in the age category '25-34 years' and reported that their most performed task was 'using the computer'.

C. Procedure

The participants were asked to fill in the Office Lighting Survey (OLS) (27 items) at the end of their workday (± 16:00h) regarding the lighting conditions at the workplace they were working at that moment. Each participant completed at least one questionnaire and at most five questionnaires. In total, 113 questionnaires were collected and included in the data analyses. Overall satisfaction with lighting, assessed via the OLS, was rated on a 5-point scale from (1) 'very satisfied' to (5) 'not at all satisfied'. One of the 27 questions was regarding their self-reported general health.

D. Data Analysis

All questionnaire data were analysed in IBM SPSS Statistics 23. Normality tests showed that all data was not normally distributed; therefore, non-parametric tests were applied to analyse the data. Kendall's tau correlation coefficients were calculated to identify correlations and the Mann-Whitney test was applied to investigate differences between two groups. All tests were performed two-sided since it was expected that there were relations between external explicators and satisfaction with lighting, no direction was predicted. The significance level of 0.05 was used to identify statistical significance.

RESULTS

This section provides the results separately for satisfaction with lighting and self-reported general health.

A. Satisfaction With Lighting

Satisfaction with lighting was analysed in relation to the environmental aspects (the location of the office worker and the lighting descriptors from the OLS questionnaire) and in relation to personal aspects (the user characteristics of the office workers).

Environmental explanations for satisfaction with lighting

The office policy included flexible workplaces so the office workers were able to choose their own workplace each day. However, the office workers did not choose different workplaces across the two floors. They were working either at the ground floor or at the first floor. Office workers working at the first floor (69 questionnaires) reported to be equally satisfied with the lighting conditions compared to the office workers at the ground floor (44 questionnaires). The difference between both floors was not significant (U=1433.5, p=.585).

Many significant correlations were found within the lighting descriptors of the OLS itself (see **Napaka! Vira sklicevanja ni bilo mogoče najti.**). The overall satisfaction with lighting correlated significantly with six statements (i.e., S1: Overall the lighting is comfortable, S2: The lighting is uncomfortably bright for the tasks that I perform, S3: The lighting is uncomfortably dim for the tasks that I perform, S4: The lighting is poorly distributed here, S6: Reflections from the light fixtures hinder my work, and S7: The light fixtures are too bright). All statements but statement 1 correlated negatively with the satisfaction with lighting. This indicated that the absence of uncomfortably bright or dim lighting, a poor lighting distribution, reflections from light fixtures, and too bright light fixtures led to a higher satisfaction with lighting. In addition to statements 2 and 3, it was found that the tasks of the participants played a role in determining occupant's satisfaction with lighting. Significant correlations were found between the overall satisfaction with lighting and the rating of lighting for different office tasks (i.e., reading from paper, reading from computer, writing on paper, typing on computer, drawing on paper, and drawing on computer). There was also a significant correlation between the overall satisfaction with lighting and the evaluation of the amount of light for the work that was performed at that moment (τ=0.554, p=.000).

The lighting conditions were described in three attributes in the questionnaire: electrical lighting (i.e., (1) bad to (5) good), the brightness of the lights (i.e., (1) too much light to (5) does not get too bright), and glare from the lights (i.e., (1) high glare to (5) no glare). The overall satisfaction with lighting correlated significantly and negatively with all three attributes. The correlation between the brightness of the lights and the overall satisfaction suggests that people rather prefer too much light compared to a lighting situation in which the lighting does not get too bright.

In the questionnaire, the glare aspect was subdivided into five categories (i.e., reflected glare from work surface, glare from ceiling lights, glare from task lights/desk lamps, bright lights in workspace, and glare reflected in computer screen). The strongest correlation of these five was between overall satisfaction and the bright lights in the workspace (τ=0.454, p=.000).

The last significant correlation within the OLS was found between overall satisfaction and the appearance of lighting compared to similar workplaces.

1) *Personal explanations for satisfaction with lighting*

Male participants reported to be statistically less satisfied with the lighting compared to female participants (U=1023, p=.001). There was no significant differences in overall satisfaction with lighting between office workers younger than 35 and office workers equal or older than 35 years (U=1440, p=.673) and between office workers with or without glasses or contacts (U=1454, p=.812).

Office workers who reported that their most performed task was not computer-related reported a higher overall satisfaction with lighting compared to the office workers who said their most performed task was using a computer. However, this difference was not significant (Mean Rank no comp= 53.04, Mean Rank comp=57.47, U=558.5, p=.627).

B. General Health

General health was assessed on a five-point scale from (1) excellent to (5) poor. Self-reported general health (Mean=2.08, SD=0.734) correlated significantly with the overall satisfaction with lighting, five lighting statements (i.e., S1,S2,S4,S6,S7), the three attributes, five of the six tasks (task 5 not significant), four of the five glare cases (glare case 5 not significant), the amount of work, and the evaluation of the amount of light for the work that is performed. A significant correlation was also found between general health and the overall satisfaction with lighting of the office workers (τ=0.398, p=.000). People who reported a higher satisfaction with lighting also reported a higher general health. When the correlations between the lighting descriptors and general health were controlled for overall satisfaction with lighting, all correlations became not significant.

TABLE IV. CORRELATION COEFFICIENTS BETWEEN OVERALL SATISFACTION WITH LIGHTING AND SUBJECTIVE LIGHTING DESCRIPTORS WITHIN THE OFFICE LIGHTING SURVEY (τ= KENDALL'S TAU CORRELATIONS, P=SIGNIFICANCE LEVEL, TWO-SIDED TEST, * INDICATES SIGNIFICANCE (P<0.05))

Subjective OLS Items	**Overall satisfaction with lighting**
S1: Overall the lighting is comfortable (agree – disagree)	τ = 0.740, p=.000*
S2: The lighting is uncomfortably bright for the tasks that I perform (agree – disagree)	τ = -0.672, p=.000*
S3: The lighting is uncomfortably dim for the tasks that I perform (agree – disagree)	τ = -0.250, p=.005*
S4: The lighting is poorly distributed here (agree – disagree)	τ = -0.481, p=.000*
S5: The lighting causes deep shadow (agree – disagree)	τ = -0.094, p=.287
S6: Reflections from the light fixtures hinder my work (agree – disagree)	τ = -0.394, p=.000*
S7: The light fixtures are too bright (agree – disagree)	τ = -0.515, p=.000*
S8: My skin is an unnatural tone under the lighting (agree – disagree)	τ = -0.061, p=.488
S9: The lights flicker throughout the day (agree – disagree)	τ = -0.164, p=.062
How does light appear compared to other buildings (Worse – about the same – better – I don't know)	τ = -0.255, p=.002*
Attribute 1: Electrical lighting (Bad 1 2 3 4 5 Good)	τ = -0.557, p=.000*
Attribute 2: How bright are the lights? (Too much light 1 2 3 4 5 Does not get too bright)	τ = -0.356, p=.000*
Attribute 3: Glare from lights (High glare 1 2 3 4 5 No glare)	τ = -.367, p=.000*
Task 1: Reading from paper (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.324, p=.000*
Task 2: Reading from computer (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.580, p=.000*
Task 3: Writing on paper (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.347, p=.000*
Task 4: Typing on computer (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.578, p=.000*
Task 5: Drawing on paper (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.181, p=.026*
Task 6: Drawing on computer (Excellent - Pretty good – Neutral – Not very good – Poor – Not applicable)	τ = 0.385, p=.000*
How would you describe the amount of light (Much too bright – A bit too bright – Just about right – A bit too dim – Much too dim)	τ = -0.467, p=.000*
Glare case 1: Reflected glare from work surface (Not at all bothersome – Not very bothersome – Fairly bothersome – Bothersome – Not applicable)	τ = 0.290, p=.000*
Glare case 2: Glare from ceiling lights (Not at all bothersome – Not very bothersome – Fairly bothersome – Bothersome – Not applicable)	τ = 0.378, p=.000*
Glare case 3: Glare from task lights/desk lamps (Not at all bothersome – Not very bothersome – Fairly bothersome – Bothersome – Not applicable)	τ = 0.361, p=.000*
Glare case 4: Bright lights in workspace (Not at all bothersome – Not very bothersome – Fairly bothersome – Bothersome – Not applicable)	τ = 0.454, p=.000*
Glare case 5: Glare reflected in computer screen (Not at all bothersome – Not very bothersome – Fairly bothersome – Bothersome – Not applicable)	τ = 0.308, p=.000*
Would you say that the amount of light for the work you do is (excellent – good – fair – poor)	τ = 0.554, p=.000*

DISCUSSION

The significant correlations between overall satisfaction with lighting and the lighting statements indicated that the aspects 'brightness', 'distribution', and 'reflections' are considered as relevant. These aspects can be determined with the lighting parameters 'illuminance', 'uniformity', 'luminance distribution', 'glare', and 'luminance'. It is notable that statement 8 (i.e., my skin is an unnatural tone under the lighting) did not correlate significantly with overall satisfaction with lighting. This may be explained by the fact that only two questionnaires were filled in with 'agree' and therefore no significant correlation was found. The lighting conditions may have differed too less to get more discrepancy in the answers on this statement.

Based on the separate glare cases within the OLS, it was found that glare from bright lights influenced the overall satisfaction with lighting the most. Reflected glare from the work surface influenced overall satisfaction the least (i.e., the lowest correlation coefficient). All desks within the office space were white coated but were covered by a black desk pad. This black surface may have caused less reflections from the work surface.

All significant correlations between general health and the lighting descriptors disappeared when the correlation was controlled for overall satisfaction with lighting. This demonstrates the importance of people's satisfaction with lighting regarding their general health. Former studies also demonstrated this link between environmental satisfaction or satisfaction with lighting and self-reported general health [2][7].

The current study demonstrated that multiple subjective lighting characteristics influence overall satisfaction with lighting. Although The International Commission on Illumination (CIE) recommends researchers to investigate a wide variety of behavioral and health outcomes that might reasonably be affected by light exposure [8], often only one or a few lighting parameters were investigated in light effect studies. The CIE mentions that it is not impossible to write recommendations for healthful lighting; however, there should be a cautious and conservative approach in which the recommendations describe the total lit environment and not individual elements within it [8].

CONCLUSION

The office workers' satisfaction with lighting was significantly related to almost all OLS questions (except three statements including lighting descriptors). The large number of correlations within the OLS highlights that satisfaction with lighting concerns a combination of multiple lighting descriptors. Therefore, it is recommended to include a large variety of lighting characteristics (e.g., illuminance, uniformity, luminance distribution, glare, and luminance) when investigating occupant's satisfaction with lighting and/or occupant's general health.

This research shows the relevance of investigating overall satisfaction with lighting and its possible (beneficial) aftereffects. Including this knowledge in the lighting design process is important as office workers' satisfaction with lighting and their health will clearly be determined by the overall lighting situation provided at their workplace.

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Metrics to Predict Visual Discomfort in a Daylight Classroom

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Abstract—**This paper reports on a pilot experiment to test the applicability of a group of metrics to the prediction of visual discomfort in a daylit classroom environment. In particular, if the position in relation to the window has an impact in the way visual discomfort from glare is reported, and if the metrics predict that discomfort accordingly. Subjects (N=21) performed a typical classroom task in four different positions in a classroom and were asked to rate visual discomfort from glare via a questionnaire at the same time that luminance measurements were collected. Daylight Glare Probability (DGP) provided the best agreement with the reported glare overall, but the ratio between the maximum luminance to mean task luminance of 30:1 in the 172º field-of-view depicted most of the reported discomfort votes. The results show that glare is reported for situations of low vertical eye illuminance, as also found in previous studies.**

Index Terms-- **Classrooms, daylighting, DGP, glare, visual discomfort**

INTRODUCTION

There are several metrics in use for the analysis of visual discomfort from daylight glare, but no standard accepted method to assess it. The shortcomings of the existing metrics and the challenges regarding their applicability to daylighting design have been widely described [1] - [4] with an impact on design practice [5] - [7].

Several attempts to improve the base glare index formula created by Hopkins to the prediction of discomfort caused by daylight have been carried out since the actual glare index research started in 1960, culminating with the creation of the Daylight Glare Probability (DGP) [8], the first daylight-based glare index resulting from a large scientific investigation. After that, several field studies investigating visual discomfort in daylit spaces have emerged, making use of High Dynamic Range (HDR) luminance capture and large samples of human subjects.

It can be observed that the successful metrics differ in all these studies. Hirning et al. [9] conducted surveys in five open plan office buildings, and found the highest correlation between the subject's reporting of visual discomfort and a metric for the average FOV luminance. Konis [10] conducted observations in the core zones of an office building, and found the best correlation for the luminance contrast ratio metrics, particularly the window to task luminance ratio. Jakubiec et al. [11] surveyed occupants of a multi-story open plan studio space and found the best agreement for the presence of direct sunlight and for the computer screen luminance contrast ratio. Van Den Wymelenberg et al. [12] conducted a comprehensive study in a cellular-office space and found the highest correlation for vertical eye illuminance. All these studies took place in spaces where the arrangement of sitting and the distance and view direction in relation to the daylight source were more diverse than in the small cellular-office environment where the DGP research has been carried out. Only the study of Van Den Wymelenberg took place in a space with similar characteristics as the one used for the DGP.

This paper reports on a pilot study to test the applicability of a group of recently proposed visual discomfort and glare metrics to a classroom. Unlike the office space, luminance based metrics in classrooms are rarely investigated [13] and the authors are not aware that DGP has ever been investigated in this context. It is here investigated in particular, if a subject's position in relation to the window daylight source has an impact in the way visual discomfort from glare is experienced, and if the metrics predict that discomfort accordingly.

INVESTIGATED METRICS

The metrics that were investigated in this study were selected following a literature review on the subject of daylight glare and visual discomfort. It includes the DGP proposed by Wienold et al. [8], the luminance and FOV metrics proposed by Van Den Wymelenberg et al. [14] and the FOV metrics from the Dutch 'Programma van Eisen Frisse Scholen' [15] that offers guidance for the design of new schools in the Netherlands. The metrics, their glare threshold criterion and their interpretation in this study are described in Table I.

TABLE I. INVESTIGATED METRICS

Wienold et al, 2006 [8]	**Imperceptible**	**Noticeable**	**Disturbing**	**Intolerable**
DGP	≤ 0.35	0.35-0.40	0.40-0.45	≥ 0.45
Van Den Wymelenberg et al, 2015 [14]	**Comfort**	**Borderline**	**Discomfort**	
Mean window luminance (mean window L)	≤ 2000	2000 - 2500	≥ 2500	
Window luminance standard deviation (window L std dev)	≤ 2500	2500 - 4000	≥ 4000	
Mean FOV40º band luminance (mean FOV40º band L)	≤ 500	500 - 700	≥ 700	
Mean window luminance (L) to mean task luminance ratio (L)	≤ 22		> 22	
Rijksdienst Ondernemend Nederland, 2014 [15]	**Comfort**	**Comfort**	**Discomfort**	**Discomfort**
	Minimum	*Best*	*Minimum*	*Best*
Maximum task surroundings luminance to mean task luminance ratio (max FOV30º L to mean task L ratio)	≤ 10:1	≤ 3:1	> 10:1	> 3:1
Maximum periphery luminance to mean task luminance ratio (max FOV172º L to mean task L ratio)	≤ 30:1	≤ 10:1	> 30:1	> 10:1

EXPERIMENT DESCRIPTION

The experiment was conducted in a regular classroom at the Faculty of Architecture, TU Delft, over five days in October and November 2016, between the hours of 10:00 and 17:00. It was attended by n=21 subjects, between the ages of 20 and 44. The sky was overcast for four days and clear for one day. The room received daylight from only one side, through a full-length window to the Southwest. The blinds were kept open in all sessions. The electrical lighting was switched off. Each subject was asked to sit in four different positions in the room (Fig. 1), two near-window positions (P1 and P2) and two-near wall positions (P3 and P4) and perform a visual search test with Landolt rings. Luminance measurements were collected right after the subject finished the test, at the same time that the subject filled in the questionnaire. To obtain simultaneous luminance measurements and the subjective glare assessments, the camera was located with an offset of 0.75 m from the subjects sitting position.

The independent variable of this study is the daylighting conditions experienced by a subject in different positions in space. The variable position in space encompasses a variable view direction and a variable distance to the task surface, a screen located in the centre of the classroom. The dependent variables of the study are the subject's reporting of discomfort from glare via a questionnaire, and several visual discomfort metrics that were calculated from field-of-view (FOV) luminance images captured during the experiment.

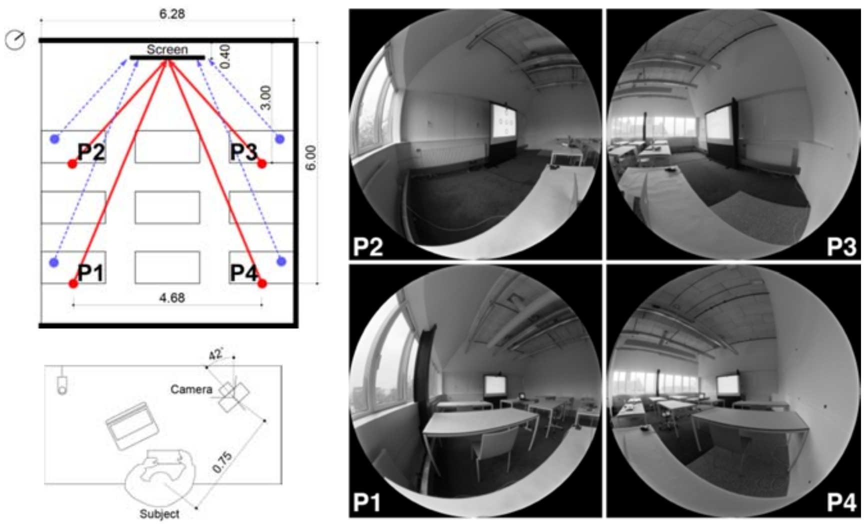

Figure 1. (Topf left) Layout of the classroom, showing position 1 (P1), position 2 (P2), position 3 (P3) and position 4 (P4). Hidden blue lines show the direction that the camera points to. Solid red lines show the direction that the subject looks at. (Bottom left) Layout of desk in position 3. (Right) Field-of-view from the 4 positions.

In the questionnaire, the subjects were asked: "When doing the test in this position, which degree of glare from the window have you experienced?". They were requested to respond using a 4-point rating scale as in [15]. The rating scale was described in the following way: "Imperceptible - I do not feel any discomfort", "Noticeable - This is a very slight discomfort that I can tolerate for approximately one day if I was placed in a desk under these conditions", "Disturbing - I can tolerate this discomfort for 15 to 30 minutes, but I would require a change in lighting conditions for any longer period" and "Intolerable - I can't tolerate these lighting conditions".

The luminance capture was done with a LMK luminance-calibrated photocamera [16] that is based on the Canon EOS70D and equipped with a sigma 4.5mm/2.8 EX DC Circular Fisheye lens. The system was calibrated according to [17] and has an uncertainty of +/-6%. The output of the system is a luminance image with a view angle of 172º and an equidistant projection. The captures were done via a sequence of 14 shots, spaced by 1EV at F22, with shutter speeds between 0.001″ and 8″. The absolute and contrast-based luminance metrics were calculated based on the data from the LMK luminance image files. These files were converted into the Radiance Synthetic Imaging System file format and used for the calculation of DGP and vertical eye illuminance with Evalglare v1.11. The threshold used for the detection of the glare source for the calculation of the DGP was 5 times the task luminance. Figure 2 shows a luminance image and resulting Evalglare output.

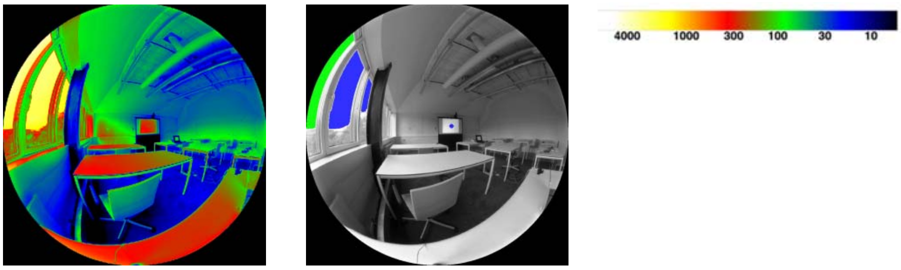

Figure 2. (Left) Luminance image and (Middle) the respective result from the Evalglare calculation. (Right) Luminance scale.

RESULTS OF THE METRICS

The average room luminances experienced by the subjects during the experiment were relatively low, ranging from 18 cd/m2 to 1592 cd/m2 and average window luminance ranging from 163 cd/m2 to 11030 cd/m2. Table I shows an overview of the results.

TABLE II. METRCIS RESULTS

Metrics results	**Position 1**		**Position 2**		**Position 3**		**Position 4**	
	Min	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***
DGP	0.02	0.39	0.01	0.42	0.01	0.49	0.01	0.37
Mean window L	229	3675	163	4368	194	11030	202	7388
Window L std dev	7	150	14	141	14	211	14	98
Mean FOV40º band L	56	1906	36	1795	34	2194	35	1868
Mean window L to mean task L ratio	1	10	1	14	2	21	1	16
Max FOV30º L to mean task L ratio	1	9	1	10	1	8	1	11
Max FOV172º L to mean task L ratio	5	2482	8	2689	5	1592	5	324

The values obtained for the *window L standard deviation* in this experiment were far too low in comparison to the ranges proposed in [14]. For this reason this metric was not further investigated.

RESULTS OF THE QUESTIONNAIRE IN RELATION TO THE METRICS

Most subjects reported some degree of glare from the window (57% of the total votes), with position 3 being the position where glare was most reported and position 2 being the position where glare was the least reported. However, the metrics generally predicted low levels of glare, particularly the DGP and some of the luminance ratios.

DGP values were generally much lower that what would be expected when subjects reported noticeable, disturbing and intolerable glare. In fact, 64% of the measurements in this study have delivered a DGP below 0.20, therefore outside the valid range of the metric. The vertical eye illuminance, extracted from the DGP calculation, follows the DGP trend with values below 2600 Lux (imperceptible glare threshold) occurring in 14% of the measured conditions. The subjects also reported glare for very low values of *mean window L to mean task L* ratios and for *max FOV30º L to mean task L* ratios. The reported imperceptible glare was well predicted by the *mean FOV40º band L*, but it was the *mean window L* and *max FOV172º L to mean task L* ratio the only metrics that did generally predicted both imperceptible and perceptible glare.

Reported imperceptible glare was correctly predicted by all metrics whereas reported noticeable, disturbing and intolerable glare was only predicted by some of the metrics. The analysis of the maximums of the glare predicted by the metrics when the subjects reported imperceptible glare gives some further information about the metrics predictability success (Table III).

TABLE III. MAXIMUM OF THE METRICS WHEN SUBJECTS REPORTED IMPERCEPTIBLE GLARE

Maximum of the metric for reported imperceptible glare	**Position**			
Metric	***P1***	***P2***	***P3***	***P4***
DGP	0.27	0.29	0.20	0.30
Mean window L	2796	1367	1194	7388
Mean FOV40º band L	1453	893	207	1059
Ratio mean window L to mean task L	6	6	4	11
Max FOV30º L to mean task L	5	3	1	3
Max FOV172º L to mean task L	70	52	21	70

Shaded area indicates the values that are above the imperceptible glare threshold of the metric.

It can be seen that, there was more tolerance to glare than what was predicted by some of the metrics in positions 1, 2 and 4. In position 1, subjects reported to be comfortable for a *mean window L* as high as 2796 cd/m2, for *mean FOV40º band L* of 1453 cd/m2 and for *max FOV172º L to mean task L ratio* of 70:1. In position 2, subjects reported to be comfortable for *mean FOV40º band L* of 893 cd/m2 and for *max FOV172º L to mean task L ratio* of 52:1. In position 4, subjects reported to be comfortable for *mean window L* as high as 7388 cd/m2, for *mean FOV40º band L* of 1059 cd/m2 and for *max FOV172º L to mean task L ratio* of 70:1. In position 3, all imperceptible glare votes fall within the metrics comfort or imperceptible glare ranges. However this is also the position where most glare was reported, suggesting that there is lower tolerance to glare in this position than what the metrics tend to predict.

COMPARISON OF METRICS BASED ON THE AGREEMENT BETWEEN THE REPORTED AND PREDICTED GLARE

To find out how the metrics compare to each other in terms of their success in predicting reported glare, an analysis was done, consisting of finding the percentage agreement between the reported degree of glare and the degree of glare predicted by the metrics. A 100% agreement means that the metric fully predicts the glare reported by the subjects. As the degree of glare is categorized in different ways by the different metrics, there was a need to group the results of the "reported glare" and of the "predicted glare" in the same number of categories, so the metrics would be comparable. Glare votes and metrics were grouped into two categories, a "comfort" category and a "discomfort" category, as shown in Table IV. It is important to stress that in the context of this paper, "comfort" and "discomfort" refer to the comfort and discomfort caused by window glare solely.

If we consider that reported noticeable glare should be integrated in a general comfort category for the purpose of this comparison, the results show that overall the DGP is the metric that is in best agreement with the reported glare (Table V). However, when we look at the percentage agreement for the comfort and discomfort categories separately (Table VI), it can be seen that "comfort" is much more easily predicted by the metrics than "discomfort", with metrics like DGP, the *mean window luminance to mean task luminance ratio* of 22:1 and *max FOV30 luminance to mean task luminance ratio* of 10:1 predicting 100% of the comfort votes but 0% of the discomfort votes in some or all positions. The *max FOV172º luminance to mean task luminance* ratio seem to be the most successful of the metrics at predicting "discomfort", with the less stringent ratio of 30:1 doing slightly better overall.

Position 4 also emerges as the position where "discomfort" is less well predicted by the metrics. Low levels of glare were generally reported in this position, with a high percentage of noticeable glare votes but almost no disturbing or intolerable glare votes. This is the position that is most deep in the room in relation to the task and to the window and where less influence of daylight glare source could be expected. More extreme sky conditions are required in order to understand the impact of window glare in this position.

TABLE IV. GROUPING STRATEGY FOR GLARE VOTES AND METRICS

Grouping of votes and metrics	**Comfort**		**Discomfort**	
Glare votes:	***Imperceptible***	***Noticeable***	***Disturbing***	***Intolerable***
DGP	Imperceptible	Noticeable	Disturbing	Intolerable
Absolute luminance metrics	Comfort	Borderline	Discomfort	
Luminance-contras ratio metrics	Comfort		Discomfort	

TABLE V. PERCENTAGE AGREEMENT BETWEEN REPORTED GLARE AND GLARE PREDICTED BY THE METRICS

Percentage agreement (%)	**Position**				
Metrics	***P1***	***P2***	***P3***	***P4***	***All positions (Avg.)***
DGP	77	81	77	96	83
Mean window L	86	86	81	71	81
Mean window L to mean task L (22:1)	76	76	71	95	80
Max FOV30º L to mean task L (10:1)	76	76	71	90	78
Max FOV30º L to mean task L (3:1)	76	81	62	90	77
Mean FOV40º band L	76	81	72	76	76
Max FOV172º L to mean task L (30:1)	67	81	81	71	75
Max FOV172º L to mean task L (10:1)	43	52	67	52	54
All metrics (Avg.)	72	77	73	80	75

TABLE VI. PERCENTAGE PREDICTED GLARE BY THE METRICS, WITHIN THE COMFORT AND DISCOMFORT CATEGORY

Percentage predicted comfort and discomfort (%)	**Position**							
	P1	***P2***	***P3***	***P4***	***P1***	***P2***	***P3***	***P4***
Metrics	***Comfort***	***Comfort***	***Comfort***	***Comfort***	***Discomfort***	***Discomfort***	***Discomfort***	***Discomfort***
Max FOV172º L to mean task L (30:1)	62	87	80	70	79	58	83	100
Max FOV172º L to mean task L (10:1)	25	43	60	50	100	79	83	100
Mean window L	87	100	86	75	79	42	66	0
Mean FOV40º band L	74	87	86	80	79	58	33	0
DGP	100	100	100	100	0	20	17	0
Max FOV30º L to mean task L (3:1)	87	100	86	95	42	21	0	0
Mean window L to mean task L (22:1)	100	100	100	100	0	0	0	0
Max FOV30º L to mean task L (10:1)	100	100	100	95	0	0	0	0
All metrics (Avg.)	79	90	87	83	47	35	35	25

CONCLUSION

This document reports on a pilot study to test the applicability of a group of metrics to the prediction of visual discomfort from glare in a classroom environment. In this experiment, that took place in a real classroom with a mock set-up, it was investigated how these metrics predict the discomfort reported by n=21 subjects when they sit in four different positions in space, doing a classroom typical activity.

Subjects reported they felt some degree of glare from the window in 57% of the tested situations, with position 3 (near-wall, front) being the position where more glare was reported and position 2 (near-window, front) being the position where less glare was reported. The results show that there is less tolerance to glare in position 3 and that there is more tolerance to glare in positions 1 and 4 (near-window, back and near-wall, back) than what was predicted by most metrics. The fact that in position 3, the subject is facing the window more directly, and that the task surface is fairly close to the window due to the view direction, might explain why there is lower tolerance to glare in this position. The results also show that glare is reported for conditions of low *vertical eye illuminance*, with an effect on DGP. The calculated v*ertical eye illuminance* was only above the upper imperceptible glare threshold of the metric in 14% of the tested conditions, while participants reported feeling glare in 57% of these conditions. It is important to state however that a lower threshold for the detection of the glare source than the one that was chosen for the calculation of the DGP in this study (5 times the task luminance) might have delivered a better result, an aspect that will be investigated in future studies.

A percentage agreement analysis was done to find out how the metrics compared to each other in terms of their success in predicting the degree of glare reported by the subjects. DGP showed a higher agreement with the reported glare overall but failed to predict most of the discomfort votes. The *max FOV172º luminance to mean task luminance* ratios was the most successful of the metrics at predicting the discomfort votes (around 80%), with the less stringent ratio of 30:1 doing slightly better overall. Position 4 was found to be as the position where "discomfort" is less well predicted by the metrics. This is the position that is most deep in the room in relation to the task and to the window and where less influence of daylight glare can be expected. It is expected that a future experiment under more extreme sky conditions will help in the understanding of the actual impact of daylight glare in this position.

A larger sample of subjects and a wider range of sky luminance conditions will be required in future experiments so more robust statistical analysis methods can be used and more definite answers can be provided.

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Modelling the Luminance Coefficient Uncertainty Using a Bidirectional Goniophotometer Facility

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***Abstract*—The luminance coefficient q is used to describe the measurement model and its accompanied uncertainty in the measurement of a scattering material using the bidirectional goniophotometer facility at the Department of Lighting Technology of Technische Universität Berlin.**

***Index Terms*—Bidirectional Goniophotometer Luminance-Coefficient Measurement Uncertainty**

INTRODUCTION

Modern light-directing daylight systems combine the advantages of directing light into the depth of the room with coincidental sun and glare protection. This can be realized, for example, by special shaping of lamellae, with which an incidence angle-dependent light coupling is achieved. The direct irradiation is to be prevented for high solar elevation angles, as they occur at noon and especially during the summer. This can be combined with good daylight supply into the room. An outlook through the lamellar system is usually ensured, which can improve the well-being of the person.

For planning the daylighting detailed knowledge about the distribution of the light into the interior, i.e. the transmission characteristics, is necessary for different angles of light incidence. The measurement of the distribution of the luminance coefficient q is the task of the bidirectional goniometer facility, which was developed at the lighting technology department of TU Berlin.

DESCRIPTION OF THE MEASURING SYSTEM

The bidirectional goniometer facility is constructed in a completely darkened room in order to ensure that no light other than that emitted by the projector hits the sample. To avoid residual light caused by reflections, all room surfaces are blackened.

The experimental setup and instrumentation used to disseminate the luminance coefficient of a daylighting system under test is shown in Fig. 1. The projector carriage accommodates the lighting system consisting of a high intensity source, 24V / 250W quartz tungsten halogen lamp combined with a mirror and a collimator lens. Through the lens, the light is focused and aligned onto the sample. This allows a measurement similar to direct sunlight. The projector carriage moves on a fixed semicircular guide rail. Thus, sun elevation angles γ_1 of −73° to +75° can be simulated. For the simulation of diffuse sky light, an additional lighting device is available, which uses a back-lit diffuse transmitting hemisphere of acrylic glass. With that the sample can be lit with semi- or quarter hemispheric light. The halogen lamp does not represent the spectral distribution of daylight, its benefit lies in a most stable illuminance. The spectral characteristics of the daylight systems are not measured in this facility.

The entire device for fixing and rotating the sample to be measured is referred to as a sample holder. The sample is attached with various joints bolted to the base plate. An aperture is attached to the front of the holder. Available diameters are 100 mm, 150 mm and 200 mm. In order to minimize stray light effect a good shielding between the source and the detectors is achieved by attaching a 3m x 3m black fabric. The sample holder can be adjusted to incident azimuth angles α_1 from −97 ° to + 97 °.

The movable measuring arc positions the sensor ribbon and the camera carriage at the azimuth angle α_2. The sensor ribbon moves the 18 sensors mounted on it in order to be able to measure at the different elevation heights γ_2. The first 17 sensors are mounted on the belt at 10° intervals; the 18th sensor is attached at a smaller distance of ca. 7° due to the mounting suspension of the sample holder and the measuring arc.

These 18 broadband silicon detectors are attached with a V(λ) filter. The photo current of a detector is converted into an output voltage by an impedance converter integrated in the housings of the photometer heads. The voltage is measured using a Keithley 2700 digital multimeter with scanner inputs. For increased stray light suppression additional tubes with a diameter of 13 mm and length from 27 mm to 92 mm depending on elevation height are attached.

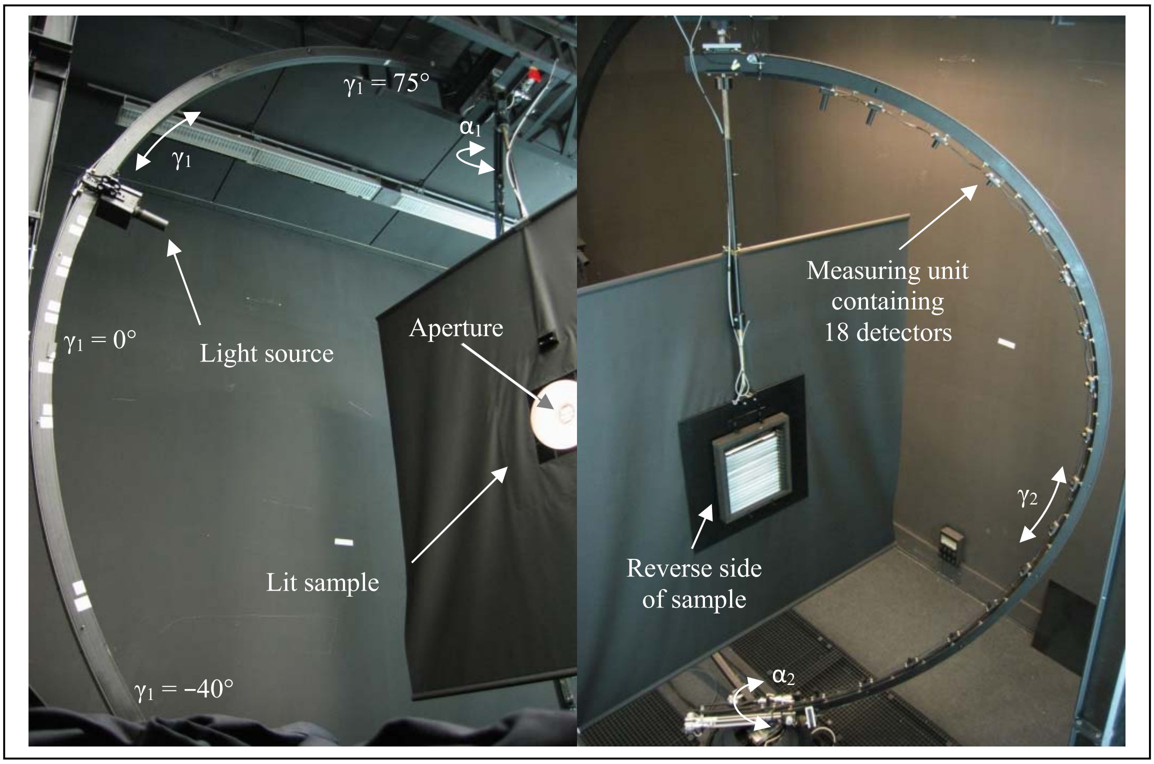


Figure 1. Bidirectional goniophotometer at TU Berlin; left: front view, right: view from the back

DESCRIPTION OF THE MEASURING PROCEDURE

For the determination of the distribution of the luminance coefficient, the sample is successively constantly illuminated at different angles of incidence. During each measurement the source is fixed and the photodiodes can rotate altogether around the lit portion of the material under test.

The luminance coefficient is defined as the quotient of the luminance L of a scattering material in a given direction in cd/m², related to the illuminance E in lx on the medium for a given light incidence.

$$q = L/E_1 \tag{1}$$

The luminance L is calculated by measuring the illuminance $E_{Detector}$ respectively the sensor voltage at a known and constant distance r = 2.5 m and sample area A_{Sample} = 80 cm² (Fig. 2).

$$L = \frac{E_{Detector} \cdot r^2}{A_{Sample} \cdot \cos i_2} \tag{2}$$

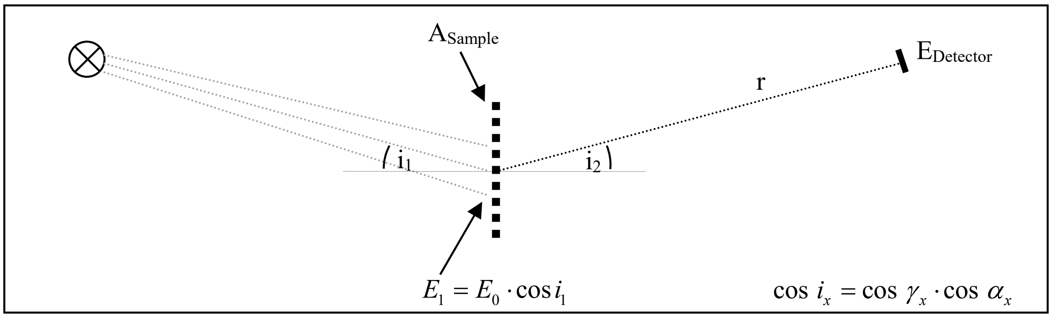


Figure 2. Derivation of the luminance coefficient

The sensors are calibrated using a reference opal glass with a known distribution of the luminance coefficient. This distribution has previously been determined on a swivel arm photometer described in [1]. The rotationally symmetrical distribution was tested at the bidirectional goniometer facility.

This reference sample is constantly illuminated at a perpendicular incidence angle. With that it is sufficient to measure the photo voltage of the detector at a certain emergent angle. This photoelectric voltage is then related to the known luminance coefficient of the reference sample associated with this angle and a calibration factor is determined. As long as the illuminance E_0 on the sample does not change, the q value can be determined directly. Changes in the illuminance on the sample due to aging of the light source can be compensated by measurement and input in the measuring software.

The transmittance can be calculated by doing the integration of the luminance coefficient values of the hemisphere (3). The result can be compared with measurements done using different methods, e.g. an integrating sphere.

$$\tau(\gamma_1,\alpha_1) = \int_{\alpha_2=\frac{\pi}{2}}^{\frac{3\pi}{2}} \int_{\gamma_2=-\frac{\pi}{2}}^{\frac{\pi}{2}} q(\gamma_1,\alpha_1,\gamma_2,\alpha_2)\cdot\cos(\alpha_2)\cdot\cos^2(\gamma_2)\cdot d\gamma_2\cdot d\alpha_2 \tag{3}$$

UNCERTAINTY

The associated uncertainty must be quoted whenever the results of a measurement are reported. Uncertainty analysis is thus a fundamental part of metrology. Calculating the associated uncertainty in luminance coefficient measurement results is important for repeatable and comparative measurements for scattering material products in comparison with standard. Also, a better evaluated process contributes to greater credibility and consistency of the measurement results of the tested material.

Evaluation of the accompanied uncertainty is done using the Guide to the expression of Uncertainty in Measurement (GUM) method of the GUM Workbench software. This method is adopted and described in detail by the International Organization for Standardization (ISO) [2], [3].

According to the GUM, the first step for evaluating the measurement uncertainty is defining the measurand. A measurand Y, in this case the value of q, is not measured directly, but is determined from N other input quantities X_1, X_2, … X_N through a function f:

$$Y = f(X_1, X_2, \ldots X_N) \tag{4}$$

The second step is the evaluation of the uncertainty of each input quantity. Here the GUM distinguishes between two types of uncertainty evaluation: The evaluation of the uncertainty through a statistical analysis of series of observations, the so-called Type A evaluation, and the evaluation of the uncertainty by means other than the statistical analysis, named Type B evaluation. A type A evaluation of the standard uncertainty is obtained generally by means of repeated observations of the input quantity X, where the distribution of the random errors is obtained through its standard deviation. This means that the standard uncertainty u_A due to the repeatability of the measurement is estimated by the experimental standard deviation of the mean value, that is:

$$u_A(x) = s(\bar{x}) = \frac{1}{\sqrt{n}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2} \tag{5}$$

Type B evaluation of the standard uncertainty refers to any method different from the statistical analysis. It is based on scientific judgment using all the relevant information available; e.g. manufacturer's specifications, previous measurement data, data provided in the calibration and other reports etc. The probability distribution may be Gaussian, rectangular or triangular.

The combined standard uncertainty $u_c(y)$ is obtained by combining the individual standard uncertainties u_i, these can be of evaluation type A or type B, that is:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \tag{6}$$

The uncertainty of the measurement result is frequently expressed as an expanded uncertainty U(y), and is obtained by multiplying $u_c(y)$ by a coverage factor k, that is:

$$U(y) = k \cdot u_c(y) \tag{7}$$

The coverage factor k(v, p) depends on the "degree of freedom" v of the output quantity and the confidence levels p wished or required in the application. A confidence level p of 95.45 % (k=2) is recommended in most fields.

According to the GUM, in (4) a model in the form of a mathematical equation derived from (1) describes the luminance coefficient measurement of the scattering material under test. With that the various factors that contribute uncertainty to the measurement are taken into account:

$$q_t = \left[\frac{q_s}{U_s - U_{sd}} (E_s - E_{sd})(\cos\gamma_2 \cdot \cos\alpha_2)(\cos\gamma_1 \cdot \cos\alpha_1) \cdot \frac{U_t - U_{td}}{E_t - E_{td}} (E_s - E_{sd})(\cos\gamma_2 \cdot \cos\alpha_2)(\cos\gamma_1 \cdot \cos\alpha_1) \right] \cdot f_c \tag{8}$$

where

q_t: Luminance coefficient of test material, sr^{-1}.

q_s: Luminance coefficient of standard material, sr^{-1} (Certified).

U_s, U_t: Photometer signal from the standard and test, volt.

U_{sd}, U_{td}: Photometer dark signal from the standard and test, volt.

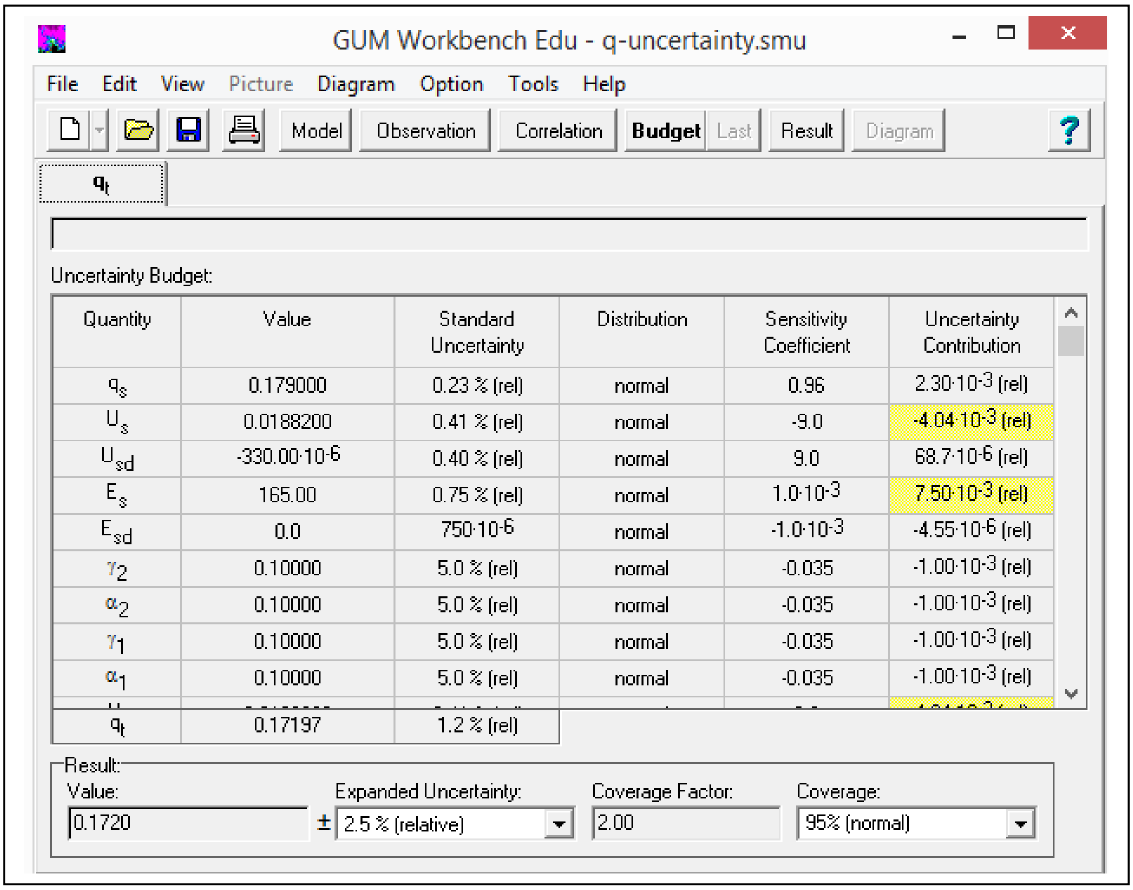
E_s, E_t: Illuminance in the standard and test measurement, lux.

E_{sd}, E_{td}: Illuminance dark signal in the standard and test measurement, lux.

γ_2, α_2, γ_1, α_1: Azimuth and height angles to determine the incident and observed angles (i_1, i_2), degree.

f_c: Correction factor due to distance, temperature etc.

The expanded standard uncertainty is evaluated by combining the individual standard uncertainties and using the GUM workbench program with an estimated result equal to ±2.5 % (k = 2). See Fig. 3 for details.



Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution
q_s	0.179000	0.23 % (rel)	normal	0.96	$2.30 \cdot 10^{-3}$ (rel)
U_s	0.0188200	0.41 % (rel)	normal	-9.0	$-4.04 \cdot 10^{-3}$ (rel)
U_{sd}	$-330.00 \cdot 10^{-6}$	0.40 % (rel)	normal	9.0	$68.7 \cdot 10^{-6}$ (rel)
E_s	165.00	0.75 % (rel)	normal	$1.0 \cdot 10^{-3}$	$7.50 \cdot 10^{-3}$ (rel)
E_{sd}	0.0	$750 \cdot 10^{-6}$	normal	$-1.0 \cdot 10^{-3}$	$-4.55 \cdot 10^{-6}$ (rel)
γ_2	0.10000	5.0 % (rel)	normal	-0.035	$-1.00 \cdot 10^{-3}$ (rel)
α_2	0.10000	5.0 % (rel)	normal	-0.035	$-1.00 \cdot 10^{-3}$ (rel)
γ_1	0.10000	5.0 % (rel)	normal	-0.035	$-1.00 \cdot 10^{-3}$ (rel)
α_1	0.10000	5.0 % (rel)	normal	-0.035	$-1.00 \cdot 10^{-3}$ (rel)
q_t	0.17197	1.2 % (rel)			

Figure 3. Evaluated expanded uncertainty by GUM workbench program in measured (q) value using a Bidirectional Goniophotometer Facility.

EXAMPLE OF MEASUREMENTS

Results of the luminance coefficient measurement of two different types of louvre blinds are shown in Fig. 4. The incident angle is γ_1=30°, α_1=−30° with observation angles γ_2 from −90° to 90° and α_2 from 90° to 270°. The results are obtained using specially programmed computer software to process the measured values.

It is clear to see how the two louvre blinds differ. The lamellas whose measured values are shown on the left side are suitable for directing sunlight into the depth of the room. This type of lamella is intended for use in the upper window area. The lamellas whose measured values are shown on the right side direct the light steeply to the ceiling. The q values are significantly lower, that is, a smaller part of the light is transmitted. This ensures glare and sun protection. These slats are inserted in the lower window area.

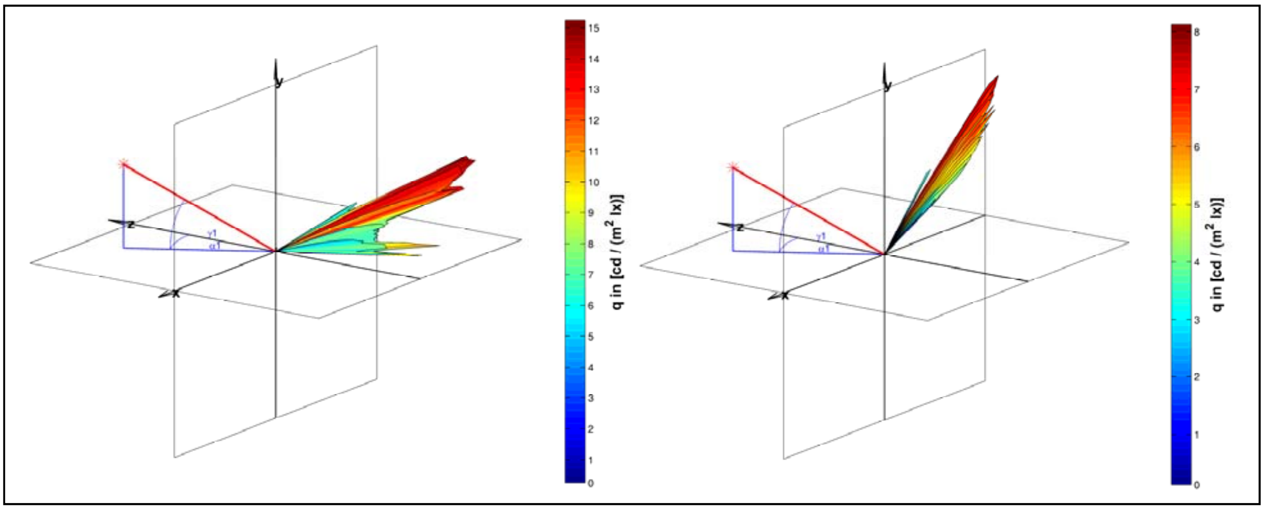


Figure 4. Examples of measurement data for two different types of light redirecting louvre blinds;
left: type used for directing light in the depth of the room, right: type used for glare protection by directing light to the ceiling

Conclusion and Outlook

The importance of luminance coefficient measurement is highlighted, and a measuring technique is briefly described. Attention is focused on the scattering surface under investigation and on the errors which can appear in the assessment of the performance which are realized by the bidirectional goniophotometer facility. A major issue with testing and the resulting accuracy is the uncertainty of the complete process. The uncertainty contribution in the luminance coefficient measurement is calculated by the GUM method using the GUM workbench software and is equal to 2.5 % at k=2.

At the moment the goniometer facility is able to determine the luminance coefficient for transmission of scattering materials. Using the silicone detectors for reflectance measurements would lead to much too high values due to the method of lighting larger areas of the sample holder for a most uniform illuminance on the probe. The next step will be to attach a luminance camera onto the measuring arc, with which the area to be measured can be selected. With this setup measurements of the reflection characteristics of samples of road surfaces will be possible.

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The New Generation of an Artificial Sky: Simulating Various Overcast Sky Conditions

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***Abstract*—During 1994 – 98 at the CIE IDMP Bratislava one minute illuminance and zenith luminance were gathered. Their analyses have detected groups of overcast ISO/CIE sky types 1 – 6. The renovation of the illumination system in the ICA SAS artificial sky was upgraded using new dimmable LED lamps enabling to simulate several overcast sky luminance distributions in cd/m^2 and absolute horizontal illuminance levels in kilolux at the ground.**

The artificial sky calibrations include checks of luminance patterns with standard luminance gradations using fish-eye images taken by a calibrated camera. Measured zenith luminance with horizontal illuminance were determined as reference levels to find the range of Sky Intensity Scale Factors which enable to determine skylight illuminance in klx depending on solar altitudes. Contribution discusses possibilities to simulate daylight standard conditions in an artificial sky considering current trends, i.e. verification daylight measurements in relative units and also in physical units lux and cd/m^2.

***Index Terms*-- Daylighting, artificial sky, model measurements.**

INTRODUCTION

Totally diffuse overcast skies under dark and rainy situations were historically considered as the worst feeble daylight sources without any sunlight and with low luminance distributions resulting in minimal horizontal illuminance available outdoors especially during sunrise or low solar altitudes. In early daylight photometry these were assumed to have equally uniform and unity luminance all over the whole the sky vault as defined, [1]. After the first luminance measurements during the first half of the 20th Century [2] the gradually increasing luminance pattern from horizon to zenith 0.33:1 was standardised in [3] while recently a set of fifteen standard skies were adopted in [4] and [5] containing homogeneous sky types from overcast, cloudy to clear skies under different turbidity conditions.

Due to actual low visibility, environmental reasons as well as energy saving policies worst overcast skies are accepted as critical criteria for window design and daylighting of the interior working places and therefore previously were preferred for the simulation in artificial skies for research on architectural models using the 20th Century equipment [6] and experiments were done under stable chosen overcast sky simulations in relative terms using Sky or Daylight Factors.

Recently new accurate measurements of the extraterrestrial solar irradiance and illuminance incoming towards the Earth globe enabled to define the Luminous Solar Constant 133.8 klx [7], transmittance and scattering of solar beams as well as both the gradation and indicatrix functions determining the sky luminance patterns. At the same time regular measurements of daylight illuminance and zenith luminance in minute steps worldwide organized under the CIE International Daylight Measurement Programme (IDMP) with sky scanner data and fisheye photo images were analysed to determine typical daylight sources in absolute physical units [8] and [9].

New theoretical findings [4] and [5] and new LED lighting systems allow to simulate daylight sources also in the laboratory under the artificial sky even in absolute physical units. Since 1974 [10] is in operation the hemispherical artificial sky in the Institute of Construction and Architecture Slovak Academy of Sciences (ICA SAS). During its renovations the old incandescent reflectors were removed and a new LED lighting system was installed while currently the sky is calibrated with respect to [4] and [5] recommendations.

VARIOUS OVERCAST SKY SITUATIONS MEASURED DURING THE CIE IDMP

When analysing five year data gathered during 1994-1998 at the Bratislava CIE IDMP general station under various overcast sky conditions and different solar altitudes [11] the following circumstances were discovered:

- Evaluating 5-minute data was done according to the categorisation parameter $L_{vZ}/E_{v,d}$ (i.e. zenith luminance to horizontal diffuse sky illuminance) to define values measured within the 2.5% strip region belonging to ISO/CIE sky types 1, 3 and 5 as well as for those identifying ISO/CIE sky types 2, 4 and 6. Following the survey based on the parameters $L_{vZ}/E_{v,d}$ and solar altitude γ_S the disputable cases close to the intersection regions with other sky types within solar altitudes 37-40 degrees and 54 - 60 degrees were excluded.
- The number of overcast sky groups within the ISO/CIE sky types 1 – 6 were selected in the prevailing small strips ± 0.01 of $E_{v,d}/E_{vo,h}$ (i.e. horizontal diffuse sky illuminance at ground level to horizontal extraterrestrial illuminance) separating very often occurring cases from infrequent ones. So the total number of occurring cases in every sky type characterizes the frequency of this sky type in Bratislava during the five years period, while the most often occurring atmospheric transmittance associated with a certain ISO/CIE sky type is indicated by the highest number of cases within the ± 0.01 strips of $E_{v,d}/E_{vo,h}$ in Table 1.

TABLE I. OCCURRENCE OF FIVE MINUTE OVERCAST SKY CASES IN A FIVE YEARS PERIOD AT BRATISLAVA.

ISO/CIE Overcast sky	**Number of all cases**	**Number in $E_{v,d}/E_{vo,h}$ range**			
No	***Total***	***0.05±0.01***	***0.1±0.01***	***0.15±0.01***	***0.3±0.01***
1	9716	300	600	450	75
2	12432	400	630	520	140
3	11506	275	500	360	205
4	8042	130	210	255	215
5	5777	50	140	170	180
6	5415	75	115	100	160
Sum	52888	1230	2195	1855	975

It is evident that for Bratislava are characteristic ISO/CIE sky types 2 with the highest occurrence number average of all overcast sky types 1 – 6 and are most frequent with a very low transmittance of the atmosphere with a thick overall cloudiness of 0.1, i.e. around 10% of the incoming extraterrestrial flux passing the fictitious horizontal plane at the outer atmospheric border.

The sky luminance patterns of each ISO/CIE overcast sky is different, but sky types 1, 3 and 5 because of uniform unity scattering have only different gradations from horizon to zenith and have the same luminance around all azimuth sky circles, while sky types 2, 4 and 6 besides gradation differences are characteristic due to small indicatrix changes depending on the hidden sun position defined by the momentary solar altitude and azimuth.

INOVATION OF THE ARTIFICIAL SKY INCLUDING THE LED LIGHTING SYSTEM

As already mentioned in the general paper [12] all ISO/CIE overcast skies have a perfect even and smooth luminance patterns without any extreme or patchy luminance irregularities because the solar position and sun beams are either absolutely hidden or diffusely dispersed by the overcast cloud layers. During the renovation of the Bratislava artificial sky several new features applying the LED luminaire system were already described [13] including the placement and direction of 58 LED reflectors equipped by diffuse filters enabling rough conditions to simulate various sky luminance patterns.

Specific conditions were documented during the artificial sky calibration analysing the fish-eye photo images. For the case of Bratislava artificial sky simulation in 2016 the equisolid projection of the camera lens was tested [14]. Overall luminance calibration was done in the laboratory of the Faculty of Electrical Engineering and Communication University of Technology in Brno [15]. To avoid vigneting effect of the fisheye lens the smallest aperture was set [16] and the lens cap and the adapter ring were removed when taking all images.

Thus during the first step of the calibrating procedure the new LED lamps with diffuse filters were tested in the artificial sky and using the DALI dimming adjustments were set to simulate the gradation and indicatrix characteristics of each of the six ISO/CIE overcast skies. Utilizing the DALI possibilities to set the overcast sky luminance patterns the overall scaling of the rising luminance followed in accordance to the ratios $E_{v,d}/E_{vo,h}$ in Table 1. Evidently, the darkest illuminance levels occur under sky types 1 and 2 in the range $E_{v,d}/E_{vo,h}$ = 0.05 – 0.15 with the maximal frequency 0.1. Even sky type 3 is still characteristic with this maximal frequency 0.1, but a relative rise towards 0.15 is already noticeable, which becomes the frequency for ISO/CIE sky type 4.

Under the uniform sky type 5 and 6 are remarkable brighter skies with $E_{v,d}/E_{vo,h}$ = 0.25 to 0.30. So, the DALI setting of the calibrated sky patterns should also follow these slight changes in brightness from darker to brighter illuminance levels.

CALIBRATION OF OVERCAST SKIES

Of course the obvious priority should be given to standardised sky types especially the CIE Overcast Sky type 1 not only to reproduce its gradually increasing luminance pattern but also frequent illuminance levels on the unobstructed exterior horizontal ground. After long term one-minute data gathered at the CIE IDMP Bratislava general station based on evaluated measured illuminance values during first five years 1994 – 1998 [11] indicate that frequent sky type 1 conditions occurred when $E_{v,d}/E_{vo,h}$ = 0.1 even while the range corresponded approximately with the ratio 0.05 – 0.2 with the mean 0.154 and mode 0.094 exactly. Due to the occurrence of sky type 1 mainly during the winter season the largest number of such cases were under the solar altitude 28° especially during its whole day presence. Most frequently the zenith luminance was in the range L_{vZ} = 1 - 2 kcd/m^2 and exterior horizontal illuminance were around $E_{v,d}$ = 6.3 klx [2]. If in accordance to other sky types, the assumed solar altitude γ_s would be 20° with the $E_{v,d} \approx$ 4.5 klx or at solar altitude γ_s = 30° the exterior illuminance could be $E_{v,d} \approx$ 6.7 klx. However, the ratio $L_{vZ}/E_{v,d}$ was close to 0.408.

Quite similar conditions are associated with ISO/CIE sky types 3 and 5 but except the extended gradation the ratios $E_{v,d}/E_{vo,h}$ are slightly higher. For the sky type 3 the most frequent $E_{v,d}/E_{vo,h}$ = 0.1 – 0.125 within the range 0.08 – 0.2 with a mean 0.186 and mode 0.114.

For the sky type 5 representing the Lambertian luminance distribution a special attention has to be given for its uniformity although it is not as frequent as the rest of overcast sky types in the Bratislava 1994-98 set. However, these foggy overcast skies are rather brighter in the wider range $E_{v,d}/E_{vo,h}$ = 0.1 – 0.4 with a mean 0.219 and mode 0.226. In spite of the perfect uniformity the luminance level is dependent on solar altitude in the wintertime $\gamma_s \leq 35°$ with low zenith luminance L_{vZ} under 5 kcd/m^2 and recommended $E_{v,d}/E_{vo,h}$ = 0.2, thus $E_{v,d} \approx$ 15 klx in wintertime, but $L_{vZ}/E_{v,d}$ was close to $1/\pi$ = 0,3183.

In case of the overcast artificial sky calibration it is important to note that the gradation and indicatrix distributions as well as $L_{vZ}/E_{v,d}$ ratios are not dependent on solar altitude, but all are simultaneously linked with the intensity level expressed by the $E_{v,d}/E_{vo,h}$ ratios determining the transmission, i.e. penetration of the densely overcast atmosphere. Therefore it is possible to choose the basic reference L_{vZ} and $E_{v,d}$ level at any solar altitude in the calibration to decide the relative skylight Intensity Scale Factor for the particular ISO/CIE standard sky type. When such a reference scaling is valid as calibrated for a specific sky type under a specific solar altitude and the actual or typical reference $E_{v,d}/E_{vo,h}$ precisely calculated, while the calibrating $E_{v,dm}$ is measured, then the reference diffuse/skylight Intensity Scale Factor *RISFd* is

$$RISFd = E_{v,d} / E_{v,dm} \tag{1}$$

which means that the real exterior illuminance $E_{v,d}$ is reduced in its intensity in relation to

$$E_{v,d} = E_{v,dm}\ RISFd \tag{2}$$

However, for the calibrated reference point the value of *RISFd* = 1 could be best to find for the chosen or typical ratio *RISFd* = $E_{v,d}/E_{vo,h}$ and when the gradation and indicatrix function for the specific ISO/CIE standard sky type was calibrated first, thus the *RISFd* = 1 has to be if

$$\gamma_{s,c} = \arcsin \frac{E_{v,dm}}{133800\ E_{v,d} / E_{vo,h}} \tag{3}$$

Thus a calibrating diagram for any solar altitude in the range 0 – 65° can be calculated defining the diffuse Intensity Scaling Factor which is given by the ratio of the actual solar altitude to the sine of the reference point *RISFd* = 1, i.e

$$ISFd = \frac{\sin \gamma_s}{\sin \gamma_{s,c}} \tag{4}$$

while the scale *ISFd* in integers can be calculated for any solar altitude γ_s as:

$$\gamma_s = \arcsin\left(ISFd \sin \gamma_{s,c}\right) \tag{5}$$

as applied for the scale in Fig. 1.

Which means that the real horizontal illuminance $E_{v,d}$ in lux is

$$E_{v,d} = ISFd\ \ E_{v,dm} \qquad \text{[lx]} \tag{6}$$

EXAMPLE OF CALIBRATING ISO/CIE SKY TYPE 5

In the first step the very even luminance distribution on the whole sky vault was adjusted using the DALI dimming system as roughly documented in Fig. 2.

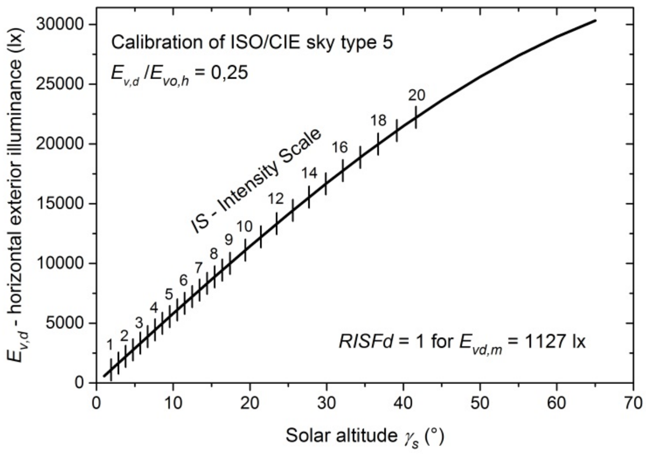

Figure 1. Calibration diagram for ISO/CIE sky type 5 defining intensity scale

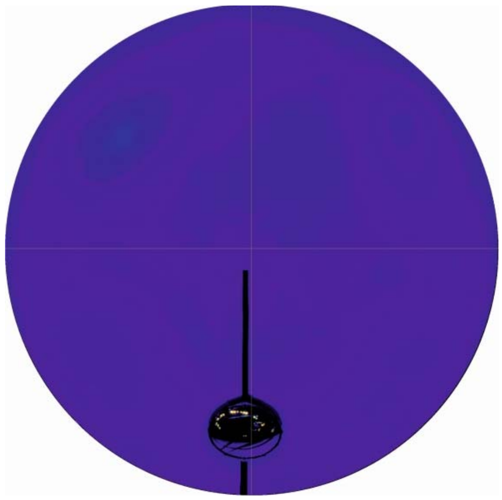

Figure 2. Fisheye luminance map of ISO/CIE sky type 5 in the ICA SAS artificial sky.

Using the program ASC V2.2 [17] further test of the gradation and indicatrix distributions are documented in Fig. 3 and Fig. 4.

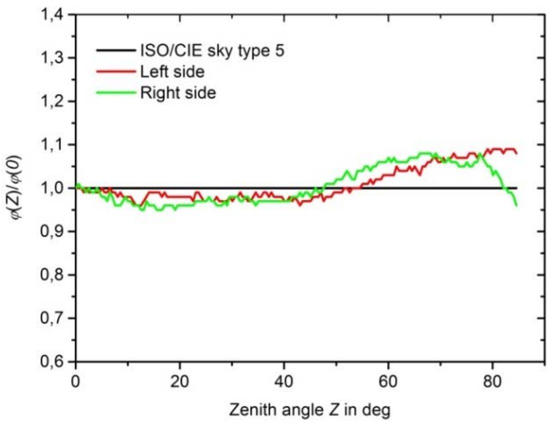

Figure 3. Theoretical and measured gradation function in the ICA SAS artificial sky.

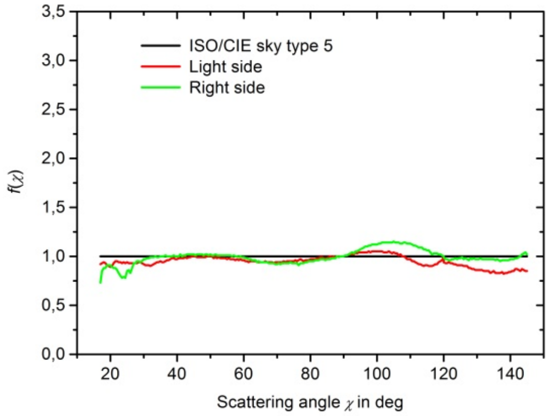

Figure 4. Theoretical and measured indicatrix function in the ICA SAS artificial sky.

Average deviation 3.05% between theoretical sky luminances and their simulation documented from the fisheye image was calculated from 323 sky elements. Zenith luminance 354,17 cd/m^2 was measured by calibrated digital camera while value of 354,9 cd/m^2 was measured by luminance meter Minolta Konica 1° and $E_{v,d}$ = 1127 lx was measured by illuminance meter Konica Minolta T-10A then measured ratio of $L_{vz}/E_{v,d}$ is 0.3149 very close to the theoretical value 0.3183.

CONCLUSIONS

The renovated Bratislava artificial sky will serve for daylight research or tests of architectural models as an accurate laboratory instrument modelling skylight and/or sunlight conditions under the whole range of ISO/CIE sky type standards with stable and accurately simulated frequent circumstances world-wide either under standard overcast, sunless cloudy or clear skies without or with sunlight with the possibility to simulate by the real sky types standardised by ISO/CIE. Contrary to older artificial skies the relative Daylight Factor evaluation system is replaced by luminance and illuminance measured in absolute units respecting their reduction in calibrated intensity scales.

ACKNOWLEDGEMENT

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High-Resolution Tilted Surface Illuminance/Irradiance Spectral Model Applicable To Arbitrary Sky Conditions

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***Abstract*— A vast database of irradiance measurements exists worldwide, which is of great importance in solar energy applications. However, illuminance data for daylighting applications are still scarce worldwide, and publicly-accessible irradiance/illuminance observations on tilted surfaces are virtually inexistent, thus making accurate predictions or model development and verification difficult. A general solution is thus needed to parameterize the sky diffuse tilted irradiance for any wavelength as a function of the diffuse horizontal irradiance, sun's angle of incidence on the surface, and other physical variables that describe the magnitude of scattering, such as the optical depth of aerosols and clouds. The ultimate goal is to obtain the global tilted irradiance spectrally and at high spatio-temporal resolution, knowing the spectral global/direct/diffuse components on the horizontal, based on a model using satellite-based cloud data.**

The model for inclined surface irradiance and illuminance computations has been developed only recently and applied here for numerical predictions of the radiance field below inhomogeneous cloudy skies. The model requires a spatial summation of many cases of theoretical sky radiance viewed from any tilted surface, excluding the circumsolar region (2.5° around the sun) since that region is actually sensed as direct irradiance by pyrheliometers, and excluded from the sky by shaded pyranometers. This provision makes the model as close to experimental conditions as possible.

The numerical modeling is expected to be applicable to large (continental-scale) areas and for various tilt geometries, while paying special attention to the impact of high albedo (snow...) on the sky radiance. This represents a huge advance in terms of volume of data, without reduction of accuracy compared to the more conventional and empirical broadband modeling using so-called “transposition models”.

***Index Terms*—Tilted surface illuminance/irradiance, high-resolution model, diffuse radiance/luminance distribution.**

INTRODUCTION

Measurements of horizontal diffuse and direct irradiance are available (even though not as widely as global irradiance), but publicly-available irradiance observations are still extremely scarce on tilted surfaces. This is why modelling is necessary to convert conventional horizontal irradiance data into the tilted irradiance that is incident on surfaces of any possible geometry, depending on application (e.g., photovoltaic solar panels, building cooling loads, or daylighting through atria and windows). Modeling the direct normal irradiance (DNI) is a straightforward procedure *if* the optical depth (OD) properties of the atmosphere are known at any moment for the considered location. Under clear conditions, most typically, DNI heavily depends on the aerosol optical depth (AOD), which is highly variable in both time and space [1–3]. However, the diffuse component of global irradiance is difficult to predict theoretically and numerically because of the larger number of underlying radiative transfer processes with nontrivial physics [4]. The use of approximate methods to model diffuse irradiance incident on inclined surfaces is usually limited in both accuracy and range of applicability [5]. The ultimate goal of the present investigation is to reduce the large amount of spectral radiance data that is necessary to easily evaluate the spectral diffuse tilted irradiance when its horizontal counterpart is known, and port that parameterization to the SMARTS model [6, 7], as a replacement for the current approximate method, considering its multiple applications in many disciplines [8].

In the solar energy community in particular, there is an urgent need to obtain the spectral irradiance incident on any tilt/azimuth as a function of the sun's angle of incidence (AI) on the surface and possibly of a few other atmospheric variables such as AOD or cloud optical depth (COD). Previous modelling effort has shown that the sky radiance is close to isotropic in the UV, and that elsewhere the anisotropic nature of the diffuse tilted irradiance is a strong function of AI under clear skies. A simple model of the diffuse irradiance tilt/horizontal ratio for any geometry and sky condition would allow the diffuse horizontal irradiance to be easily transposed into its tilted counterpart.

THEORETICAL MODEL

The radiance field under broken cloud arrays is a non-trivial superposition of all scattering orders:

$$L^{+}_{e,\lambda}(h, z_S, z, A) = \sum_{i=1}^{\infty} L^{+}_{e,i,\lambda}(h, z_S, z, A), \tag{1}$$

where $L^{+}_{e,\lambda}$ is the downward spectral radiance at wavelength λ. The observational azimuth angle A is measured from the sun's position. The remaining parameters are as follows: h is the altitude of the scattering point-source above ground-level, i is the scattering order, and z and z_S are the observational and solar zenith angles, respectively. It has been shown in [4] that the series in the RHS of Eq. (1) can be approximated by a finite sum of two scattering orders. The resulting radiance components have the following form:

$$\begin{aligned} L^{+}_{e,i,\lambda}(h, z_S, z, A) = L^{S+}_{e,i,\lambda}(h, z_S, z, A) + \delta_h(z - z_C, A - A_C) L^{R+}_{e,i,\lambda}(h, z_S, z, A) + \\ \delta_h(z - z_C, A - A_C) L^{T+}_{e,i,\lambda}(h, z_S, z, A) \end{aligned} , \tag{2}$$

where $L^{S+}_{e,i,\lambda}$, $L^{R+}_{e,i,\lambda}$, and $L^{T+}_{e,i,\lambda}$ characterize the scattered, cloud-reflected, and cloud-transmitted components of spectral radiance in the *i*-th scattering order approximation, respectively. The parameter $\delta_h(z - z_C, A - A_C)$ is a two-dimensional delta function that equals unity if the observations are made toward a cloud. This means that $[z_C, A_C]$ has to be interpreted as a set of zenith and azimuth angles at which position the sky is obscured by a cloud. For instance, the first-scattering order radiance at the ground can be expressed as follows

$$\begin{aligned} L^{S+}_{e,1,\lambda}(0, z_S, z, A) = P(z_S)\, M(z) \int_{h=0}^{hC} k_\lambda(h, \theta^+) F_\lambda(h, z_S)\, t_\lambda(h_1, h, z) dh + \\ [1 - \delta_h(z - z_C, A - A_C)]\, M(z) \int_{h=hC}^{\infty} k_\lambda(h, \theta^+) F_\lambda(h, z_S)\, t_\lambda(h_1, h, z) dh \end{aligned} , \tag{3}$$

where h_C is the cloud base height and $P(z_S)$ is the probability function characterizing the relative fraction of electromagnetic energy that penetrates through openings in a cloud array. The optical air mass $M(z)$ [7, 9] is traditionally approximated by $\cos^{-1} z$ for $z < 80^\circ$. Further, $k_\lambda(h, \theta^+)$ is the angular scattering coefficient of an elementary atmospheric volume situated at altitude h, where θ^+ is the scattering angle computed from:

$$\cos\theta^+ = \cos z_S \cos z + \sin z_S \sin z \cos(A - A_S). \tag{4}$$

Expressions for the flux density $F_\lambda(h, z_S)$ of the irradiance reaching an atmospheric layer at altitude h, the transmission functions t_λ, as well as various other parameters/functions can be found in [4]. The resulting theoretical model is generally complex, but numerical computation is fast thanks to the heavily optimized algorithm described in [10]

RESULTS AND DISCUSSION

Trial tests have been conducted for rural aerosols, with or without clouds. For compatibility with the existing aerosol models in SMARTS, the phase functions were mostly those developed by Shettle and Fenn (SF) [11]. However, other models are currently under tests: Rural (SF), Urban (SF), Maritime (SF), Tropospheric (SF), Continental (SRA IAMAP 1986), Urban (SRA IAMAP 1986), Maritime (SRA IAMAP 1986), C (Haze L) (Braslau & Dave), C1 (Haze L) (Braslau & Dave), Desert_Min (Horvath & Kocifaj 2006), and Desert_Max (Horvath & Kocifaj 2006). Current developments include the optimization of realistic phase functions based on aerosol type. Based on the literature, a double Henyey-Greenstein phase function appears very versatile and an efficient alternative to more elaborate treatments, while being numerically fast.

In recent years, a lot of progress has been made in the use of high-resolution sky imaging cameras for cloud detection and sky radiance measurement [12–14]. Such experimental sources of data may provide the basis for the validation of sky radiance models under a variety of situations, including partly-cloudy conditions—which are the most difficult to model precisely. In parallel, another development is the use of satellite observations to evaluate the surface irradiance on large scales. For a typical pixel size of ≈3–4 km, current remote-sensing-based cloud-retrieval techniques diagnose each pixel as being either clear or overcast. Over large scenes and at any instant, a mosaic of clear and overcast pixels may exist. Nevertheless, if each pixel is treated independently to evaluate its radiance as seen from the surface, the complex case of partly cloudy conditions is replaced by a simple juxtaposition of clear and overcast cases. Based on the evidence of interest from the solar community, this specific application appears to have high priority, and can be best served by the developments presented here.

A. Aerosol Scattering Phase Function

The scattering phase function of aerosol particles is computed from:

$$p_\lambda(\theta) = \left(\frac{\lambda}{2\pi}\right)^2 \int_0^\infty \frac{S_{11}(\theta,\lambda,r)}{\pi r^2} s(r)\,dr = \left(\frac{\lambda}{2\pi}\right)^2 \int_0^\infty S_{11}(\theta,\lambda,r) f(r)\,dr\ , \tag{5}$$

where $S_{11}(\theta,\lambda,r)$ is the Mie scattering function for a single particle of radius r, and is the so-called size distribution function. In practically important cases, $f(r)$ is provided by one of the aforementioned models (e.g., SF). Whenever is not known the surface size distribution function $s(r)$ —also referred to as the columnar distribution function—can be used instead. For particle populations that differ only slightly in modal radii, the scattering phase function also changes weakly over the visible spectrum (Fig. 1).

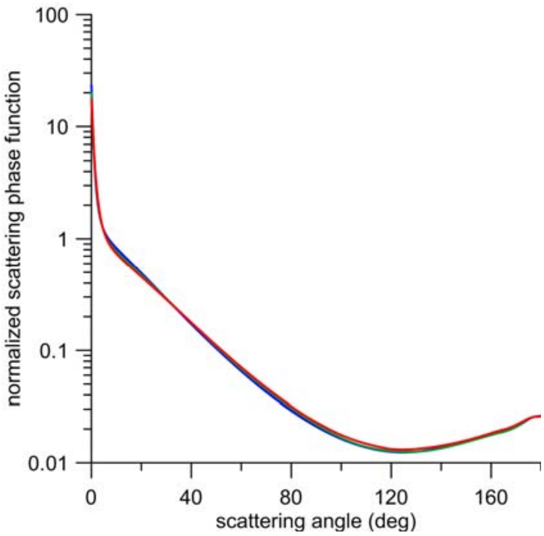

Figure 1. Scattering phase function for rural aerosol at relative humidity level of 50% and three discrete wavelengths (450, 550, and 650 nm).

However, small differences in scattering phase functions can still have a measurable effect on the radiance field due to the complexity of scattering processes. From a theoretical standpoint, knowledge of the specific size distribution of the local aerosol mixture is needed in real time to evaluate both the horizontal and the tilted diffuse irradiance fields. Under cloudy conditions, the optical properties of clouds and their phase function is also needed. This creates a major difficulty in practice, since such detailed information is lacking. Fortunately, the size distribution and phase function of aerosols can be retrieved from sunphotometric observations, thus allowing precise clear-sky evaluations of the diffuse field, but this is possible at only a few hundred sites in the world. In the vast majority of cases, some simplifying assumptions need to be considered about the type of aerosols and clouds, as well as approximations or parameterizations to reduce the computation time and limit the number of inputs to those that can be easily obtained in, e.g., regular engineering or architectural practice. One specific goal of this investigation is precisely to quantify the uncertainty in diffuse tilted irradiance caused by inadequate inputs related to aerosol or cloud type or properties.

B. Tilted Illuminance Computations For Clear-Sky Conditions

The spatial variation of tilted irradiance under arbitrary partly-cloudy conditions being still difficult to represent, a trial test is proposed for clear skies here. The input data to the model are as follows: the ground albedo is fixed at 0.2, the molecular and aerosol scale heights are respectively 8 km and 1.6 km, the single-scattering albedo of aerosol particles is kept constant at 0.9, the zenith and azimuth angles of the sun are 60° and 120°, respectively, and the AOD of the SF rural aerosol mixture is 0.2 at 500 nm. The diffuse (DIF) and direct (DNI) components of the tilted illuminance are depicted in Fig. 2 for a wide variety of receiver geometries. The peak illuminance values occur for a surface that is normal to the position of the sun. This could be expected for the direct component. The diffuse illuminance is also maximum there because of the intense scattering around the sun (circumsolar effect).

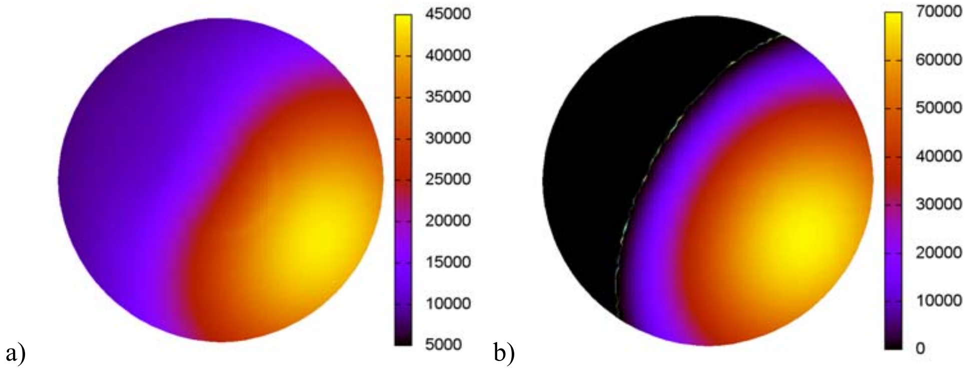

Figure 2. a) Diffuse and b) direct components of tilted illuminance (lux) for a rural aerosol. For each figure the azimuth is measured in the clockwise direction (north is at the top). The center of each plot is for a horizontal surface (normal to the zenith), while the edges are for surfaces normal to the horizon at a respective azimuth orientation.

Figure 2 illustrates that both the diffuse and direct components peak for sun-facing geometries. Moreover, the intensity of DIF smoothly decreases as the angular distance from the sun increases. However, the illumination scene can change significantly under a broken cloud deck because isolated clouds can either mask the sun (and then reduce the direct flux significantly or totally), or scatter a large portion of sunbeams downward if the angular distance between the cloud and sun is large enough. The computational results for stochastic cloud arrays will be demonstrated in subsequent contributions.

Conclusions

A new theoretical model and numerical tool have been developed that successfully predict the illuminance or irradiance incident on tilted surfaces of arbitrary geometry. This is very useful in atmospheric physics, illumination engineering, building energy calculations, and a variety of solar energy applications, since fast and accurate tools are necessary. Even though key solar applications thus far have focused on the broadband irradiance in the shortwave (integrated from 300 to 4000 nm), new applications require spectral information because of the rapid development of photovoltaic (PV) generators based on various technologies, each one having a specific spectral response. Their tilt is also highly variable, depending on location and type of project, from nearly horizontal to vertical. Moreover, tracking PV systems have a continuously changing tilt, which complicates the issue. All this constitutes a great motivation for further work in the near future.

Acknowledgement

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Measuring Sustained Attention and Mood: Effects of Correlated Color Temperature

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Introduction

Humans spend most of their time in man-made settings thus they always collaborate and react emotionally as they perceive the components of the space [1]. Those physical components of man-made settings, such as lighting; both natural and artificial, has an effect on human body and changes how humans perceive and react [2-5].

Various studies conducted with lighting to explore its quality and effects on human beings by using different detailed models and came to an agreement about visibility, visual comfort, appearance of the space, human needs and health, energy efficiency, architectural integration and costs [5]. The primary source of lighting in man-made settings is natural light, besides artificial lighting is widely using too. Since it's extensively usage, the effects of artificial lighting is at the focal point of researchers. Those studies commonly focused on other qualities of artificial lighting rather than correlated color temperature (CCT) such as illuminance and/or luminance, spectral power distribution [6], lighting arrangement, flicker rate [7] and colored lighting [8] with diverse sample groups and in diverse environments.

Research indicated that by enhancing the quality of lighting in a man-made setting occupants' visual comfort and visual capability can be increased. Among the previous lighting studies about correlated color temperature, which is one of the quality of lighting, showed that the correct application of CCT can be beneficial to occupants; it increases motivation, improves health and support cognitive processes but in contrast the use of incorrect application of CCT has significant negative effects on health such as eye strain and headaches or on circadian system, mood and productivity/performance [9-12]. In learning environments different and complex visual tasks which require attention are performed thus obtaining good lighting quality become important. Hence the aim of this study is to explore the effects of CCT on students' sustained attention and mood.

In this study, two light sources with different CCTs, 4000 K (warm white) and 6500 K (between warm and cool white) are used to compare the effects of different CCTs on university students' sustained attention and mood in learning environments with following hypotheses;

Hypothesis 1. Students' Positive Affect (PA) in PANAS will be increased at 6500 K.
Hypothesis 2. Students' Concentration Performance (CP) in d2 Test of Attention will be increased at 6500 K.
Hypothesis 3. Students' number of errors in d2 Test of Attention will be decreased at 6500 K.

Method

Participants were undergraduate students studying at the Faculty of Art, Design and Architecture. A total of different 97 students took part in the study, aged 19 to 27 and the mean age is 22. There were 19 males (19.6%) and 78 females (80.4%). After examining the contents of the courses given in this faculty, two similar courses were chosen. At each classroom, there were eight fluorescent troffers having two fluorescent tubes with 36 watt lamps. Only the fluorescent tubes were changed in order to have different correlated color temperatures and in order to eliminate the discomfort might be caused by flicker [7]. The existing lighting equipment was replaced with Philips Master TL-D Super 80 36W/840 1SL for 4000 K (Cool White) (See Figure 1) and Philips Master TL-D Super 80 36W/865 1SL for 6500 K (Cool Daylight) (See Figure 2) which were selected according to their spectral power distributions. The classrooms were illuminated 15 minutes before the session began for warm-up time for the fluorescents and kept open until the end of the session. Illuminance levels were measured in the experiment setting with Konica Minolta T-1 Illuminance Meter (range of 0.01 to 99,900 lux and calibrated frequently). The average recorded illuminance values in the experiment setting for 6500 K was 412 lux and for 4000 K was 401 lux at the standard working level of 0.7 meters which fulfill the minimum recommended illuminance level for learning environments which is 300 lux [13].

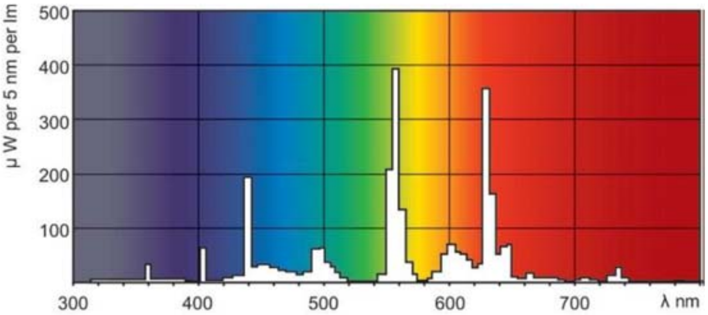

Fig. 1 - Spectral Power Distribution of Philips Master TL-D Super 80 36W/840 1SL for 4000 K (Source http://www.lighting.philips.se/prof/ljuskaellor/lysroer-och-taendare/tl-d-26mm/master-tl-d-super-80/927921084023_EU/product)

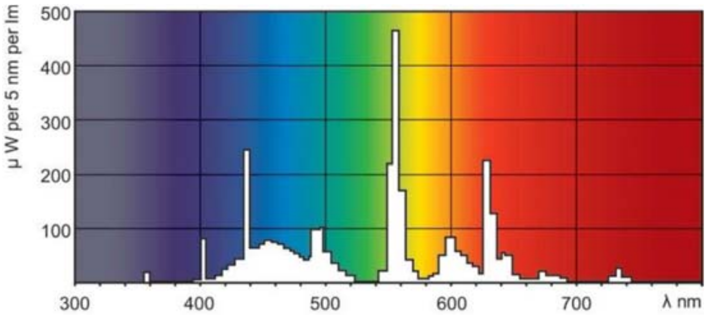

Fig. 2 - Spectral Power Distribution of Philips Master TL-D Super 80 36W/865 1SL for 6500 K (Source: http://www.lighting.philips.se/prof/ljuskaellor/lysroer-och-taendare/tl-d-26mm/master-tl-d-super-80/927921086544_EU/product)

Materials and Measures

Mood of students were measured with Positive and Negative Affect Schedule (PANAS), sustained attention were measured with d2 test of attention.

Mood Measures

A self- reported, ready- made test PANAS was used to understand the participants' current feelings [14]. There are two mood factors that are opposite to one another in PANAS; positive and negative affect (that are strongly negatively correlated with each other). Positive Affect (PA) reflects the extent to which a person feels enthusiastic, active, and alert. High PA is a state of high energy, full concentration, and pleasurable engagement, whereas low PA is characterized by sadness and lethargy. In contrast, Negative Affect (NA) is a general dimension of subjective distress and unpleasurable engagement that subsumes a variety of aversive mood states, including anger, disgust, guilt, fear, and nervousness, with low NA being a state of calmness and serenity [14]. PANAS measures participants' moods with 10 adjectives by asking the question "How do you feel now?" on a 5-point scale ranging from "not at all" to "extremely" [15]. Getting 50 points from PA and 10 points from NA is the most desired condition for an individual to be fully concentrated and calm.

Sustained Attention Measures

The d2 Test is used as a test for measuring sustained attention and it was created by Brickenkamp in 1981 in Germany [16-18]. According to Brickenkamp & Zillmer [16] the d2 Test, a cancellation test which involves simultaneous presentation of stimuli (visually similar) is useful for measuring attention and concentration processes. The task in the d2 Test is to cancel out all the target characters (a "d" with a total of two dashes placed above and or below), which are interspersed with non-target characters (a "d" with more or less than two dashes, and "p" characters with any number of dashes), in 14 successive timed trials [16]. For each line twenty seconds are allowed and participants are asked to complete the test without making mistakes. The d2 Test can be administered individually or in group format [17]. The difficulty of d2 Test of attention allows the analysis of the participant's ability to achieve, shift, and maintain attention which are the elements of sustained attention and its age range is large [16,17].
The outcome measures of d2 Test are; the total number of items processed (TN), the number of errors (errors of omission (EO); d's with two dashes that were not marked), the number of false alarms (errors of commission (EC); marked d's with less or more than two dashes or p's) [16]. The evaluation criteria are; number of errors (E%) which is the sum of errors of omission (EO) and errors of commission (EC) over total number (TN) and concentration performance (CP) which is the total number of correctly marked items [4,17,18]. In this experiment d2 Test of Attention was used once for each session in order to eliminate learning effect.

Procedure

The experiments were conducted in a single phase and all the participants were tested in group format by the researcher. The participants were seated at regular school desks and they participated their regular lectures lasted 110 minutes with one 10 minutes break without leaving the classroom. For light adaptation, experiments started 10 minutes after the lecture started and the fluorescent tubes were switched on 15 minutes before the experiments. All the participants were asked to perform two paper- based tests; the d2 Test of Attention and PANAS. Before the experiment sessions, participants were informed briefly about the procedures of the tests. Before the lecture started, participants were asked to take the test; PANAS. After completing PANAS, the regular lecture started. At the end of the lecture, participants were asked to take the PANAS test again for rating their mood after the lighting exposure for 110 minutes. Then d2 test of Attention were distributed to the participants to understand the effects of CCT on their sustained attention.

Results

Statistical Package for the Social Sciences (IBM Corp. SPSS) 20.0 was used to analyze the data.

Mood

To understand the effects of CCT on university students' mood during the lighting exposure, their before PA- after PA values and before NA- after NA values were compared for 6500 K and for 4000 K with Wilcoxon Sign Test.

Wilcoxon Sign Test indicated that there were significant difference between before PA and after PA values (Z (n= 53) = -2.1, two- tailed, p= 0.034). Wilcoxon Sign Test also indicated that there were significant difference between before NA and after NA values (Z (n= 53) = -2.9, two- tailed, p= 0.003). According to Wilcoxon Sign Test, after PA values are significantly lower than before PA values and after NA values are significantly lower than before NA values at 6500 K. According to the findings, both positive and negative mood of students decreased after the lighting exposure of 6500 K. Having NA value decreased after the lighting exposure is a desired condition to be fully concentrated however having PA value decreased is not.

Wilcoxon Sign Test indicated that there were no significant difference between before PA and after PA values (Z (n= 44) = -1.4, two- tailed, p= 0.161). Wilcoxon Sign Test also indicated that there were no significant difference between before NA and after NA values (Z (n= 44) = -0.6, two- tailed, p= 0.547). Therefore, being exposed to 4000 K has no effect on mood of university students.

Sustained Attention

Total Numbers of Items Processed

Mann- Whitney U Test indicated that the effect of CCT on the total number of items processed was not significant (U (n1= 44, n2= 53) = 1050, two- tailed, p= 0.402). Therefore, CCT does not have an effect on a student's ability to visually scan the total number of items in d2 Test of attention.

Errors of Omission

Mann- Whitney U Test indicated that the effect of CCT on the errors of omission was not significant (U (n1= 44, n2= 53) = 921, two- tailed, p= 0.075). CCT does not have an effect on the number of the correct items, which omitted without marked.

Errors of Commission

Mann- Whitney U Test indicated that the effect of CCT on the errors of commission was significant (U (n1= 44, n2= 53) = 723, two- tailed, p= 0.001). Errors of commission of 4000 K was significantly higher than 6500 K. Thus, CCT have an effect on the number of incorrectly marked items; 6500 K decreases the number of errors of commission. Therefore, 6500 K enhances students' sustained attention than 4000 K and helps them to become more attentive for not to make mistakes.

Errors Percentage

Mann- Whitney U Test indicated that the effect of CCT on the error percentage was significant (U (n1= 44, n2= 53) = 697, two- tailed p= 0.0001). Error percentage of 4000 K was significantly higher than 6500 K. Therefore, CCT have an effect on the error percentage (total numbers of errors of omission and errors of commission over the total items processed) of a student makes, 6500 K decreases the error percentage. So, 6500 K enhances students' sustained attention.

Concentration Performance

Mann- Whitney U Test indicated that the effect of CCT on the concentration performance was not to be significant (U (n1= 44, n2= 53) = 1022, two- tailed p= 0.296). CCT does not have an effect on the concentration performance of a student.

Discussion and Conclusion

In this study, the effects of CCT on sustained attention and mood of university students' were explored in an actual learning environment. It was hypothesized that there are effects of different correlated color temperatures on university students' mood.

Hypothesis 1. A certain conclusion could not be derived about the effects of CCT on mood of university students. After PA and after NA values of 4000 K seems lower but not found statistically significant. There is a statistical difference between before PA and after PA values of 6500 K, after PA values are significantly lower than before PA values which means students positive mood decreased after the 6500 K lighting exposure. Negative mood of students also decreased after the 6500 K lighting exposure. Having lower after NA value is the desired condition to be calm and concentrated which was the acquired result in 6500 K; as well for 6500 K, the expected results were having higher after PA values however according to results after PA values decreased.

Hypothesis 2. It was found that there is no effect of 4000 K or 6500 K on concentration performance, errors of omission or the total number of items processed in terms of sustained attention of university students. The effects of correlated color temperature on focused and sustained attention was investigated by using three different correlated color temperature levels of white LED desk lighting; 2700 K, 4300 K and 6500 K with using Chu Attention Test by Huang et. al. [3]. The sample group was undergraduate students and the experiment shows that 4300 K increases focused and sustained attention rather than 2700 K and 6500 K. The results of Huang et. al. [3] contradicts with the results of this study. This contradiction could be caused by the type of the lighting equipment used in the study; LED desk lighting was used instead of using general lighting.

Hypothesis 3. It was found that there is a significant difference between 4000 K or 6500 K in terms of errors of commission (EC) and number of errors (E%). 4000 K significantly increases errors of commission and number of errors. Under 4000 K, university students tend to make more mistakes than 6500 K, they made higher errors of commission (EC) and number of errors (E%) which are the signs of lower sustained attention. Thus, being exposed to 4000 K for 110 minutes do not effect students' sustained attention in comparison to 6500 K. Similar experiment conducted by Sleegers et. al. [4] by using primary school students. The effects of correlated color temperature on students' concentration was investigated by using different levels CCTs; 2900 K, 6500 K and 12000 K with using d2 Test of Attention. The experiment shows that 6500 K increases students' concentration. Even though the sample group, who were primary school students, was different from the sample group of this study, the findings of Sleegers et. al. [4] support the findings of this study about the effects of correlated color temperature on concentration performances.

Depending on the literature review and the results of this study, the usage of fluorescent lighting of 6500 K is recommended for learning environments to enhance university students' sustained attention. It is important for designers to understand CCT's effects on humans for using it effectively in their application decisions since it can change the perception of environments, visibility, visual comfort, health, supports well- being, mood and sustained attention. These findings of this study have suggestion for lighting practices and might be helpful for future research about lit environments and human needs. Also the findings are useful for not only interior architects, but also for environmental psychologists or educators who may be interested in school environments, learning, mood and sustained attention. For future studies, experiments could be conducted with bigger sample sizes and wider age ranges.

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Comparison of the Measurement Methods of Road Lighting

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***Abstract*— Road lighting is very important for driver visual comfort and visual performance when is driving through the zones of the tunnel. After installation of the lighting system in practice, it is desired to verify of computed values of the photometric parameters by means of the measurement. However, they are various measurement systems present by means of which can be verification measurement performed. They are described in the technical report CIE 194:2011 On Site Measurement of the Photometric Properties of Road and Tunnel Lighting at international level also implemented in the new standard released in previous year EN 13201-4 which describe the problems and simultaneously possibilities how to measure photometric parameters of road lighting (tunnel lighting) on-site. It describes different measurement systems including traditional measurement system by luminance meter with field of view 20'x2' geometry.**

***Index Terms*—Road lighting, On-site measurements, Image photometers.**

INTRODUCTION

The still emerging technology in the field measurement is luminance distribution of lighting scene acquired by image photometers. Even more traditional way of measurement which is performed by spot luminance meter with appropriate field of view has some advantages and disadvantages especially the measurement time. The paper deals with comparison of the three measurement systems performed on measurement the lighting system with LED luminaires for road lighting and with one example of tunnel lighting with installed HPS luminaires. Furthermore, in the paper it will be performed analysis pros and cons of all three measurement systems in respect with differences found out between results from the measurement of photometric parameters at verification measurement of the tunnel lighting system performed according to present documents and standard. Simultaneously, it deals with importance of measurement grid and grid which is used at post-process evaluation with image photometers. At the end of the paper is analysed uncertainty of measurement of each measurement system.

MEASUREMENT SYSTEMS IN ROADLIGHTING

In practice, many types of measurement systems for field measurement of photometric parameters of road lighting were developed recently in past years from the traditional spot luminance meter with defined geometry to new still emerging imaging photometer systems based on analyses of digital photography [1]. Although the principle of image photometers is clear also image photometers can use two approaches from point of view of construction. First type can be CCD or CMOS-based image photometer based on camera with RGBG mask on the sensitive detector element array. Another type which is present on the market is CCD or CMOS array detector filtered over the whole area with $\bar{x}$, $\bar{y}$, $\bar{z}$ filters mounted on filter wheel. These two approaches have pros and cons due to the construction because e.g. the first type using interpolation in the analysis of luminance distribution of the picture by camera and others. Advantage of new imaging systems is to have possibility for analysis of whole lighting scene from the position of observer what is in the road lighting, car driver. This provide more rapid and less time-consuming measurements in comparison with measurement by traditional spot luminance meter. On the other hand, for these innovative systems, user should be aware about setting parameters and each image photometer should be properly metrologically characterised. In imaging systems, we can find devices based on commercial cameras with different resolutions where analysis of lighting scene is performed by analysing of raw data acquired during the measurement. These data are analysed by means of mathematical interpolation between pixels of the array sensor placed behind the optical system of the camera on which is placed RGBG mask to obtain by mathematical transformation photometric parameters from the RAW data of the camera. Another possibility to measure photometric parameters of the lighting scene is imaging system with array sensor in front of which is mounted filter wheel with responsivity of whole system close to V(λ) function, optionally in combination with colour filters to provide X and Z channels to have also colour information of the object under investigation. The examples of measuring systems are depicted in the figure 1.

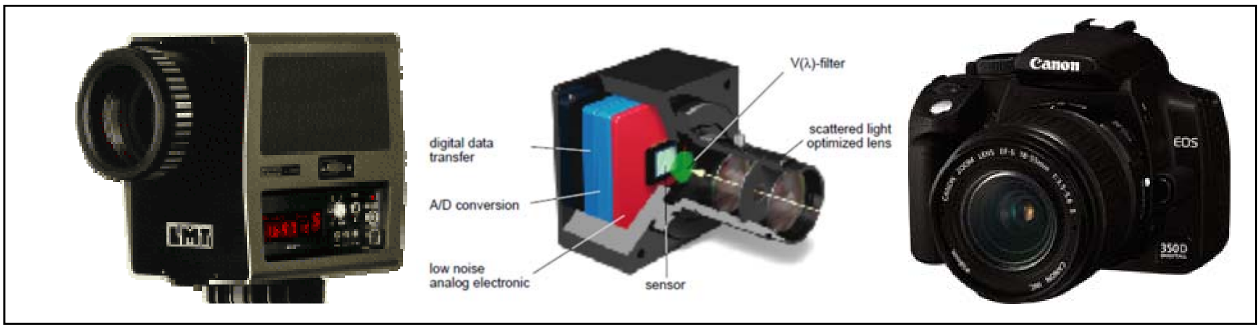

Figure 1. Examples of systems for measurement of road lighting (from left: spot luminance meter, image luminance meter, camera based image luminance meter)

A. Spot luminance meter measuring system

The approach of measurement with this kind of device was developed to reflect driver condition at the driving. It was implemented in the standard EN 13201-4 [2] about road lighting measurement. Visual field of luminance meter is set to 20’x2’ for measurement (Figure 2) in defined measuring grid depending on geometry of road lighting and same (Figure 3).

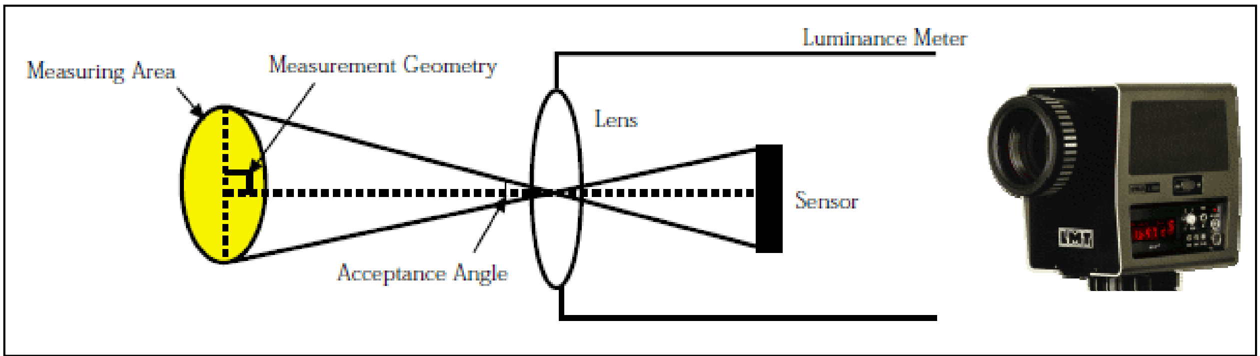

Figure 2. Schema of basic of principle of luminance meter

The measuring system based on traditional luminance meter design is static measurement method. The main disadvantage is very time-consuming measurement, especially in the case when is measured broad road lighting area with different geometry to measure luminance point by point.

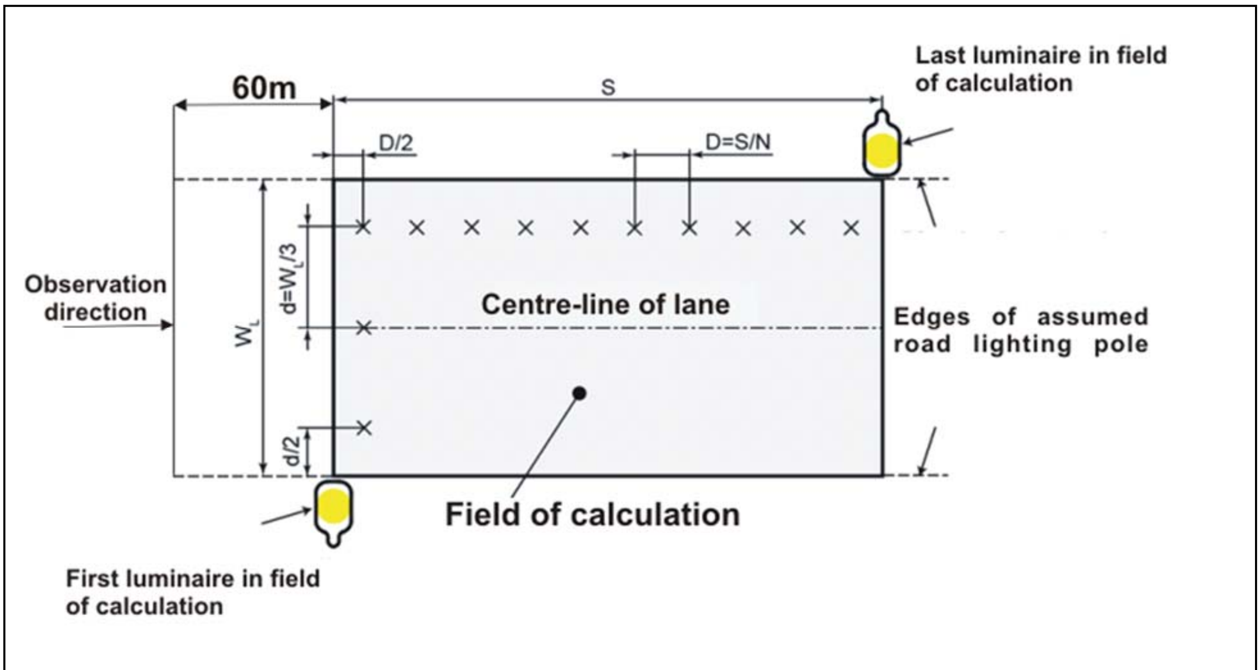

Figure 3. Measuring grid for measurement road lighting according to EN 13201-3 [3]

B.Image luminance meters

The new measuring systems of luminance in the road lighting allowed with incoming of new image processing by means of digital photography based on CCD or CMOS detector elements. The biggest advantage of this systems is that measurement of whole lighting scene can be covered by one image to be analysed in the post-processing by computer. It should be ensured appropriate integrating time, optics and position of the selected device in the measurement. Two approaches as described above can be used. It is image photometer with CCD element in front of which is placed optics including different filters (e.g. V(λ) filter) in the rotation wheel which can be selected for measurement desired parameter (e.g. colour coordinates, luminance in photopic or scotopic region). Another possibility is based on digital camera with CMOS element on which RGBG masks is mounted. In this case it should be also performed appropriate setting of parameters to ensure the real values of photometric or colorimetric parameters assumed in measurement. In both image photometers systems in the post-processing is done reconstruction of digital photography in first case as values calibrated for each pixel of the element which provide responsivity in combination of filters and detector e.g. for luminance is image photometer response close to photopic observer. For second measuring system is based on mathematical transformation of channels R,G,B provided by the digital photography to CIE (X,Y,Z) defined by the transformation matrix. Then user can analyse whole lighting scene in software environment to analyse whatever part of desired area to be investigated. Example of the measurement by image photometer is shown in figure 4.

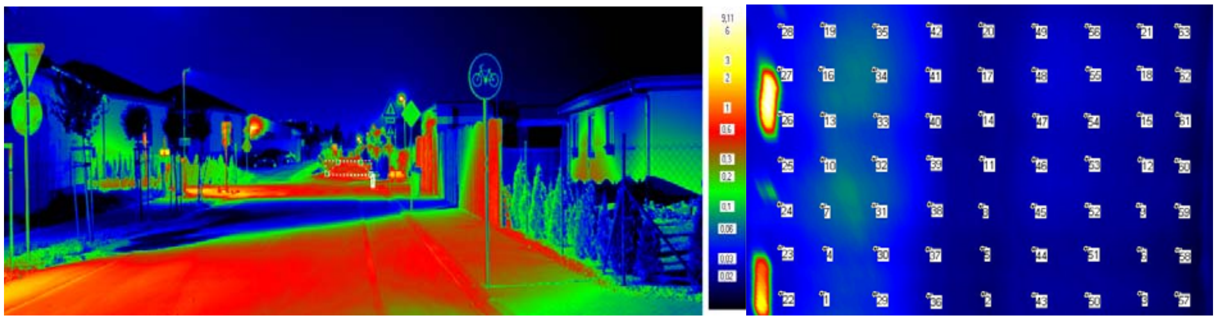

Figure 4. Luminance distribution of lighting scene from the measurement of road lighting by image luminance meter with analysis of the lane

Furthermore, the advantage of image luminance meters is the analysis of desired area pixel-by-pixel method which can be assumed as point what is used at the road lighting calculation. Also, the measurement grid for evaluation of the measurement can be selected with much more density of points in the lane or it can be assumed as whole area of measurement.

EXPERIMENT

Measurement of road lighting should serve as verification process of photometric parameters provided by lighting system of related particular requirements of luminaire. The comparison of different measuring systems with spot luminance meter and two systems image luminance photometers described above was done. The measurement was performed for different lighting systems of tunnel lighting and road lighting with HPS and LED luminaires mounted. The main problem at the evaluation is difference between lighting calculation and practice. Due to calculation of luminance in the points which not correspond to areas for spot luminance meters where area is rectangle around point should be assumed, the measurement does not correspond to calculated values. The circles and square regions were used for evaluation of the measurement by image photometers to compare results of standard method performed by spot luminance meter. Depiction of the measurement regions on the road surface are presented in the figure 5.

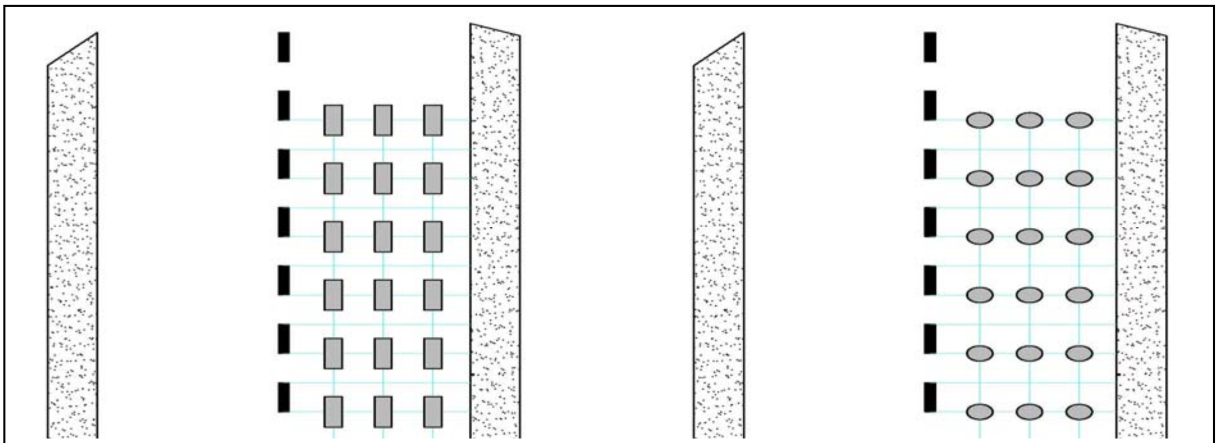

Figure 5. Regions used for the evaluation of the measurement of luminance in the lane

Therefore, objects selected for evaluation of luminance of road surface from the measurement by image luminance meter should reflect this fact. The experiment consisted comparison different objects shapes at the evaluation of photometric parameters with image photometers for area of measurement in geometry according to standard EN 13201 [2] and taken grid with more points for image photometer at calculation of luminance on the road surface.

RESULTS

Two road lighting situations is present in the results. First is the case of tunnel lighting at the entrance level for higher and lower luminance levels and mounted HPS luminaires. Second is the road lighting situation of city in Slovakia reconstructed lighting system by LED luminaires. In both measurements (Figure 6) was used geometry for observer defined in standard EN 13201-3.

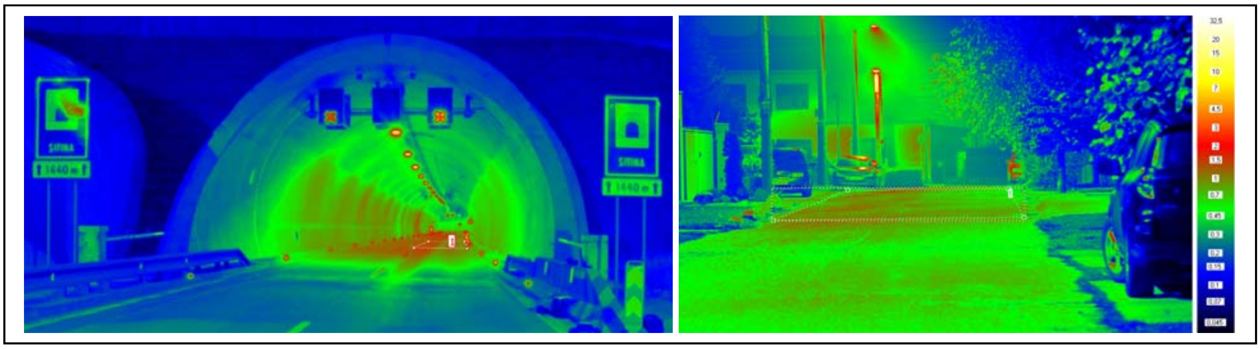

Figure 6. Tunnel lighting situation – HPS luminaires (left), road lighting situation – LED luminaires

In following tables are listed results for both situations for evaluated area of measurement depicted in Figure 7.

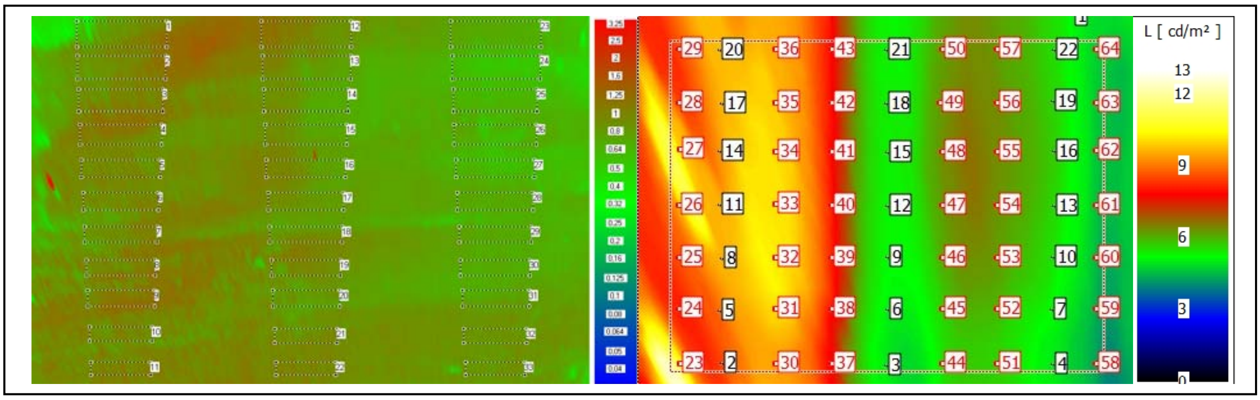

Figure 7. Example of projection of area of measurement for image luminance meters

TABLE I. TUNNEL LIGHTING SITUATION – CASE 1

HPS luminaires	Comparison measurement for tunnel lighting situation - lower luminance level				
	Spot luminance meter 21 points	*Image photometer CCD rectangle object 21 points*	*Image photometer CCD 63 measurement points*	*Image photometer CMOS digital camera rectangle obj. 21 points*	*Image photometer CMOS digital camera 63 measurement points*
Lv (cd.m^{-2})	6,11	6,75	7,32	7,24	7,53
U0	0,72	0,75	0,72	0,71	0,72
Ul	0,91	0,92	0,43	0,90	0,45

TABLE II. TUNNEL LIGHTING SITUATION – CASE 2

HPS luminaires	Comparison measurement for tunnel lighting situation - higher luminance level				
	Spot luminance meter 21 points	*Image photometer CCD rectangle object 21 points*	*Image photometer CCD 63 measurement points*	*Image photometer CMOS digital camera rectangle obj. 21 points*	*Image photometer CMOS digital camera 63 measurement points*
Lv (cd.m^{-2})	305,7	327,9	330,8	329,4	333,6
U0	0,64	0,63	0,52	0,62	0,53
Ul	0,88	0,91	0,47	0,92	0,44

TABLE III. ROADLIGHTING SITUATION

LED luminaires	Comparison measurement for road lighting situation				
	Spot luminance meter 21 points	*Image photometer CCD rectangle object 21 points*	*Image photometer CCD 63 measurement points*	*Image photometer CMOS digital camera rectangle obj. 21 points*	*Image photometer CMOS digital camera 63 measurement points*
Lv (cd.m^{-2})	0,75	0,85	0,87	0,79	0,84
U0	0,66	0,65	0,49	0,67	0,47
Ul	0,77	0,78	0,75	0,79	0,70

CONCLUSIONS

Comparison of three road lighting situation was performed with different devices which can be used for luminance measurement of the road surface by using also different objects assumed at evaluation for image photometers. From the results of comparison, it can be seen, that if is taken much more density grid for calculation of uniformity some discrepancies occur. These differences are present due to using of unequal areas for each measuring system. The longitudal uniformity for tunnel lighting of case 1 significantly differs when more points for this parameter is assumed, because of uneven surface of road. Also for overall uniformity of road lighting for the case 3 can be observed. Also it can be concluded due to fact that some points hit dark areas which can obviously influence of uniformity parameter. At the measurement by means of image photometers should carefully be taken into account, what object area will be used at the evaluation. Regarding to average luminance levels, it can be concluded that the majority of results are in the frame of estimated expanded uncertainty of measurement which were 8,7 % for spot luminance meter, 7,5 % for image CCD luminance meter and 10,4 % for CMOS digital camera for coverage factor k = 2, which for a normal distribution corresponds coverage probability of approximately 95%.The standard uncertainty of meas.has been determined in accordance with EA-4/02. assuming normal distribution. All results also environment factors were assumed to the results. Some differences between average luminances for some measurement systems should be investigated in the future work with better characterized conditions at the measurement and also for different road lighting situations and different luminaires with various LIDC.

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Measurement of Luminaires for Road Lighting

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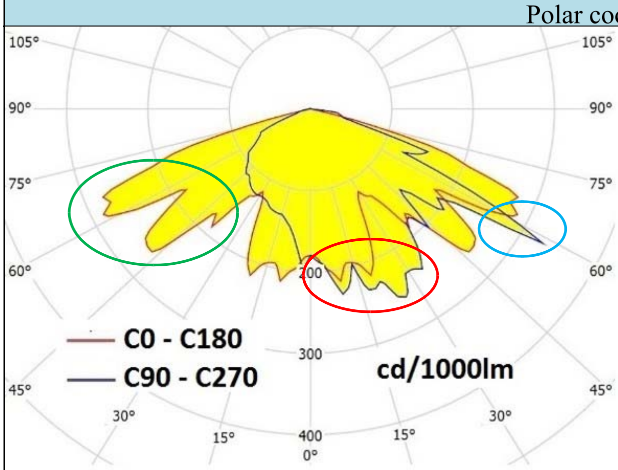
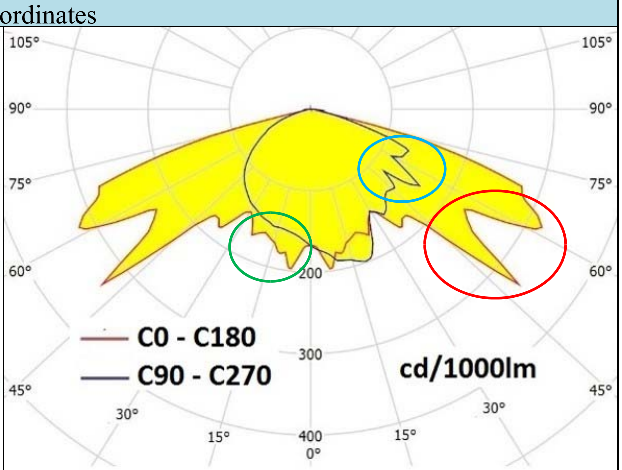
***Abstract*—For the calculation of the photometric parameters of the road lighting are needed photometric data of the used luminaires. These data are in the form of an intensity table (I-table) which gives the distribution of luminous intensity emitted by the luminaire in all relevant directions. A goniophotometer is needed to measure the luminous intensity distribution of luminaires. We know the various goniophotometers which adopting different test methods for testing luminous distribution. The results from goniophotometric measurements are very important for lighting engineers who are using these results in lighting calculation of photometric parameters of the various lighting systems. Especially in road lighting calculation distance between angles should be measured as much as possible providing sufficient photometric data for the calculation. Some new optical systems and some LED luminaires which as found by measurement may contain various local extremes in the luminous intensity distribution curve.**

***Index Terms*--goniophotometry, road lighting, luminous intensity distribution curves, polar coordinates, angular interval**

INTRODUCTION

Luminous intensity is measured in defined angular intervals in the (C, γ) system of coordinates. In CIE document for the lighting calculation of photometric parameters of road lighting is defined that angular interval in photometric azimuth (C) shall at most be 5° and angular interval in vertical photometric angle (γ) shall at most be 2.5°. Due to this fact is in the CIE note that the some types of luminaires, in particular those with LED light sources require smaller angular intervals. Luminaires that could generate critical TI values require smaller angular intervals in the critical directions too. Some luminaires may contain various local extremes in the luminous intensity distribution curve. The reason is that the LED devices are used secondary optics. In secondary optics, depending on the system and the lens, there are diffractions and reflections of light, which form peak intensity narrow angles with resolution ≤ 1º. Luminaires with facetted optical system may also contain various local extremes. Samples of luminaires for road lighting aplication which contains various local extremes are shown in table I. [1] [2]

TABLE I. SAMPLES OF LUMINOUS INTENSITY DISTRIBUTION CURVES WHICH CONTAINS LOCAL EXTREMES

<table>
<tr><th colspan="2">Polar coordinates</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Sample 1</td><td>Sample 2</td></tr>
</table>

In evaluating the LIDC is used software as to identify the correct type of emission characteristics, which is necessary processing of the measured values of angles. Photometric parameters together with electrical parameters can be placed into the file format. The most commonly used processing software is Qlumedit, LDTeditor and others.

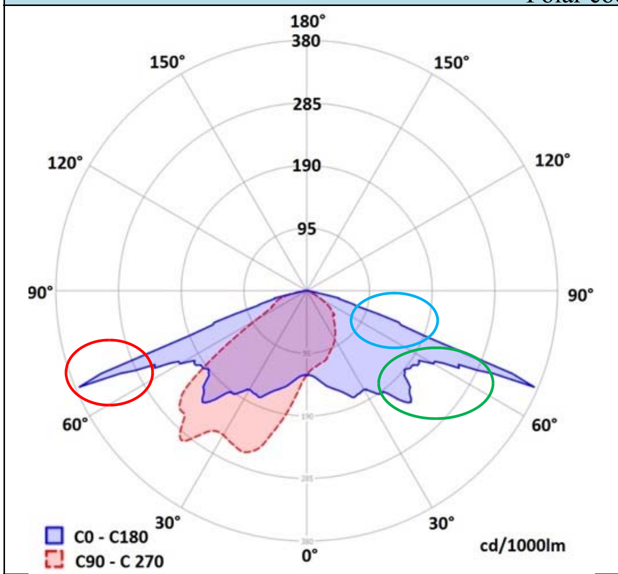
Software for creating LIDC is dozens of areas of commercial or non-commercial. Companies that photometric measurements made for self are often equipped with its own software. [3]

Measurements of Luminous intensity distribution curves

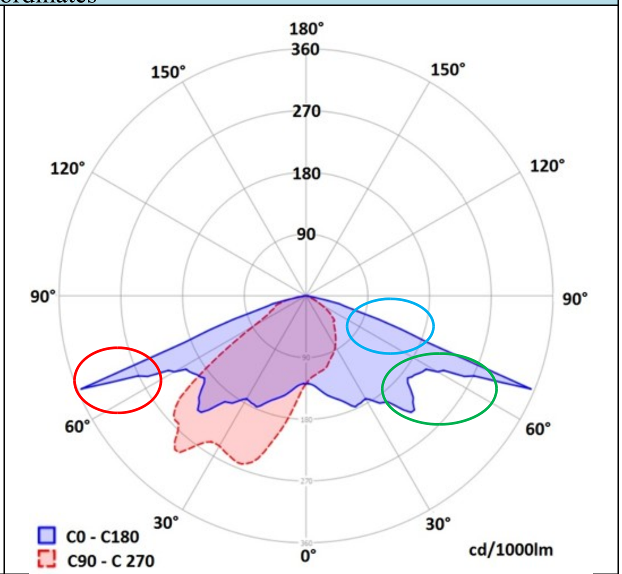
For the measurement were selected three samples of luminaires for road lighting with the typical luminous intensity distribution for this purpose. Measurement of luminous intensity was provided by moving mirror goniophotometer type C. During the measurement were luminaires stabilized from view of photometric and electric parameters. Angle setting has been inspected and calibrated with precise digital Inclinometer with resolution 0.1 degree. For comparison and evaluation of changes have been selected angular intervals γ (1; 1.5; 2; 2.5) which are used for measurements. For each angular interval was created light intensity distribution curve in polar coordinates and calculate the luminous flux. The differences for each luminaire are shown in the tables below. [4]

TABLE II. Change of LIDC for a various angular intervals (luminaire 1)

Polar coordinates



$\gamma = 1^{o}$



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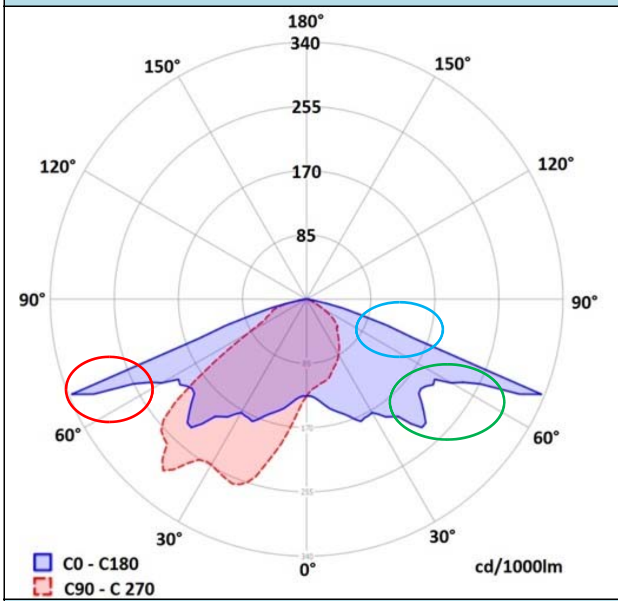
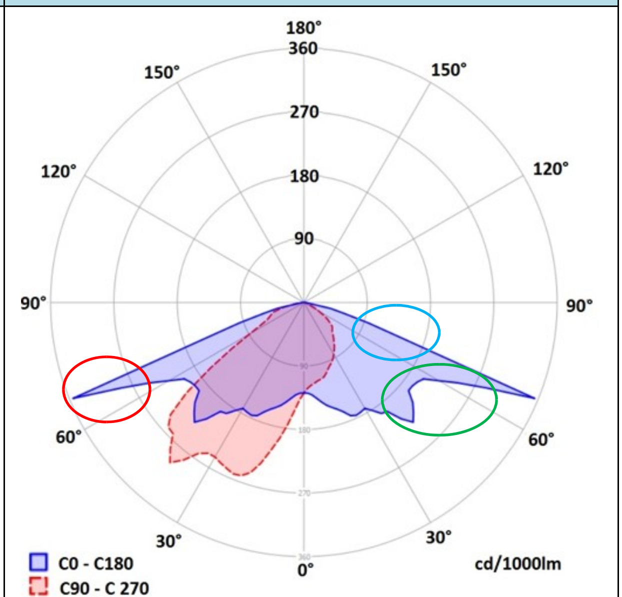


$\gamma = 2^{o}$



$\gamma = 2.5^{o}$

TABLE III. LUMINOUS FLUX FOR VARIOUS ANGULAR INTERVALS (LUMINAIRE 1)

luminaire				
γ (°)	1,0	1,5	2,0	2,5
Φ_v (lm)	5 797,4	5 796,7	5 797,4	5 801,8
Δ_Φ (%)		-0.012%	0%	0.075%

From the measurement results of luminaire1 can be seen that measurement step γ = 1° is a very accurate to captured the minimal differences in intensity. At angular intervals (1.5; 2; 2.,5) can see the change in value of maximum intensity marked by the red circle. Luminous flux in the evaluation (table III), had a negligible error not more than ~ 0.07% compared to the measurement for γ = 1 °.

TABLE IV. CHANGE OF LIDC FOR A VARIOUS ANGULAR INTERVALS (LUMINAIRE 2)

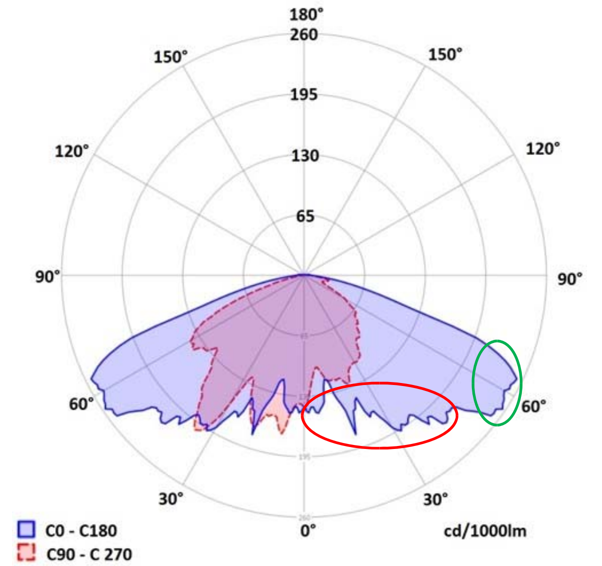
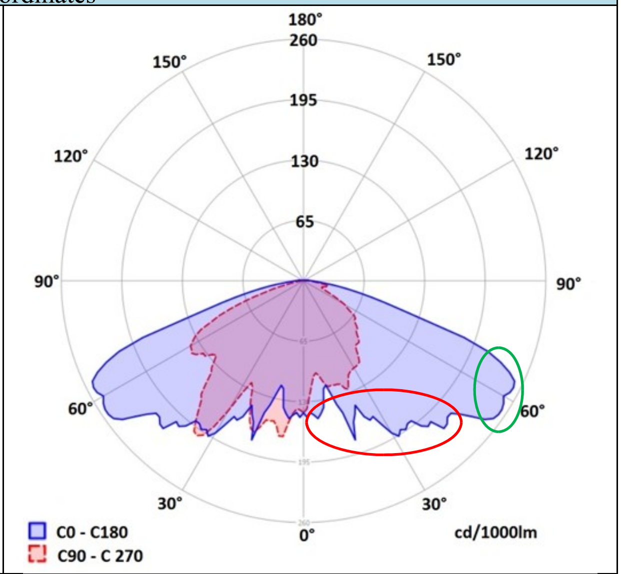
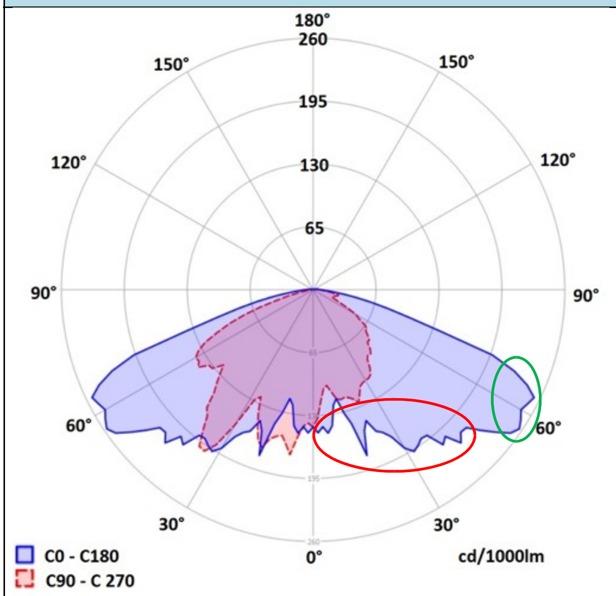
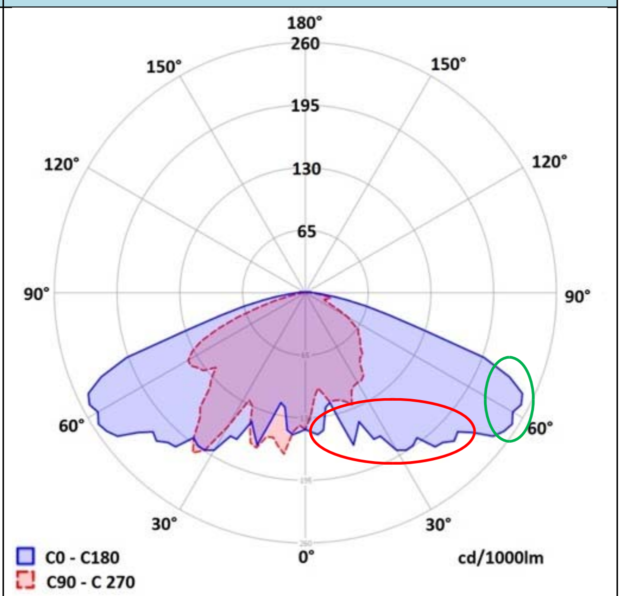
Polar coordinates	
	
$\gamma = 1°$	$\gamma = 1.5°$
	
$\gamma = 2°$	$\gamma = 2.5°$

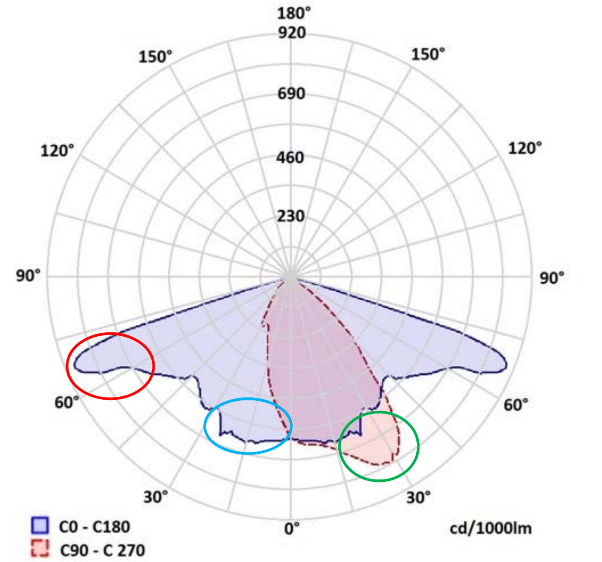
TABLE V. LUMINOUS FLUX FOR VARIOUS ANGULAR INTERVALS (LUMINAIRE 2)

luminaire				
γ (°)	1,0	1,5	2,0	2,5
Φ_v (lm)	12 341	12 355	12 336	12 364
Δ_Φ (%)		0.113%	-0.043%	0.184%

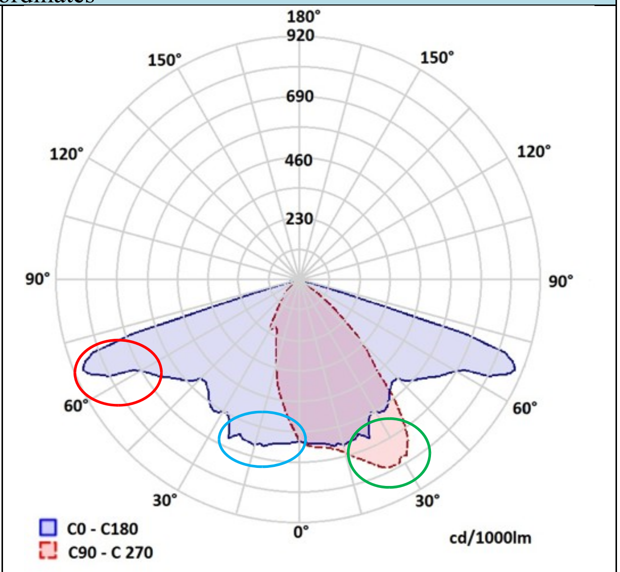
In the table IV are shown differences in luminous intensity marked by the green and red ellipse. Change of luminous flux in the table V is not more than ~ 0.18% compared to the measurement for γ = 1°.

TABLE VI. CHANGE OF LIDC FOR A VARIOUS ANGULAR INTERVALS (LUMINAIRE 3)

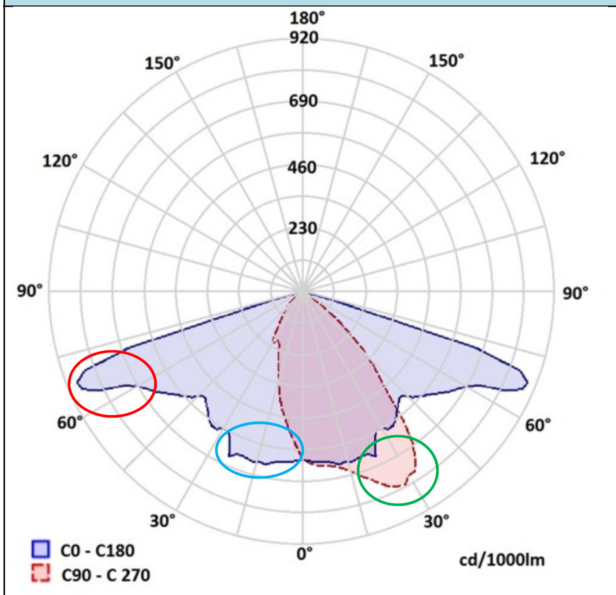
Polar coordinates



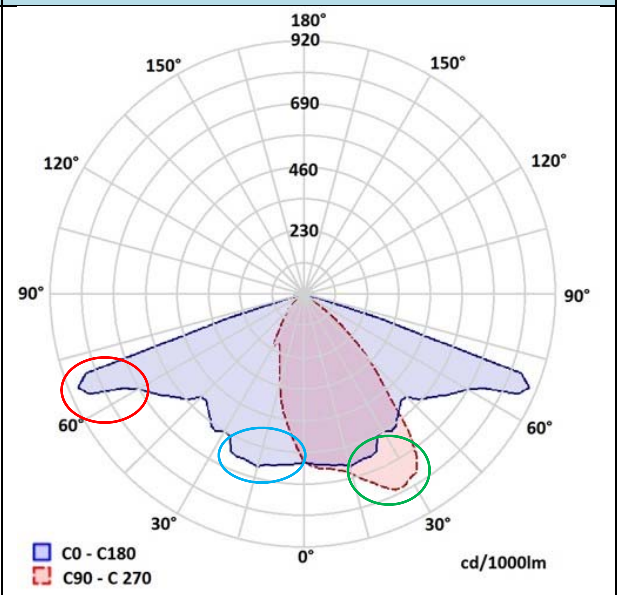
γ = 1°



γ = 1.5°



γ = 2°



γ = 2.5°

TABLE VII. LUMINOUS FLUX FOR VARIOUS ANGULAR INTERVALS (LUMINAIRE 3)

luminaire				
γ (º)	1,0	1,5	2,0	2,5
Φ_v (lm)	11 033	11 047	11 056	11 020
Δ_Φ (%)		0.127%	0.208%	-0.118%

In the table VI are shown the areas that are affected by changing the angle of measurement of luminous intensity curve for luminaire 3. There are changes in the shape of the curve in the plane C0º - 180º in angles γ = 60º - 70º and γ = 0º - 28º. In the plane C90º - 270º are changes not so pronounced except γ = 30°. Change of luminous flux for luminaire 3 (table VII) is not more than ~ 0.21% compared to the measurement for γ = 1°.

CONCLUSIONS

The paper deals with the influence of the density of measurement angular intervals to the resulting light intensity distribution curve. On individual cases is shown difference between the light intensity distribution curve measured by the maximum angular intervals due to CIE 140 and the smaller angular intervals. From the results is obvious that at smaller angular intervals (1°) are necessary to obtain a more accurate shape of light intensity distribution curve and also capture the local extremes in a very narrow range of angles. Smaller angular intervals have a minimal effect to the resulting luminous flux. The change of luminous flux on selected samples was maximum about 0.2%.

The opinions about the right distance between angles are different also inside professional lighting communities although stated angular intervals are at present in the standards so far. For luminaires that may contain local extremes, it is necessary to use smaller angular intervals, especially in critical directions.

ACKNOWLEDGEMENT

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Problems Identified During Measurement and Assessment of Blue-Light Hazard from Arc Welding Process

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***Abstract*— The welding arc emits strong optical radiation and can be classified as one of the strongest artificial non-laser radiation sources. Apart from the UV range, important part of arc radiation occurs in range 400-500 nm, which is perceived as a blue light. Radiation in this range can be responsible for photochemical retinal injury, melatonin suppression and AMD development. Exposure to that range of radiation may pose potential occupational risks for workers, who perform their work in the surrounding of welding workstation. Under the current legislation the level of welder's exposure to optical radiation has to be evaluated. But this evaluation is not performed for other workers (not welders) who are staying nearby the welders workstation and perform their work. Apart from radiation emitted by the arc, substantial part of blue light radiation measured in the surrounding of welder's workstation come from multiple reflections from equipment and surfaces around welding workstation. On the base of results from three series of measurements performed for different welding processes, the attempt of evaluation of the risk of workers in the vicinity of welder caused by radiation in blue light spectrum range has been done. The evaluation took into account both risk of photochemical injury of retina and potential negative effects of melatonin suppression and development of age-related macular degeneration (AMD).**

***Index Terms*-- blue light hazard, arc welding, workers in the vicinity of welding.**

I. INTRODUCTION

Welding is a widely used method of joining metals where the fusion of metals is achieved by heating the joined material up to the melting point. Among of many energy sources used for melting material such as gas flame, laser, electron beam, friction and ultrasound, the most commonly used is an electric arc. Many types of welding processes based on electric arc have been developed and the most popular of them are Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (TIG), Gas Metal Arc Welding (MIG/MAG), Fluxed Core Arc Welding (FCAW) and Submerged Arc Welding (SAW). Advantages of electric arc welding caused that it is widely used in the industry. Low costs of use and affordable price of low-end welding equipment makes this method of joining metals also popular in small workshops as well as on amateur consumer market.

The electric arc welding can be harmful for human body. It creates many risks such as heat and fire exposition, inhaled matter and optical radiation. Some of these hazards affect mostly the welder, while the other, as an optical radiation could be also dangerous for persons working in the vicinity. Welders are usually well protected with personal protective equipment while the others as welder's assistants, welder's supervisors and other workers in the surroundings of welder workstation are usually weakly or not protected against optical radiation. This fact creates serious health hazard both for eyes and skin.

Electric arc used for melting metals is a source of strong optical radiation. The spectrum and intensity of arc radiation depends on the type of welding process, arc current, voltage, welding arc length, parameters of the electrode (material, diameter) and welded material. The most harmful is considered radiation in UV range (200-400 nm), but the strong emission in visible and IR range of optical radiation can also be responsible for injuries. Until now the main attention was concentrated on UV radiation [1] and rarely on blue light hazard [2][3], but only focused on welders [4]. The most accurately assessed risk factor is associated with photochemical damage to the retina of the eye [5]. Light-induced retinal injury appears as retinal changes such as edema or a hole and is accompanied by symptoms such as decreased visual acuity, blurred vision, or scotoma [3].

Nowadays the blue light hazard is considered in much wider range of possible negative effects for health. Beside photochemical retinal injuries which is covered by legislation [4] and for which exposure limit values are defined, there are new discovered blue light hazard factors like melatonin suppression effect and age-related molecular degeneration (AMD). These hazards have being investigated widely and still there is no exposure limit values defined. Melatonin suppression as an effect of exposure for blue light is responsible for disturbing circadian rhythm [6] which creating discomfort and in a longer period is suspected of increasing risk of development of prostate or breast cancer. The only threshold value for melatonin suppression effective irradiance (MSE irradiance) which is determined is the MSE irradiance sufficient for alertness increasing [7] and it is estimated at 0.3 W/m^2 for young people and twice of this for elders. There are strong evidences of relation between blue light exposure and development of age-related molecular degeneration (AMD) but there is no clearly defined exposure limit values (ELV). Recently the huge interest aroused around blue light emitted by light sources (especially LEDs) and even electronic displays. The aim of this paper is to present different aspects of potential blue light hazard observed in the environment nearby welder's workplace.

II. MATERIALS AND METHODS

A. Welding processes

Three welding processes were chosen for experiment: Gas Metal Arc Welding (MAG), Pulsed Gas Metal Arc Welding (MAG-P) and Gas Tungsten Arc Welding (TIG). In case of all three methods the radiation was measured while welding arc was controlled by automated welding workstation. This choice was dictated by the need for minimize fluctuation of welding arc radiation and keep possibly constant position of the welding arc. In case of TIG method the welding arc was struck and maintained by welding robot on rotating steel cylinder. For MAG and MAG-P processes the electrode was motor-driven by movable stage and the welding arc was struck on 8-mm-thick flat plate. Parameters of welding as well as rotation of the steel cylinder in case of TIG and movement of the electrode in case of MAG/MAG-P were controlled by the automated welding workstation although the uncertainty of the parameters was not determined. Welding parameters for measurements discussed below are presented in TABLE I. The experiment was carried out in a large room with good ventilation and extraction of fumes.

B.Measuring equipment

Measurements of spectral irradiances were performed with two spectroradiometers Spectis 5.0 Touch (GL Optic). These spectroradiometers are based on back-thinned type CCD image sensor and provide optical FWMH 2.5nm - 3.5nm in wide spectral range 200 nm– 1050 nm. The irradiance probes of these instruments are intended for measuring irradiance [W/m^2] and illuminance [lux]. This accessory has extended spectral range and can be used for the assessment of photobiological safety in conformity with EN 14255-1 and EN 14255-2 [8, 9]. Both probes were providing cosine corrected response in class A ($f2 < 1.5\%$). Calibration of probes were confirmed with factory certificates of absolute spectral calibration dated on one and three months before the measurements day [10]. Factory calibration in UV and blue light range was carried out with deuterium lamp what ensures higher accuracy in this range with respect to the halogen reference light source.

TABLE I. WELDING PARAMETERS

Parameter	Process		
	MAG	*MAG-P*	*TIG*
Shielding gas	Ar + 8%CO_2 Ar + 18%CO_2 Ar + 12%CO_2+2%O_2	Ar + 8%CO_2 Ar + 18%CO_2 Ar + 12%CO_2+2%O_2	Ar 20 l/min
Welding voltage	21-30 V	20-30 V	16 V
Welding current	70-240 A	70-240 A	20-200 A
Length of arc	10±1 mm	10±1 mm	3 mm
Wire diameter	1.0 mm, 1.2 mm	1.0 mm, 1.2 mm	without wire
Welded material	Armox 550, 8 mm	Armox 440, 8 mm	stainless steel chrome-nickel with low carbon content

Expanded uncertainty of spectral irradiance measurement with GLSpectis 5.0 (expanded uncertainty of instrument calibration with coverage probability 95% and k=2) has been determined according to material available from manufacturer [10] and equals 6% for range 200 nm – 220 nm, 5% for range 220 nm – 400 nm and 4% for range 400 nm – 1050 nm. Comparison of results obtained from measurements of reference deuterium lamp unveiled 1% of difference between results from these instruments. In case of welding arc radiation the main source of random uncertainty is instability of arc radiation which is much higher that uncertainty of spectroradiometers.

Instability of welding arc was indirectly estimated with two photometers GL PHOTOMETER HSL 2.0 manufactured by GL Optic. These devices can provide continuous measurements, returning results every 20 ms. It allowed for recording whole arc welding action from arc ignition till the end of welding with 20 ms resolution. Both photometers are equipped with cosine corrected probe in class B (f2 < 3.0%).

TABLE II. POSITION OF PROBE

Parameter	Process		
	MAG	*MAG-P*	*TIG*
Probe distance from welding arc	2.46m	2.46m	2.08m
Probe height	1.42m	1.42m	0.94m
Arc height	0.84m	0.84m	0.94m
Observation angle	13.6º	13.6º	0 º

C.Measurement setups

The optical probe of the spectrometer was attached to the tripod. The height of probe and distances from welding arc for each process are described in TABLE II. . Position of the detector was adjusted to the welding arc using the laser pointer. The Photometer was installed 10 cm below spectroradiometer probe at the same distance from welding arc.

D.Measurements

Measurements at the welding workplace were conducted during a normal work day, with limited possibilities to reduce amount of daylight incident on the probe. As the daylight radiation poses significant signal in blue-light range, each measurement of welding arc were preceded with measurement of ambient light. The spectral data of ambient light has been then subtracted from spectral data of welding arc. Automatic integration time adjustment has been disabled in spectroradiometer configuration and according to arc radiation the manual integration time value has been chosen in range between 0.5 s – 10 s. Additionally measurements of computer screen irradiance at distance 0.40 m were carried out.

RESULTS

Precise assessment of welding arc radiation is difficult due to instability of welding arc. The observed radiations varied for similar welding conditions what was consistent with results obtained by other researchers [11].

The measurement results for all processes were recalculated according to inverse square low to distance 2.08 m and these data were used for determination of blue-light effective irradiance (Figure 8. For each of investigated processes all measurements were ordered by blue-light effective irradiance and then 15% of measurements with highest values of irradiance were selected for further evaluation of occupational exposure hazard. The selected measurements were used to determine average values of blue-light hazard effective irradiance E_B , calculated according to actual regulations [4, 9], irradiance effective for development of age-related molecular degeneration $E_{AMD,}$ calculated as nonselective total irradiance from the range 400 nm -500 nm and irradiance effective for melatonin suppression E_{MEL}, calculated as effective irradiance (Brainard's acion spectrum for melatonin suppression).

Average blue light hazard irradiances determined from selected measurements were a base for calculation of maximum permissible exposure time T_{EL} according to exposure limit values for blue-light hazard [4] using the equation (1).

$$T_{EL} = \frac{100}{E_B} \tag{1}$$

The maximum permissible exposure time T_{EL} for highest irradiation (MAG-P process, welding current 240A) is 43s and there is a low probability that cumulative time of direct observation of welding arc will reach this level during the work shift. The most possible situation of unintentional direct observation of welding arc is moment of arc ignition in the field of view. Analysis of data recorded by photometer unveils that during the ignition phase of welding arc the peak value of irradiance can be observed Figure 9.

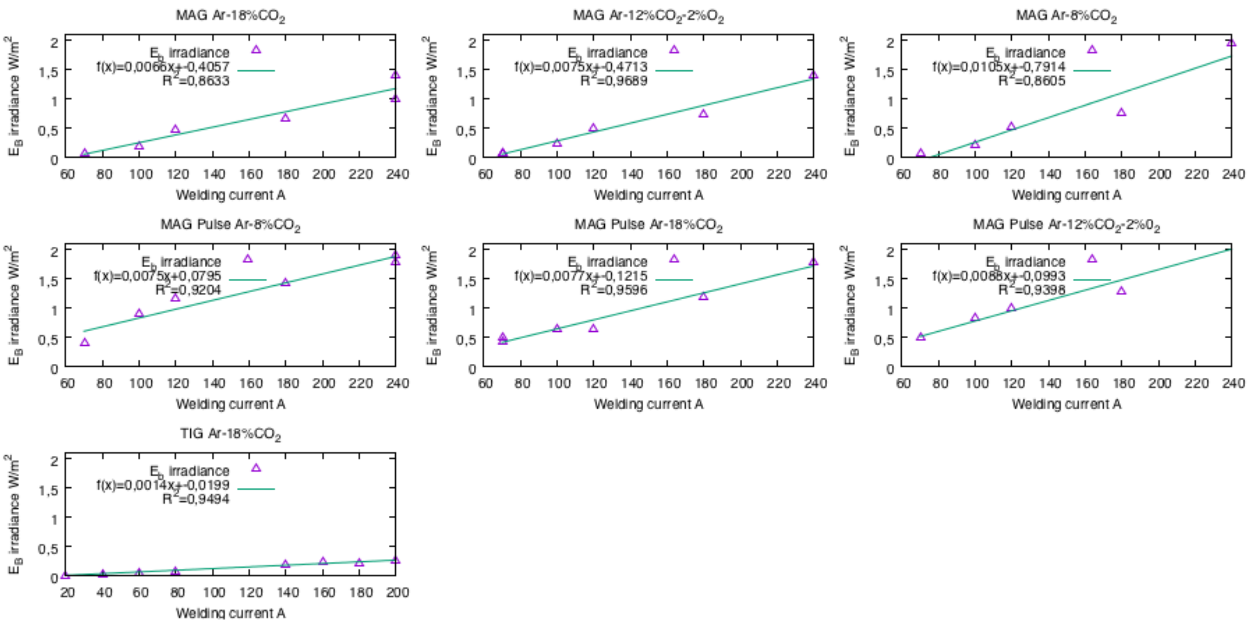

Figure 8. Measured blue light hazard effective irradiance

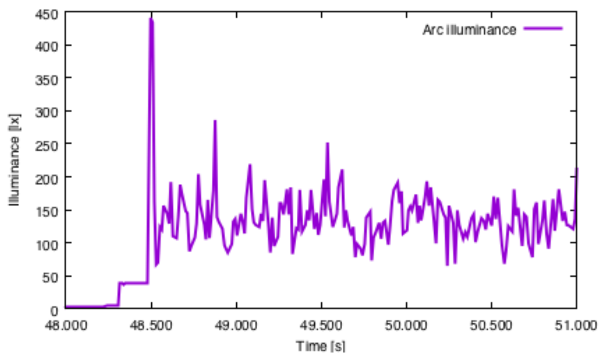

Figure 9. Illuminance peak during arc ignition.

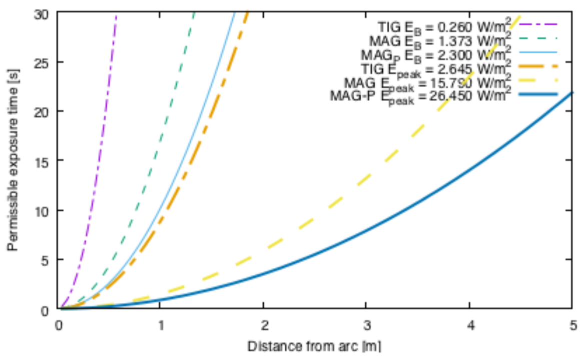

Figure 10. Maximum permissible exposure time.

The irradiance peak measured during the arc ignition was about 11.5 times higher than the average irradiance of arc depending on welding process and used materials, and last about 60 ms. Average aversion response time of eye is around 250 ms what means that there is no chance to avoid exposure caused by this peak. To estimate hazard arising from arc ignition the calculation of peak irradiance E_B for selected measurements was carried out and appropriate maximum permissible exposure time T_{EL} for arc ignition was determined and presented in TABLE III.

The shortest permissible time of exposure by peak irradiance was 4 s what corresponds with 16 unintentional glances at arc ignition from assumed distance of 2.08 m and could be even less for shorter distances (Figure 10. For distance to arc lower than 0.6 m the aversion response doesn't protect the eye against photochemical retinal hazard. This situation is possible for welders starting arc ignition with eyes uncovered by protecting helmet or hand shield. This risk seems to be less danger for persons working in surroundings of welder workplace however other risks related to blue light hazard are still possible. It concerns mainly melatonin suppression (E_{MEL}) and AMD development (E_{AMD}). The calculated E_{MEL} and total (nonselective) blue light irradiance E_{AMD} are presented in TABLE III.

TABLE III. AVERAGE AND MAXIMUM VALUES OF MEASURED IRRADIANCES AND CALCULATED PERMISIBLE TIME OF EXPOSURE

Welding technique / PC screen	E_B		E_{AMD}		E_{MEL}		T_{EL}	
	average	peak	average	peak	average	peak	Based on average E_B	Based on peak E_B
TIG	0.260 W/m^2	2.998 W/m^2	0.250 W/m^2	2.877 W/m^2	0.294 W/m^2	3.386 W/m^2	283 s	33 s
MAG	1.373 W/m^2	15.790W/m^2	1.393 W/m^2	16.014W/m^2	1.298 W/m^2	14.922 W/m^2	73 s	6 s
MAG-P	2.300 W/m^2	26.452 W/m^2	2.214 W/m^2	25.460 W/m^2	2.166 W/m^2	24.911 W/m^2	43 s	4 s
PC screen	0.050 W/m^2	-	0.048 W/m^2	-	0.065 W/m^2	-	1912 s	-

Based on results of irradiance effective for melatonin suppression, the value of E_{MEL} which is sufficient to increase the alertness is 0.3 W/m^2 for young people and 0.6 W/m^2 for elders[7]. Therefore, considering irradiance results (E_{MEL}) from TABLE III. the influence of blue light radiation from welding arc on workers in the vicinity, especially during night shift can lead to disorder of circadian rhythm and chronic exposure can contribute to the development of AMD [12] or hormone dependent breast cancer [13].

III. CONCLUSIONS

Although obtained results of welding arc irradiance are not critical considering risk factor associated with photochemical damage to the retina, the values of MSE irradiance and a AMD irradiance can pose a health risk to worker in vicinity of welder workplace.

The Vision Council warns against the thread of blue light [14] emitted by both lighting equipment and displays of electronic devices as monitors, tablets [15] or smart phones. It is even recommended the use of protective glasses with appropriate blue-light filter. The values of blue light irradiance emitted by computer screen are much lower than values of irradiance measured in the vicinity of welding workstation (TABLE III.).

The current state of knowledge does not allow for a clear assessment of the hazard posed by blue light radiation on suppression of melatonin emission or age-related macular degeneration, but the above results indicates that such a threat exists and requires further investigation to determine proper limits that will guarantee safe working conditions for people working in welder's vicinity.

IV. ACKNOWLEDGMENTS

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Improvement of Monitor Calibration Using Other than CIE 1931 Color Matching Functions

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***Abstract*—The application of different Color Matching Functions (CMF) on the calibration of various monitors is demonstrated. Two experiments were proceeded to determine which is the best fitting data set. It was done a survey with 22 test persons and the results were summarized. It was shown that the preferred CMF depends on the monitor technology, so from the kind of the spectrum.**

***Index Terms*-- Broadcast displays, Color Matching Functions, Visual Appearance.**

INTRODUCTION

Modern broadcast and postproduction studios must rely on a precise calibration of their monitors. This is essential to ensure a high quality of the productions concerning the color management from the recording to the final product, either of a TV show or a movie. It must be secured that the visual appearance is as the director has intended it.

Nowadays monitors of different technologies like LCD with LED, CCFL or quantum dot backlight, OLED, Plasma and still CRT are used in studios. In case of video walls in production rooms mixed configurations of these technologies are usual.

Figure 1. Example of a small video wall in a studio

Therefore two problems arose in modern monitor measurement:

- The correct calibration of some displays usually ends with a slightly colored appearance of the white patterns. If an OLED will be calibrated to the D65 xy chromaticity values with a precise spectro radiometer based on the CIE 1931 2° standard observer CMFs, its white setting will mainly look somewhat greenish.
- Due to the very different spectra of monitors questions of metameric failures come into play. Therefore it is also difficult or even not possible to adjust models of different technologies to exactly the same visual appearance.

A simple solution, often applied to such problems, is to work with xy offsets for the white point setting. These offsets are obtained by visual comparison experiments or by calculation using e.g. the Judd Vos CMF data.

Sony recommends typically to subtract 0.006 from the original x readings and 0.011 from the original y readings to obtain a neutral white appearance of their OLED displays [1]. But this procedure will work for gray scale patterns only, not for the whole gamut.

Flanders Scientific proposes to match two monitors by setting a perceptually match of both in white pattern by adjusting one of them, measure the white point of the adjusted monitor and calibrate it in view of this white point [2]. This approach is better than simply to apply a xy shift for the white setting, but it is based on the perceptual and hence individual matching.

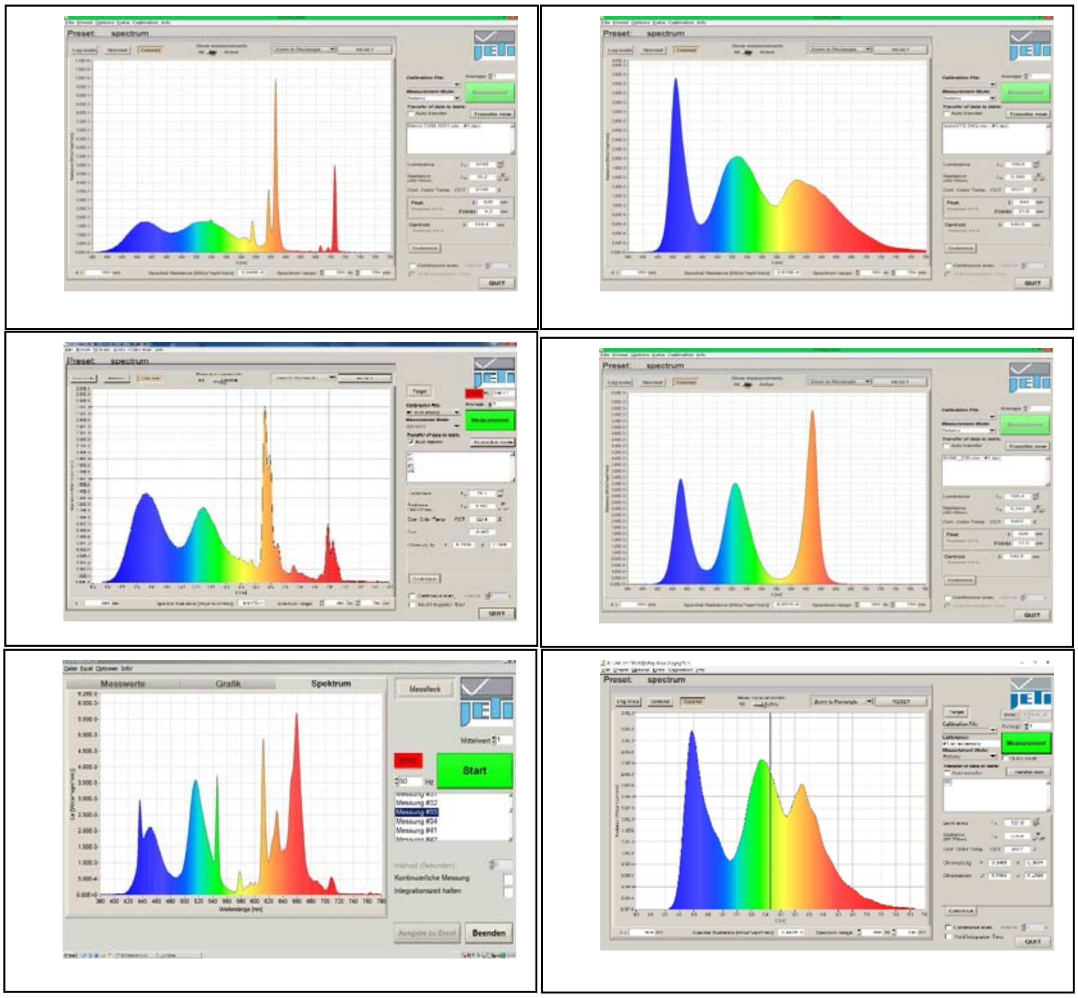

Figure 2. White spectra of different monitor technologies (CRT, LCD with LED wide gamut, Plasma, LCD with LED, LCD with CCFL and OLED)

ALTERNATIVE COLOR MATCHING FUNCTIONS

Doubts about the precision of the CIE 1931 Color Matching Functions (CMF) appeared shortly after their definition. Already in the 1950th alternatives were proposed. Especially with the increased application of power LEDs in general lighting the research in the field of alternate CMFs was reinforced.
Today commonly used alternative CMFs are:

- Stiles/ Burch 1955 [3]
- Jud modified by Voss 1978 [4]
- Data of CIE 170 publication (2006/ 2015) [5]
- Modification of CIE 170 by Schanda/ Csuti University Veszprem [6]
- Modification of CIE 170 by Polster TU Ilmenau [7]

The following diagrams show different CMFs in comparison with the CIE 1931 data:

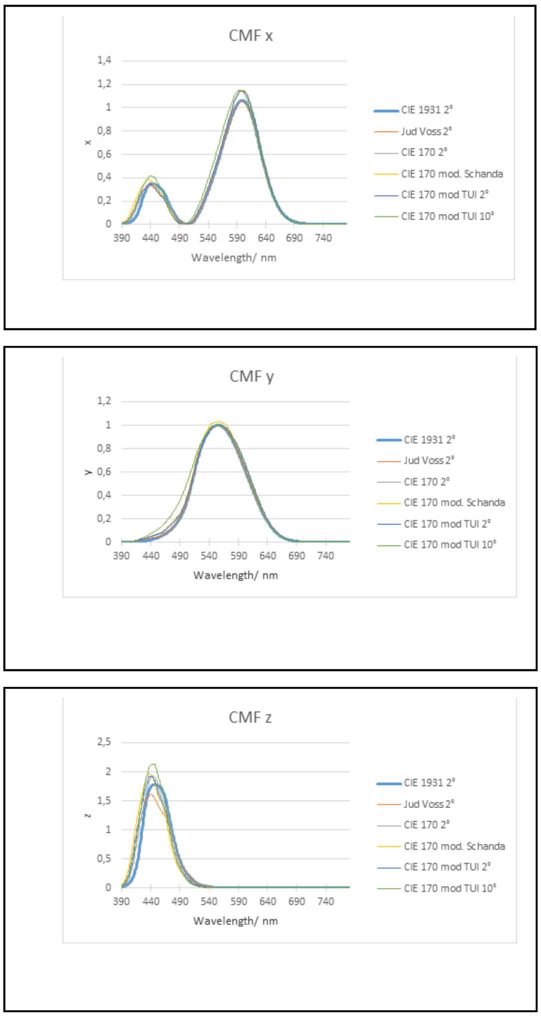

Figure 3. Different Color Matching Functions (CMFs) in comparison

It can be clearly seen, that the main differences arise in the blue wavelength range.
The different CMFs create different xy chromaticity diagrams and hence the whole gamut settings of a monitor will be changed if they are used.

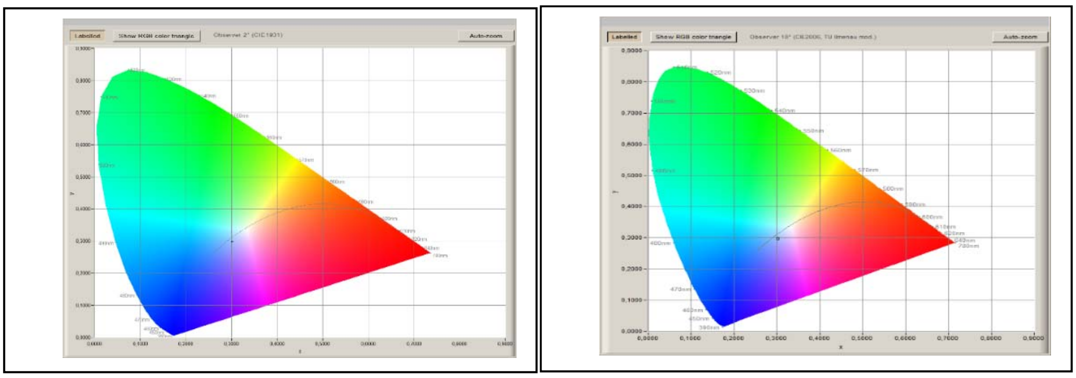

Figure 4. xy diagrams of CIE 1931 (left) and CIE 170, modified by TU Ilmenau (right)

The widely used target white point in monitor calibration is x 0.3128 y 0.3291, the chromaticity of the D65 spectrum in CIE 1931 definition. When other CMFs will be applied, this target point must be changed according to the following table:

TABLE I. XY COORDINATES OF D65 WHITE POINTS FOR DIFFERENT CMFS

CMF	**CIE 1931 2°**	**CIE 1964 10°**	**Jud Voss 2°**	**CIE 170 2°**	**CIE 170 10°**	**Schanda Csuti 2°**	**TUI 2°**	**TUI 10°**
X	0.3128	0.3138	0.3160	0.3135	0.3138	0.3161	0.3145	0.3149
Y	0.3291	0.3310	0.3351	0.3308	0.3313	0.3344	0.3325	0.3330
Δ x		0.0010	0.0032	0.0007	0.0010	0.0033	0.0017	0.0021
Δ y		0.0019	0.0060	0.0017	0.0022	0.0053	0.0034	0.0039

EXPERIMENTS

Practical tests were done using a spectraval 1501 spectroradiometer (JETI GmbH) [8]. It has an optical resolution of 4.5 nm (FWHM) and is therefore applicable for all kinds of monitors. The test objects were the following monitors:

TABLE II. MODELS OF MONITORS USED IN THE EXPERIMENTS

Technology	OLED	LCD/ CCFL backl.	LCD/ LED backl.	Plasma
Model	LG55EG9109	DT-V24G1	24PHK5210	LG42PT353
Manufacturer	LG	JVC	Philips	LG

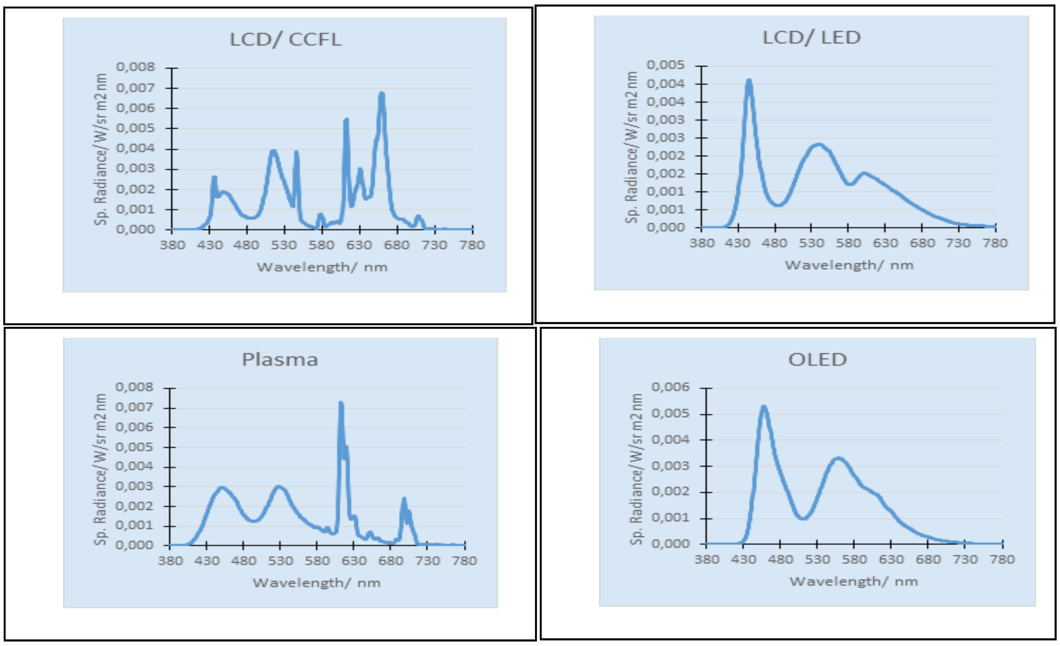

Figure 5. Spectra of monitors used in the experimants

All four monitors were adjusted to around 150 cd/m2 in their white pattern.
The radiometric software JETI LiVal [9] includes the listed CMFs. Additionally it calculates the RGB values depending from the selected gamut and white point. These features were used for the following two experiments (see fig. 6).
The pattern generator was a Murideo Fresco G-6 type. The complete set up is shown in fig. 7.

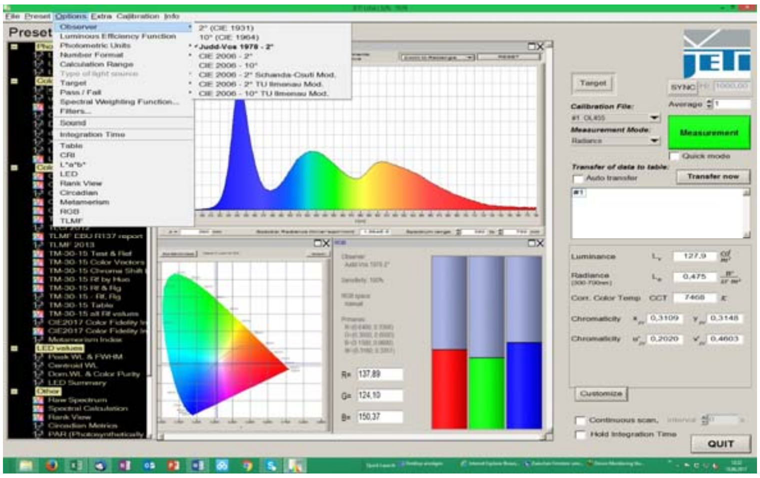

Figure 6. Screen shot of the radiometric software JETI LiVal used for the experiments

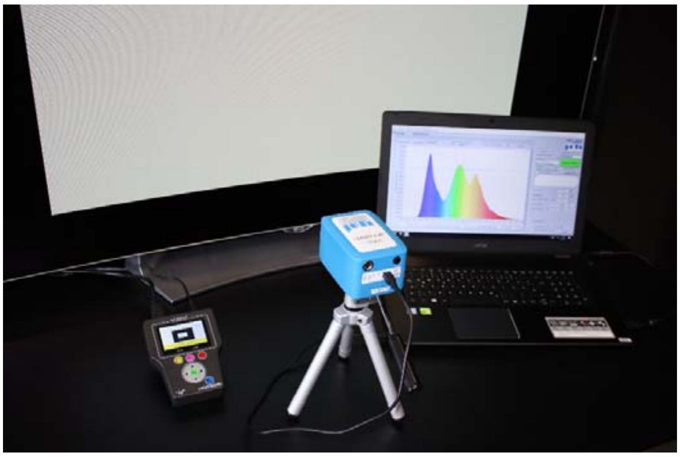

Figure 7. Measurement set up: spectraval 1501 in front of the OLED monitor

First Experiment

In the first experiment all four monitors were calibrated to the target white point of the different CMFs (tab. 1). This was done by adjusting the R, G and B signals of the pattern generator. The used pattern was 90 % white. Afterwards 22 test persons (experienced observers in the age of 25 to 63 years) were asked which white setting gave them the best neutral visual impression for every type of monitor (the monitors were operated separately). The switching between the different white points was done relatively fast to avoid a white adaptation by the observers. The following diagram shows the number of preferred selections of most neutral white for the four monitors. It was possible for the test persons to choose two favored CMFs instead of one in case of a very close visual agreement.

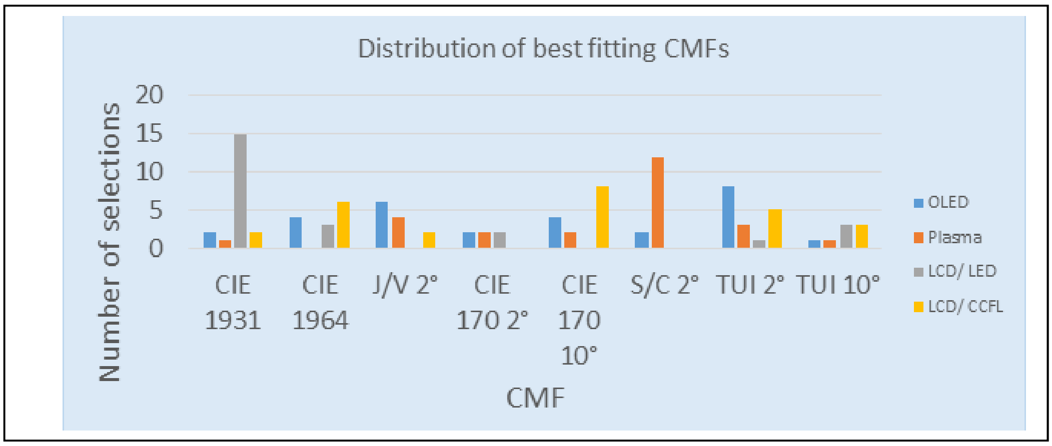

Figure 8. Distribution of the best fitting CMFs for the white setting of the four monitors

The CIE 1931 data were the significantly preferred CMF for the LCD with LED backlight, whereas the CIE 170 10° were the dominant data of the LCD with CCFL backlight. Schanda/ Csuti modified 2° dat were preferred for the plasma type and finally the TUI modified 2° for the OLED monitor. It means that the preferences in this experiment depend from the display technology and hence from the shape of spectrum. It is not possible to recommend one data set for all four monitors.

Second Experiment

A second experiment was done with a scene of two adjacent monitors in the viewing environment of the observer. The left monitor was the LCD/ CCFL type and the right one the LCD/ LED model.

Figure 9. Experiment 2 with tow different LCD monitors (left: CCFL backlight, right: LED backlight)

A white pattern was applied to the LCD/ CCFL display. The xy color coordinates were measured when applying the different CMFs. Afterwards the right display (LCD/ LED) was set to these coordinates and the same group of observers as in the first experiment had to estimate where the best visual agreement appeared. Again it was allowed to choose two CMFs in case of close visual agreement. Both displays were used with large white pattern because this is the normal practice during useage in studios. The surrounding black areas were covered by black cardboard to avoid any influence.

It was expected that either the CIE 1931 data or the CIE 170 10° ones give the best agreement because of the first experiment.

The results of the survey are shown in the following diagram:

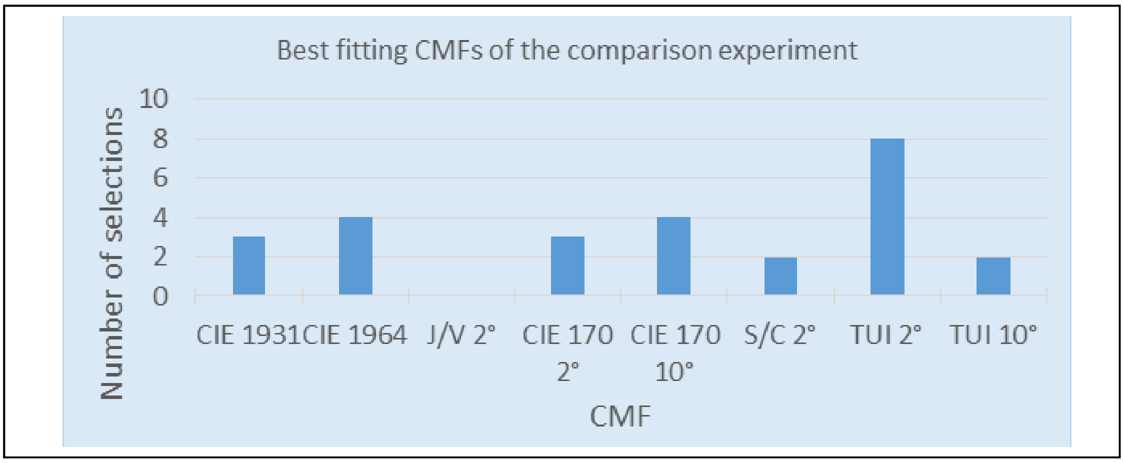

Figure 10. Best fitting CMFs for the comparison experiment

One can see that the favored CMF for the equalization of a CCFL and a LED based LCD screen is the 2° version of the TU Ilmenau modified data. They were identified by 36 % of the test persons as best fitting. All other CMFs were selected in lower quantities and Jud/ Voss 2° was never selected.

SUMMARY

The poster shows the application of different Color Matching Functions on the measurement of four different monitors. Two experiments were conducted and the result was, that four different CMFs were selected as preference, depending from the type of monitor.
Additionally the test persons mentioned different hues for the tiny color differences of the monitor settings. This shows that a common white setting is also not possible due to individual observer sensitivities.
In summary one can say that it is not possible to recommend one set of CMFs in general for the calibration of monitors of different technologies. It is always necessary to check the specific application.

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Review of State of The Art and New Measurement Methods for the Determination of the Reflection Properties of Road Surfaces

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***Abstract*—A review of known and new methods to determine the reflection properties of road surfaces is presented. Measurements and calculations of r-tables are made by two different approaches: (1) destructive, where a drill core sample is taken out of the road's cover layer for laboratory measurements, and (2) non-destructive, where in situ measurements are made. Advantages and disadvantage of each method are shown to help find the appropriate one for a specific application. Additionally, the review determines how the resulting r-tables and luminance coefficients fit with standardized r-tables which were published in international standards [1]. In conclusion, there is a high demand to know the reflexion properties of roads exactly. Unfortunately, so far none of the methods has prevailed. The presented review can support the selection of an easy, practical and as exact as possible method, that will be accepted by many users and standardization committees.**

***Index Terms*—r-tables, reflection properties, road surface, measurement methods, simulation**

Introduction

The evaluation of street lighting installations can be done with the help of the measures illuminance and luminance as it is described in the and international standards [2]. The illuminance is, for historical reasons, described well and easy and precise to measure and calculate in simulations and renderings. Therefore, planners tend to use it when categorising their installations according to standards. But for the evaluation of a street regarding safety measurements, for example the visibility level or other contrast based measurements, it is unusable. It is rather recommended to use the luminance because it is the measure which describes the radiance observed by the human eyes which were send out by light sources and reflected on the road surface. Planners avoid calculating with the luminance because of the lack of knowledge about the reflection properties of road surfaces.

The luminance coefficient q is a measure to describe the reflection characteristics. It is defined by the illuminance divided by the luminance of a point depending on the incidence light angles β and γ and the observation angle α as shown in Fig. 1 and equation (1)

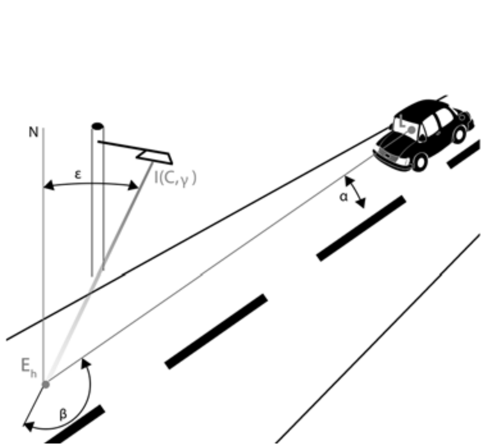

Figure 52. Relevant angles and measures for the evaluation of reflection characteristics in a street lighting scene

tan γ	β Grad																			
	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
0,25	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
0,5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
0,75	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1,25	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1,5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
1,75	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2,5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3,5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4,5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5,5	X	X	X	X	X	X	X	X	X	X										
6	X	X	X	X	X	X	X	X	X											
6,5	X	X	X	X	X	X	X	X	X											
7	X	X	X	X	X	X	X	X												
7,5	X	X	X	X	X	X	X													
8	X	X	X	X	X	X	X													
8,5	X	X	X	X	X	X	X													
9	X	X	X	X	X	X														
9,5	X	X	X	X	X	X														
10	X	X	X	X	X	X														
10,5	X	X	X	X	X	X														
11	X	X	X	X	X	X														
11,5	X	X	X	X	X															
12	X	X	X	X	X															

Figure 53. Example of a standard r-table relevant angles

$$r(\beta,\gamma) = \frac{L(\beta,\gamma)}{E(\beta,\gamma)} * cos^3(\gamma) \tag{1}$$

For road surfaces, there are r-tables used which contain reduced luminance coefficients r for the relevant angles β and γ and α = 1° as shown in Fig. 2.

In [1] the Commission Internationale de l'Eclairage (CIE) also provides standardised r-tables for several types of road surfaces. They are used in simulations and rendering software. All luminance distributions shown in this paper are made with the raytracing software Radiance Version 5.0.a.12. The measurement field has been simulated for a standard observer according to [2] and graphical rectified. The street which was rebuild in all simulations here is an urban road with many pedestrians and cyclists and low motorised traffic and is categorised to the M5 lighting class according to [2]. Fig. 3 and Table 5 show the luminance distributions and measures of simulations with several standard r-tables of the R, C and W category for the same road.

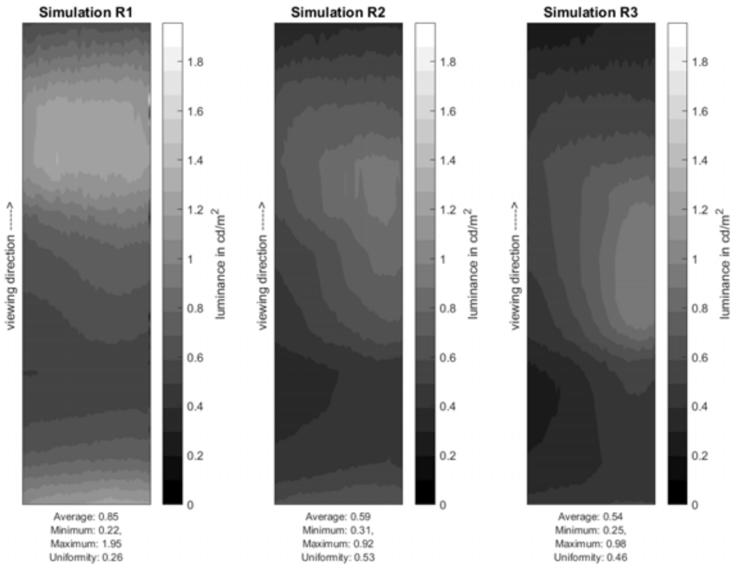

Figure 54. Luminance distribution of the observation field for r-tables R1, R2 and R3

TABLE 5. COMPARISON OF MEASURES FOR DIFFERENT STANDARD R-TABLES, SIMULATED WITH RADIANCE RAYTRACING PROGRAM

r-table		simulation							
		luminance				illuminance			
name	Q_0	L_{av} in [cd/m²]	L_{min} in [cd/m²]	L_{max} in [cd/m²]	U_0	E_{av} in [lx]	E_{min} in [lx]	E_{max} in [lx]	g_1
R1	0.10	0.85	0.22	1.95	0.26	10.6	3.2	22.5	0.3
R2	0.07	0.59	0.31	0.92	0.53				
R3	0.07	0.54	0.25	0.98	0.46				
R4	0.08	0.56	0.15	1.26	0.27				
C1	0.10	0.92	0.25	1.57	0.27				
C2	0.07	0.59	0.14	1.02	0.24				
BRDF	0.05	0.48	0.12	1.71	0.25				

The simulated road surface luminances can differ up to 50 % in minimum and maximum values and in the distribution when using different r-tables. Besides a real measurement there is no standard way to define the r-table of a road surface which should be used in the calculation. When planning an installation, the value of the mean luminance coefficient Q0 is often only estimated by the planner and then the matching r-table is chosen. This can result in a miscalculation of the street lighting scene. The mean luminance can differ a lot in the simulation depending on the Q0 and r-table. Besides the M5 class of the presented street, the standard also allows the classification according to the C-classes where illuminances are given depending on the Q0. Assuming the road has a Q0 = 0.07, then the average illuminance should be 7.5 lx (C5-class) and 0.50 cd/m² (M5-class) according to the standard. With this, the planner would do well with choosing the R2 road surface table which has a Q0 of 0.07. But the real reflection characteristics can be much different, like R1 or BRDF r-tables.

This may generate too high or too low luminances and incalculable luminance distributions in street lighting installations. As this can result in lower safety and/or energy efficiency, it is important for lighting planners to know the road's reflexion properties and the resulting luminance distributions as accurate as possible. More precise properties are relevant to the research community as well as the quality rating of street lighting scenes, for example by means of visibility level and through revealing power methods, requires an exact simulation of luminance distribution on pavements. In addition, this knowledge can help to optimize different lighting situations depending on the weather, which influences the reflective characterisation of the road surface, too. For example, there is a need for a completely different luminance distribution curves of the luminaires (LDCs) for dry and wet roads.

MEASUREMENT METHODS

Standard measurement method

The standardised method is to take a drill core sample out of the road and determine it in the laboratory. Than a measurement is taken according to the standard r-table angles (Fig. 4). These are alpha = 1° for the viewing angle, gamma = 0° to 90° for the light incidence angle and beta = 0 to 180 ° for the reflected light angle. The measurement results are very precise and differ depending on the place where the sample was taken out and the degree of wear. This results in unprecise knowledge of the actual r-table at every point on the road at any time. In simulations, the r-table format can be used easily but normally it is taken the same r-table for all points on the road. Figure 56 and Table 6 show the results of two simulations with the use of two r-tables measured from two drill core samples of the same road shown before (Fig. 3). The results of the two simulations vary in the amount of the luminance coefficients but have nearly the same distribution.

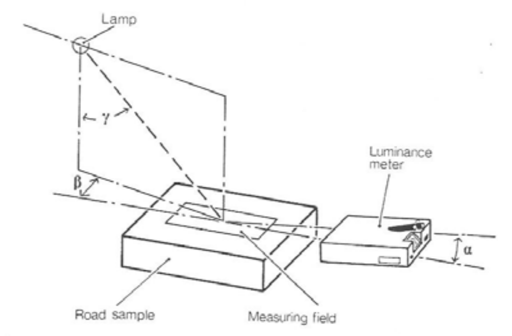

Figure 55. Measurement principle of a drill core sample in the laboratory [1]

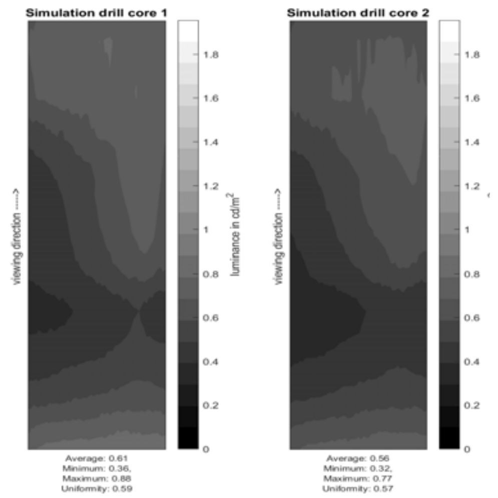

Figure 56. Simulation of luminance with the use of two different drill cores of one road

TABLE 6. COMPARISON OF MEASURES FOR DIFFERENT R-TABLES OF DRILL CORES, SIMULATED WITH RADIANCE RAYTRACING PROGRAM

r-table		simulation							
		luminance				illuminance			
name	Q0	L_{av} in [cd/m²]	L_{min} in [cd/m²]	L_{max} in [cd/m²]	U_0	E_{av} in [lx]	E_{min} in [lx]	E_{max} in [lx]	g_1
drill core 1	0.067	0.61	0.36	0.88	0.59	10.6	3.2	22.5	0.3
drill core 2	0.061	0.56	0.32	0.77	0.57				

The measures are quite like the R2 standard r-table but the luminance distribution on the road has not the same shape at the beginning and at the end of the relevant and evaluated measurement field. In terms of visibility level this may generate uncalculatable dark areas which results in less safety.

In situ measurement methods

There are other measurement methods which can be made directly on the road, "in situ", without destroying it.

2) *In situ, Germany*

The physical instituion IBP built an in situ measurement system (Figure 57) which measures the luminance for the calculation of the average luminance coefficient with the help of a white luminance screen which has LED-arrays as backlight [3]. Furthermore, there are direct LED-arrays which illuminante the surface by S1 calculation relevant angles. This instrument helps to calculate the Q0 and S1 measures for chosing a standard r-table. The determination of angle dependant luminance coefficients is not supported.

3) *BEKA Schréder Memphis, Belgium:*

In sum, the measurement systems which measure Q0 can provide easy and fast measurements on various places of the road to analyse the mean luminance coefficient and specular factor on different places on the road to include the deviations. With this it is possible to prevent too high or too low illumination of a street – but without the knowledge of the angle dependent reflection characteristics, the luminance distributions on the road and therefore too dark areas can never be foreseen. The calculation of angle dependent reflection characteristics is needed.

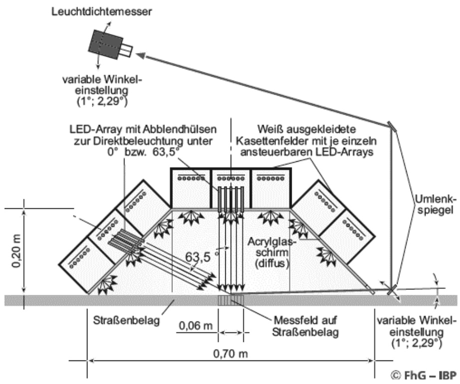

Figure 57. In situ measurement principle inside the housing [3]

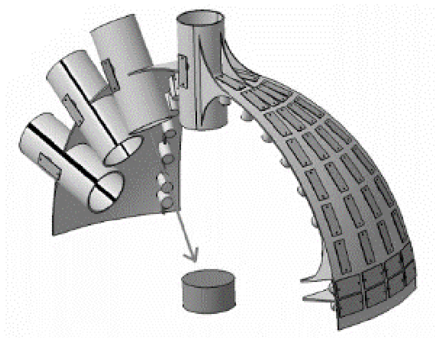

Figure 58. Memphis measurement principle inside the housing [4]

4) *Coluroute, France*

The Coluroute [5] is a measurement system which measures directly on the road, too. It was patented and developed by the Strasbourg LRPC. In principle, it is more near to the gonio-photometric measurement in the laboratory because the luminance sensor observes the road surface at an angle of $\alpha = 1°$ and various combinations of γ and β represented by 27 light sources around the quarter of the hemisphere. The standard observation angle makes approximations from other observing angles unnecessary. Nevertheless, an approximation is necessary to calculate all r coefficients for all 400 γ and β combinations from the measured 27 (Fig. 8). The measurement results are inter- and extrapolated to all standard γ and β angles and were compared to defined samples. The standard error is not given, but the results look quite good in the graphs. The calculated average luminance coefficient Q0 is 4 % different to the measured samples, which is quite sufficient, too. [6] supports a calculation of the resulting r-table with the standard angles and finds a standard error of 10.3 % for the same sample as in the calculation with the Memphis measurement results. The higher error is not explained and should be determined by taking other approximations or road samples.

5) *MoFOR, Switzerland*

In [7], another mobile reflectance measurement system, called MoFOR, is shown. The principle is very similar to the gonio-photometric measurement in the laboratory. It has a halogen lamp as light source, a luminance meter and variable axes with which all relevant γ and β angles can be measured at an observation angle of $\alpha = 1°$ (Fig. 9). Measurement uncertainties occur because of the use of deflector mirrors and an unequally illuminated measurement field, but the authors utter a standard error of not more than 1 % regarding the calculation of Q0 and S1 in comparison to the measurement in the laboratory.

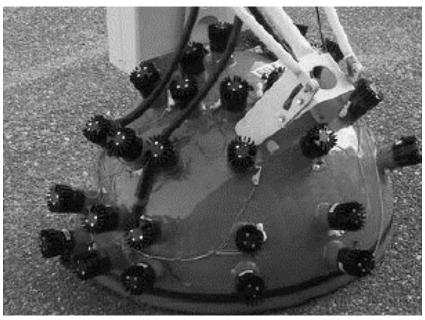

Figure 59. Coluroute measurement housing with 27 light sources representing γ and β [5]

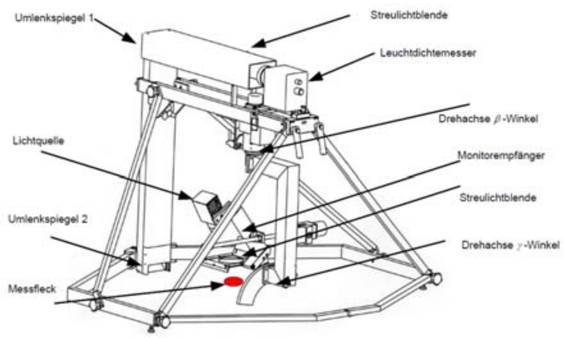

Figure 60. MoFOR measurement principle [7]

These two measurement systems support the measurement of r-tables with standard format. They promise a very precise determination of significant measures and sufficient calculation of r-tables.

In sum, all presented measurement systems need special equipment. The measurement results given by the authors seem to be promising an exact determination of the mean luminance coefficient or the whole r-table, directly measured or approximated. In further research, it should be determined what is needed in terms of safety and energy efficiency of street lighting installations. It must be questioned how precise the measurements should be to predict the real luminance distributions on the road. The question arises whether it is possible to measure the reflection properties with equipment which is used in street lighting anyway.

Development of an image based measurement method

Therefore, in a research project a CCD luminance image camera is currently being tested for the determination of reflection characteristics of road surfaces from the observers site of view. In a first step, an algorithm which calculates reflection properties of the determined road surface was developed. For this, measurements were taken in the laboratory and on the research area at the LEDLaufsteg in Berlin where r-tables of the pavements were given by previously made investigations in the laboratory as shown in chapter Standard measurement method0. Figure 61 shows the measured luminance distribution on the measurement field and the according one which was simulated in radiance by the calculated r-table and the two drill core samples already mentioned above.

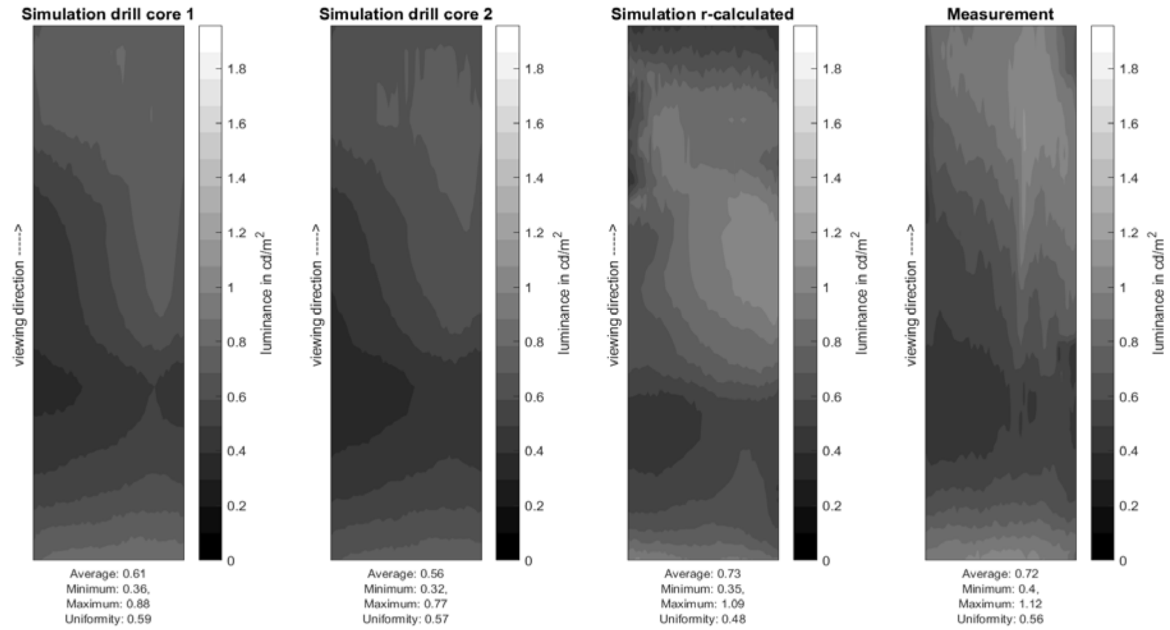

Figure 61. Simulated and measured luminance distribution of a testcase

It is shown that the results of the luminance distributions are not representative enough but minimum and maximum values are quite similar. Further research aims to improve simulation results by varying the measurement testcases, geometries, luminance distribution curves of the test luminaires and calculation algorithms. It is predicted to lower the differences of the r-tables and luminance distributions to 10 %.

CONCLUSION

There is a high need to know the reflection characteristics of road surfaces exactly for the improvement of luminance distributions in terms of safety and energy efficiency. The standard r-tables are outdated and often used without measurements to prove their validity. The standardised gonio-photometric measurement of drill core samples in the laboratory are exact but not representative enough and not used. In situ measurement systems have been developed to measure and calculate the Q0 factor and/or r-tables and the results are very accurate. Unfortunately, so far none of the methods has prevailed. The presented review can support the selection of an easy, practical and as exact as possible method, that will be accepted by many users and standardization committees. Further research must be done whether these or improved measurement methods can be used to generate better simulations for the evaluation of street lighting scenes in terms of safety and energy efficiency.

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Results from Monitoring the Energy Certification of Lighting in Buildings

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***Abstract*— Energy performance of lighting in buildings is one of the four components of overall energy performance of buildings. It is compulsory to assess energy performance of many types of buildings. Methodology of the assessment of energy performance is laid down in a series of European standards while the legislative framework and requirements are stated in the Energy Performance of Buildings Directive (EPBD) that must be implemented on national level in all member countries. In the field of lighting, methodology is described in the European standard EN 15193. Currently this standard is undergoing an update and release of its new editions is being expected this year. This paper aims to present Slovak approach in monitoring energy performance related parameters.**

***Index Terms*—Energy certification, Energy Performance of Buildings Directive (EPBD), Monitoring, Statistical data**

INTRODUCTION

With the rapid increase of human population resulting in higher energy demands day by day, critical level of greenhouse gas emissions (particularly CO_2) has already been reached [1]. Thus, many studies, actions and implementation plans have intensively been realized for more than fifteen years. As one of the main objectives is to reduce the CO_2 emissions, efficient use of energy hand-in-hand with efficient energy production are identified as actions of paramount importance. Therefore, many countries deal with legislative tasks to create legal force to decrease energy consumptions.

In the EU political and economical area, several directives aiming at the reduction of greenhouse gases have already been published, such as energy end-use efficiency and services, ecodesign, energy performance of buildings etc. European Parliament and the Council adopted the Directive on Energy Performance of Buildings (EPBD) [2] 2002/91/EC on December 16, 2002 in order to improve the energy efficiency of buildings. This was the starting point for dealing with energy performance of buildings, and energy certification of buildings in particular. Within four main areas of energy consumption in buildings, lighting plays an important role and thanks to very rapid development in this field (like e.g. implementation of the LED technology), it offers promising potential for improvements of energy performance [3], [4], [5].

EU member countries were obliged to implement and start the energy certification by not later than January 2006. Since then the legal requirements as well as corresponding methodical standards have been improved several times as this is a living process. Monitoring of energy certificates is one of the measures that has been implemented later – and it is expected that it will provide a cluster of useful information on the state-of-the-art of building technologies and their energy performance. Corelating the historical data with time it will bring further information on development of building technologies and their energy performance. Today we have 10 years of experience with energy certification of buildings and almost 5 years with monitoring of energy certificates.

SLOVAK LEGISLATION ON ENERGY PERFORMANCE OF BUILDINGS

National Parliament of the Slovak Republic released its first legal document implementing EPBD as the Act No. 555/2005 on Energy Performance of Buildings [6], prepared by the Ministry of Construction and Regional Development of SR, under tight collaboration with experts responsible for individual energy systems concerned. Requirements for lighting and issues relevant to lighting have been prepared with participation of authors of this paper. The Act 555/2005, valid since January 1, 2006, came in force 1st January 2008. Basic methodological principles, having force of legislation, were given by the Ordinance No. 625/2006 [7], later upgraded by consequent Ordinance No. 311/2009 [8], Ordinance No. 364/2012 [9], Ordinance No. 324/2016 [10]. Example of Slovak energy certificate of a building is depicted in Figure 1.

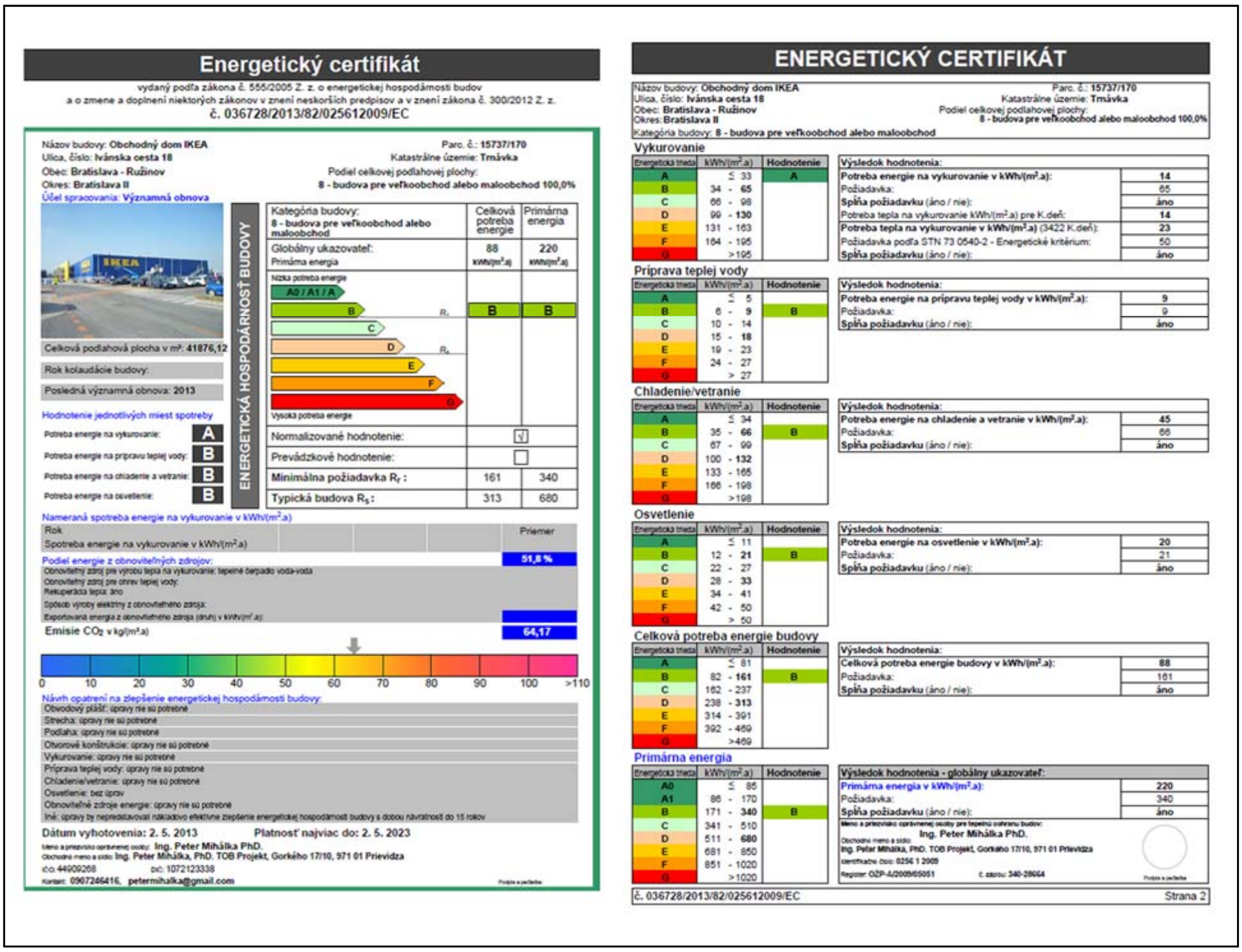

Figure 1. Energy performance of buildings certificate (two-page sample)

MONITORING OF ENERGY CERTIFICATES IN SLOVAKIA

Since January 2010, all energy certificates of buildings must be submitted electronically to the Ministry of Construction and Regional Development of SR (further as "Ministry") via the INFOREG on-line information system [10] (Figure 2). Here the relevant data are collected for further processing and archiving purposes. According to the current law, the obligations regarding energy certificates of buildings are as follows:

- electronic delivery of energy certificates by authorized persons to the Ministry
- management of energy certificates in the Central Register
- assignment of registration number to each energy certificate
- evaluation of the data on energy certificates
- providing data to the supervisor of the energy efficiency monitoring system
- publishing information on energy certificates
- publishing a list of energy certified buildings
- performing supervision of the process including inspection of the certificates and the authorized persons

Since January 2012, besides assessment of energy performance and energy certification of buildings, it is legally required to gather selected data from the assessments. In Slovakia, Ministry of Construction and Regional Development is responsible for continuous monitoring of energy certificates, gathering and processing of data on national level. A comprehensive selection of parameters and information for monitoring in the field of lighting has been prepared at the Slovak University of Technology. Table I shows the data to be provided to the system INFOREG in a form of a technical report which is an indispensable annex to every single issued energy certificate of a building. Grey column in Table I is to input the data. Note that providing the data in Table I is a legal requirement.

Although data selected for monitoring is quite comprehensive, its processing in the system is not efficient enough. For the purpose a spreadsheet template is used which do not allow to process the data directly. Thus data are collected but not evaluated statistically – except the resulting energy class of the building. Available outputs of the INFOREG system are presented in Figure 3 (number of the issued energy certificates in Slovakia according to measures or activities applied to buildings) and Figure 4 (number of the issued energy certificates in Slovakia according to the energy classes). Presented data comprise energy certificates issued in the period 2010 – 2016 when the automatic registration system of energy certificates is in use.

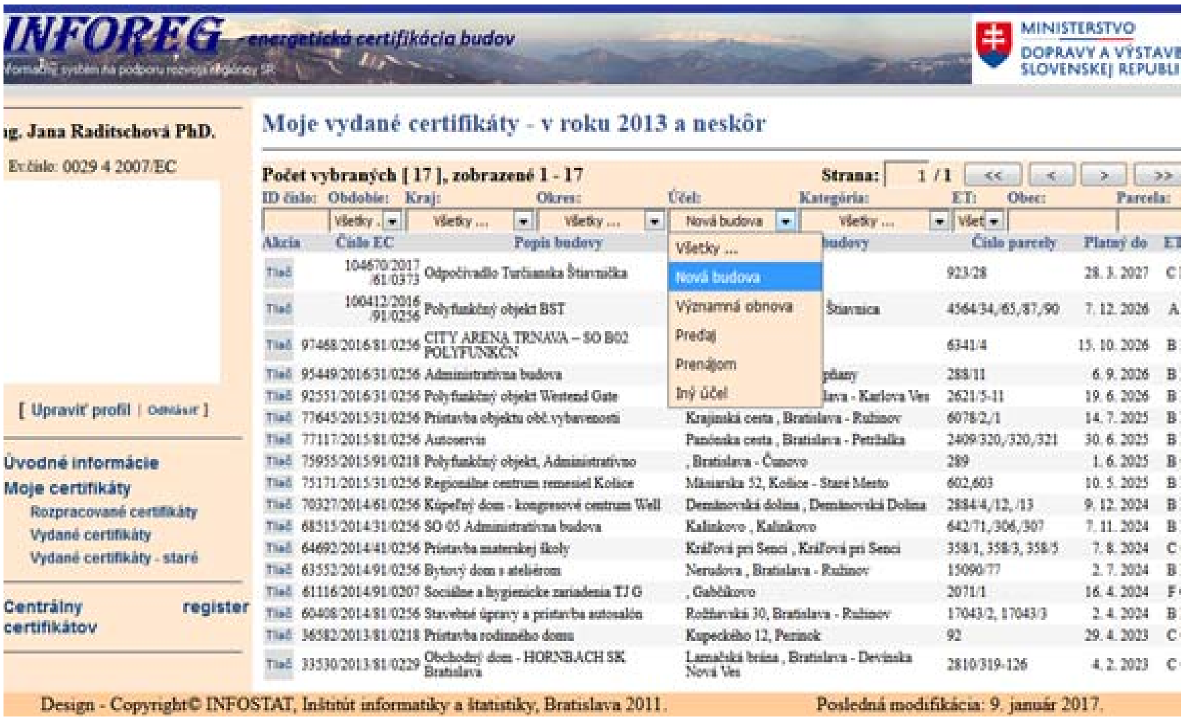

Figure 2. The INFOREG official information system – a sample screenshot of the system

TABLE I. SELECTION OF DATA ON LIGHTING SYSTEMS FOR MONITORING PURPOSES

Row	INPUT DATA			
7	Building	Building category		-
8		Total number of rooms in the building		-
9		Number of rooms selected for verification of illuminance level		-
10		Number of verified rooms with satisfactory results		-
11		Total floor area		m^2
12		Locality – geographical latitude		°
13		Locality – geographical longitude		°
14		Operation time FROM:		h
15		Operation time TO:		h
16		Correction factor for weekends (C_{we})		-
17	Luminaires	Total number of installed luminaires		pcs
18		Total installed power of luminaires		kW
19		Total charging power of emergency luminaires		kW
20		Total parasitic power of control units installed in luminaires		kW
21		Total installed power of all lamps in luminaires		kW
22		Summary power of all control gears installed in luminaires for fluorescent lamps		kW
23		– summary power of conventional control gears		kW

TABLE II. SELECTION OF DATA ON LIGHTING SYSTEMS FOR MONITORING PURPOSES (CONTINUATION)

Row	INPUT DATA			
24	Daylight	Total number of fasade windows		ks
25		Total area of fasade openings		m^2
26		Total area of zone with daylight		m^2
27		Total area of openings for conventional rooflights		m^2
28		Total area of openings for shed rooflights		m^2
29	Lighting Control	Prevailing lighting control in the building - code		-
30		Average daylight factor in the building (F_D)		-
31		Average occupancy factor in the building (F_O)		-
32		Average constant light output factor in the building (F_C)		-
	RESULTS			
33		Annual lighting energy consumption (W_L)		kWh/m^2
34		Annual parasitic energy consumption (W_P)		kWh/m^2
35		Lighting energy numerical indicator (LENI)		$kWh/(m^2.year)$
36		Specific annual lighting energy consumption (h_e)		$kWh/(m^2.lx.year)$
37		Share of the lighting energy in total energy demand of the building		%

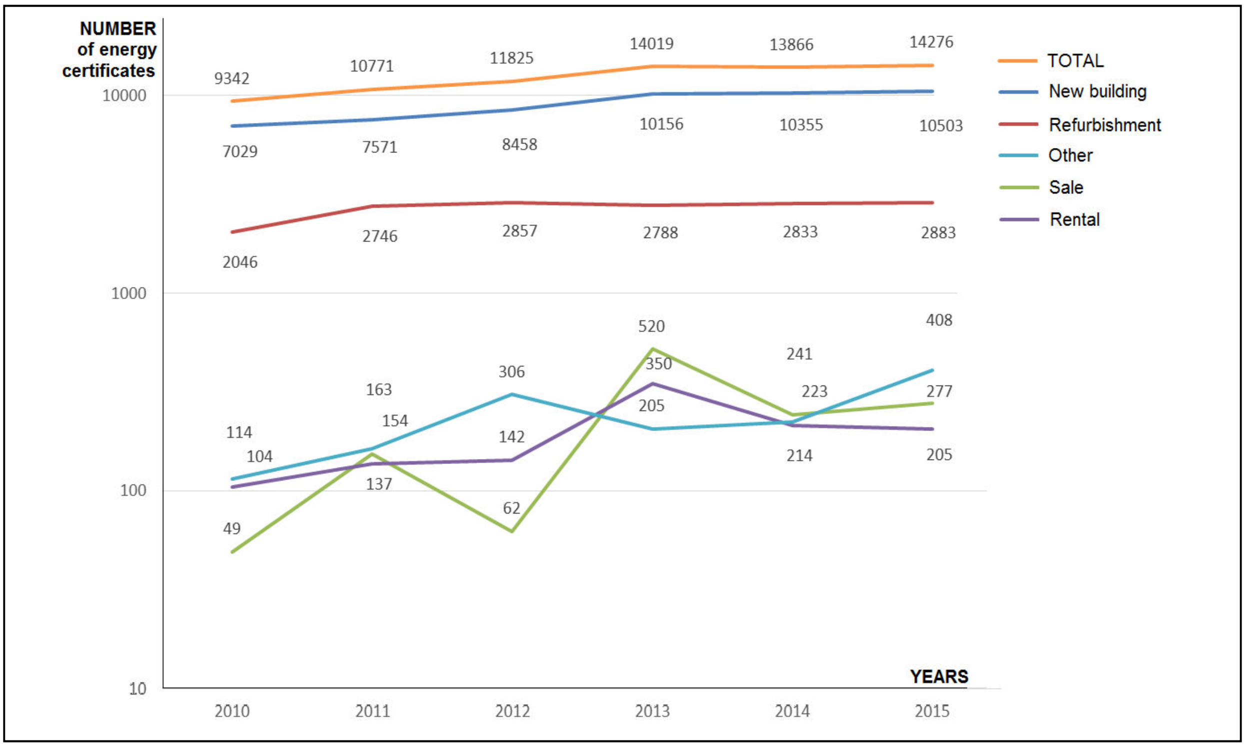

Figure 3. Number of the issued energy certificates in Slovakia according to measures or activities applied to buildings

INSPECTION OF ENERGY CERTIFICATES

Statutory inspection of issued energy certificates is carried out by the SOI (*Slovak Trade Inspection*) on request of the Ministry of Construction and Regional Development. Inspections have been carried out in a wave covering period of the first quarter 2016 until first quarter of 2017. Summary of the inspections is presented in Table II. The table shows that 86 % of the issued certificates was evaluated as satisfactory with respect to the statutory requirements.

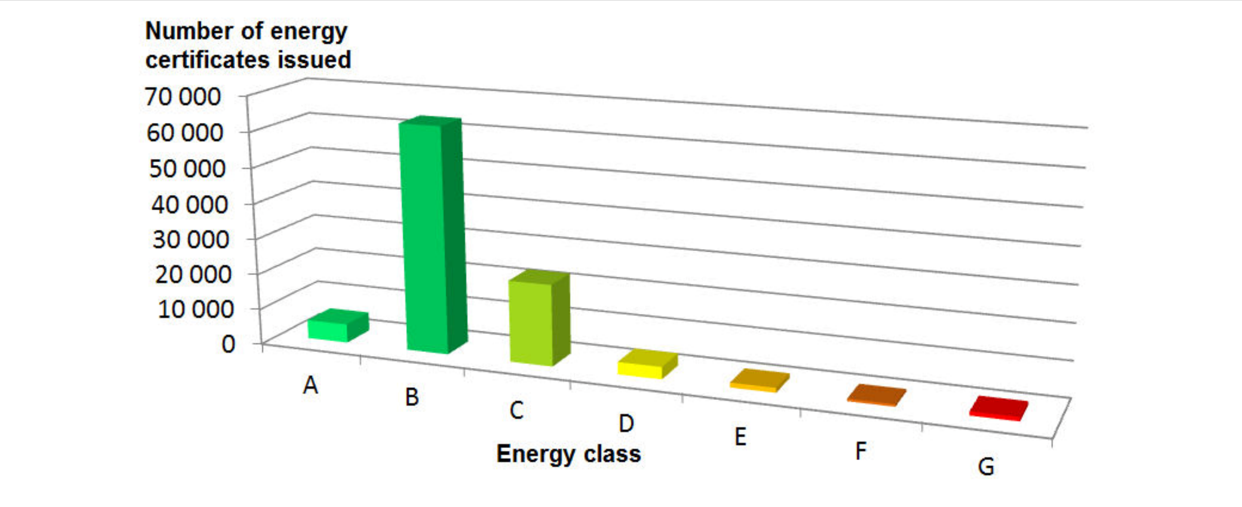

Figure 4. Number of the issued energy certificates in Slovakia according to the energy classes (in the period 2009 – 2016)

TABLE III. RESULTS OF INSPECTIONS OF THE ISSUED ENERGY CERTIFICATES

Region	**Number of inspections carried out**	**Satisfactory results of the inspection**	**Unsatisfactory results of the inspection**
Bratislava	30	22	8
Trnava	15	15	0
Trenčín	10	10	0
Nitra	20	15	5
Žilina	30	24	6
Banská Bystrica	33	32	1
Prešov	46	38	8
Košice	16	16	0
Total	**200**	**172**	**28**

CONCLUSIONS

It can be concluded that energy certification of buildings is still a developing process with necessity to implement further improvements. Data for archiving and statistical evaluation are well chosen and can provide useful information on the status and development of energy performance of lighting in buildings. Current system is, however, not satisfactory. The data must be input directly to the system and not through an annex to energy certificate. Then the system will be capable to process the data and to provide useful outputs. Data uploaded up to now are not lost but to process them, they need to be re-typed from archived annexes. It must be emphasized that monitoring of energy certificates is the most important feedback and confirms that this European measure is meaningful and leads to overall improvement of energy performance of buildings.

ACKNOWLEDGEMENT

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Lighting Culture

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***Abstract*— Based on a survey in our paper we would like to refer to some public comments which may be relevant to the lighting technicians. In this context firstly we show the regional distribution of colour temperature preference. Then we show how everyday people understand and use basic lighting technical terms. We would like to demonstrate peoples' shopping habits, showing their preferred places, the ways they choose light sources and how satisfied they are with the quality of the products and the professionalism of the service. Concluding from the findings of our research, lighting technicians can decide what are the most necessary parameters of light sources that we have to indicate on products in order to help the public choose the optimal product for their use. Based on the research, we got information about how to increase consumers' confidence.**

***Index Terms*-- Colour temperature preference, customer satisfaction, lighting technical terms, parameters of light sources, shopping habits.**

INTRODUCTION

Lighting technology is a human engineering science – we believe and teach this in higher education. All the sciences are human in so far as these are for people, and lighting technology is directly related to our life: it serves our comfort and security in all walks of life. The way we can have it serve us is a major part of our culture.

Looking around in our official or private environment and looking around on the shelves of supermarkets or lighting shops also with a professional eye, we can find such a wide range of modern(?) products that it is quite difficult to get through it, even for us.

What is the reason for the fact that in spite of the ample supply and rapidly developing product range, the lighting solutions realized with these – with rare exceptions – only lag behind the possible technical standards? Maybe the function of lighting in human life is not effectively imprinted in the public consciousness? Or maybe there is a lack of general professional rudiments?

Having involved lighting technical professionals in a research project, we tried to answer these and similar questions in 2004 with a survey made by asking 128 respondents in Hungary. Based on the answers we found that the majority of Hungarian people recognize the importance of good lighting but they have little knowledge about professional concepts and expressions and are uncertain mostly about the reliability and technical parameters of products. Several people are not aware of the existence of a special lighting technical training in Hungary and maybe due to this fact, they are not looking for the help of lighting specialists.

During these 13 years many changes have taken place in the field of lighting technology, consequently, as a continuation of our research, we repeated the survey by asking more participants, extending to other central European countries. Economic experts from our university also contributed in the compilation and evaluation of the questionnaire. In this new questionnaire we also considered the technical changes that have occurred during this time. In this presentation we would like to draw conclusions based on the new results and we would like to explain how the opinion of the population has changed over this period.

ABOUT THE SURVEY

Based on a questionnaire of more than ten years ago, we wrote a new questionnaire for people who did not receive any lighting technical training. The questionnaire was completed in 8 countries of Central and Eastern Europe (mainly in Hungary) in their own language. This research can be useful for both instructors and professionals and it can also help improving sales methods. We sent the questionnaire to people who claimed that they did not have any lighting technical education with a wide dispersion in age, education, and region. The answers arrived between 25 September 2016 and 25 November 2016. There were only 6 not evaluable answers from the 2021 pieces we received. The countries participating in the survey and the number of received answers are the next: Czech Republic (101 pcs), Croatia (99 pcs), Poland (92 pcs), Hungary (1406 pcs), Romania (96 pcs), Serbia (71 pcs), Slovakia (56 pcs), Slovenia (100 pcs).

RESULTS

In this paper we would like to show our main findings for example colour temperature preference according to the different regions, lighting technical shopping habits, trust in the market and profession, knowledge of terminology and product knowledge. In addition, we compared the results of this survey with the results we got 13 years ago, and we found that Hungarian people have become more prepared and confident in the field of lighting technology.

Colour temperature preference

People in northern regions not significantly but prefer warm white light source, while people living in southerly areas prefer cool white ones. On the Fig. 1 the green numbers show the percentage of those people who prefer cool white light sources in their home and the black numbers mean the percentage of those people who prefer cool white light sources in their workplace. It is clear that in the southern countries the cool white light sources are more preferred than in the norther countries. The difference between Serbia and Poland is more than fourfold.

We were also curious whether this colour temperature preference was reflected in the volume of products sold. The Fig. 2 shows the percentage of sold light sources of the same type but different colour temperature in the countries. The blue numbers mean the percentage of cool white light sources the yellow numbers show the percentage of natural white and the red numbers mean the percentage of warm white ones.

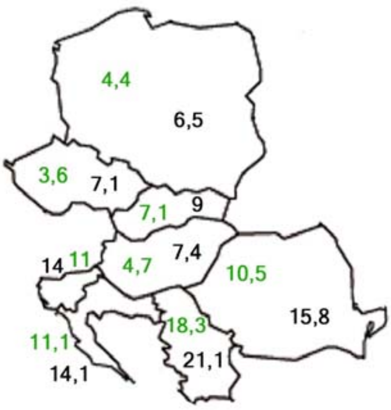

Figure 5. Preference of cool white light sources in percent

Figure 6. Percentage of sold light sources with different CCT

57.9 % of the participants agree that the colour temperature affects their mood but the deviance is very large in this field. While 80.3 % of the Hungarian participants considered this, in Serbia it was only 39.4 %.

Residents of East-centre European countries are aware that inadequate lighting can cause minor health problems. Nearly half of the respondents thought this, while only 9 % said that there is no effect on inadequate lighting for health.

Actual habits

Exceeding all expectations, most participants claim that home lighting devices are purchased in electronics stores or special lighting technical shops. Hypermarkets got to the third place. Buying on the internet and other facilities were on the last two place. Surprisingly, 7.6 % of the respondents had put the lighting specialty stores only to the last place.

Regarding the kind of light sources used, the countries can be divided into two distinct groups. In the first group containing Croatia, Slovakia, Czech Republic and Romania the most popular light sources are LEDs, replacing the CFL and incandescent light bulbs. The ratio of LED light sources is in this countries is above 85 %, but in Slovakia this value rose above 91 %. Much less LED light sources are used in the other countries. Instead, the compact fluorescent lamp and the traditional bulb are the most common. Surprising but 25.2 % of Hungarian respondents rated the halogen lamp to be the most popular light source. It is conceivable that they can't realistically differentiate between different types of light sources.

After all, it is natural that 76.3 % of the respondents think the LED light source is the most energy efficient. But it is surprising, that only 25 % of the users who prefer LEDs think the LEDs is the most effective light source. Revealed that 21.1 % of LED users think that the most effective light source is not the LED.

By asking customers we wanted to know what are the most important data for them when they choose a light source. The preference sequence is quite surprising.

It can be established that the preference sequence of lighting technic parameters during buying lighting technical products are very large. Usually the most important factor is the price for the costumers, but they also looking for the life time, energy efficiency, technical parameters, design and the brand. This establish is general but there were 2 countries who we can learn from. In Hungary and Slovenia the most important factor is the energy efficiency when they bus a light source. This is the most important parameter by the 27 % of Hungarian participants and 30% of Slovenian participants. The third important parameter what participants chose is the life time. It is very surprising that in Czech Republic 42,9% of participants think that the energy efficiency parameter is not the most important parameter. It can be connect to the different energetic politics in this country.

As we can see on the Fig. 3. 41% of respondents need help when they buy lighting technical products.

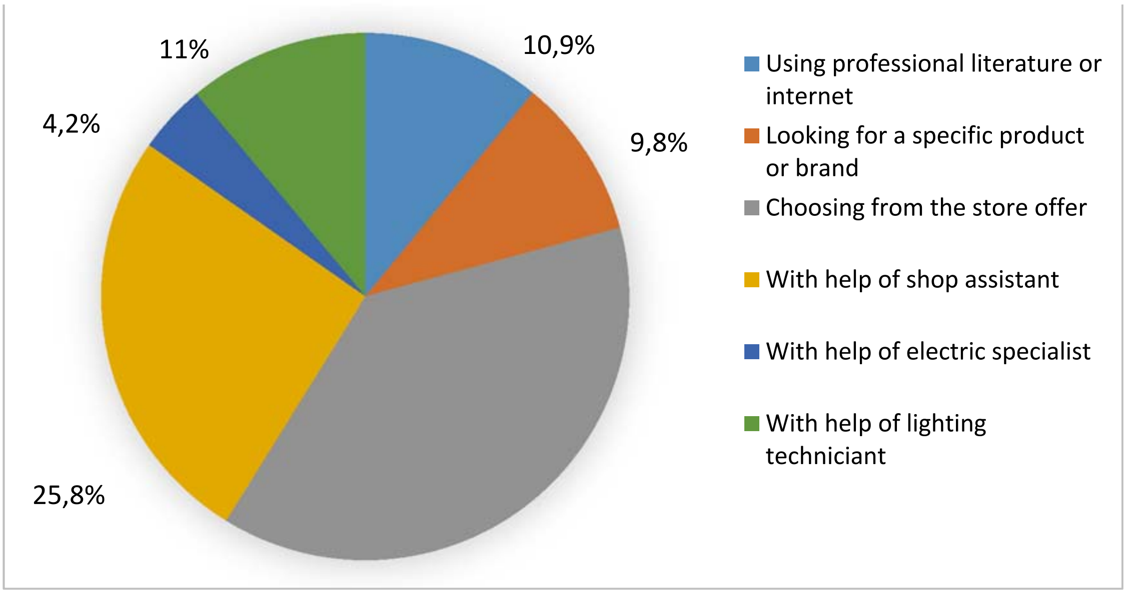

Figure 1. Choosing of light sources

This is very a good result. But it is interesting that people do not want help of lighting technicians when they rebuild or build a new house. Only the 18.3 % of Easter-centre European participants want help of lighting technical professionals during large renovation or building new houses. It is very surprising that only 10 % of participants ask help of electronics professionals.

Finally, we wanted to know what are the most important parameters what costumers are looking for on the box of light sources. These are the next: voltage, power, colour temperature, life time and the price. Just few people looking for information about waste management, product and packaging design. There is only 10 % of respondents who is looking for the CE sing on the products.

Confidence against market and professions

Most of the participants (62.6%) think that reason of the wide range of lighting technic products is connecting with market interest. Only the 29.3 % think that different luminaires types are usable for different circumstances. There is only 7.8 % of participants claims that there are esthetical reasons of these wide product range.

Regarding to the value-price range the Hungarian participants are more optimistic. Generally (52.9 %), people think that the price and the value of the products is proportional but the 32. 5 % of participants think that prices are too high to the quality. In this field there is large difference between the examined countries.

We were curios whether people believe that products are undergoing a full investigation. 43.3 % of participants think that the products they buy are perfect because somebody examined them, there is 33 % who think that products are examined by safety parameters and only 20 % think that products are examined according to health conditions. In this field the Serbian and Croatian participants have worse opinion.

We were curios whether people think that shop assistant get enough lighting technical education to solve costumers. The figure 4. shows on a 1-10 scale whether, according to customers, the shop assistants have received enough lighting technical training or not.

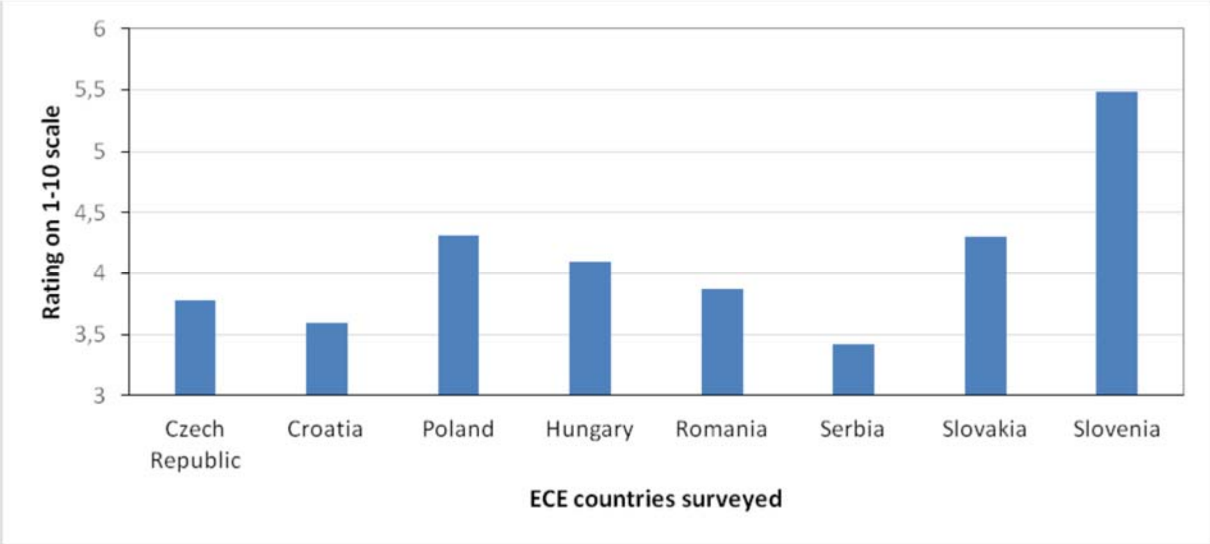

Figure 2. Competence of shop assistants by customers' opinion in East-central Europe

The cumulative average of countries is 4,1. As we can see on Fig. 4. Slovenian habitant are the most satisfied with their shop assistants knowledge but this opinion is just a bit higher than the medium level.

It is very important that in the case when there were be enough lightening technical professionals in shops 89-6 % of participants would need their assistance. There is only 15.5 % who do not need any help.

Parameters looking for by costumers

We examined that what are those parameters of light sources what costumers looking for on the package. We know there are lot of useful parameters about light sources but costumers are not interested in all of them. So, we wanted to know what are the most important parameters that they are looking for:

- 64.3 % of participants looking for the voltage parameter on the package.
- 72,6% of participants looking for the power parameter on the package.
- 49.9 % of participants looking for the life time on the package.
- 56.7 % of participants looking for the colour temperature on the package.
- 49.7 % of participants looking for the energy efficiency on the package.
- 38.1 % of participants looking for one kind of lighting technical parameter on the package but because they do not know the professional expression they could not specify the correct name of the parameter.

Knowledge of professional expressions

According to chapter D. we wanted to know whether non-professional people how can use lighting technical professional expressions. There are 4 main expressions in professional language: luminous flux, luminous intensity, illumination, lumination but ordinary persons use only one word for all of this. We were curious what they mean about this one word which in Hungary is “fényerő”, which means “light power”.

According to the Fig. 5. people think that the most important lighting technical parameter what they call “fényerő” (light power) means the illuminance or the luminous flux. Most of the people does not know the meaning of luminous intensity, illuminance, luminance or luminous flux.

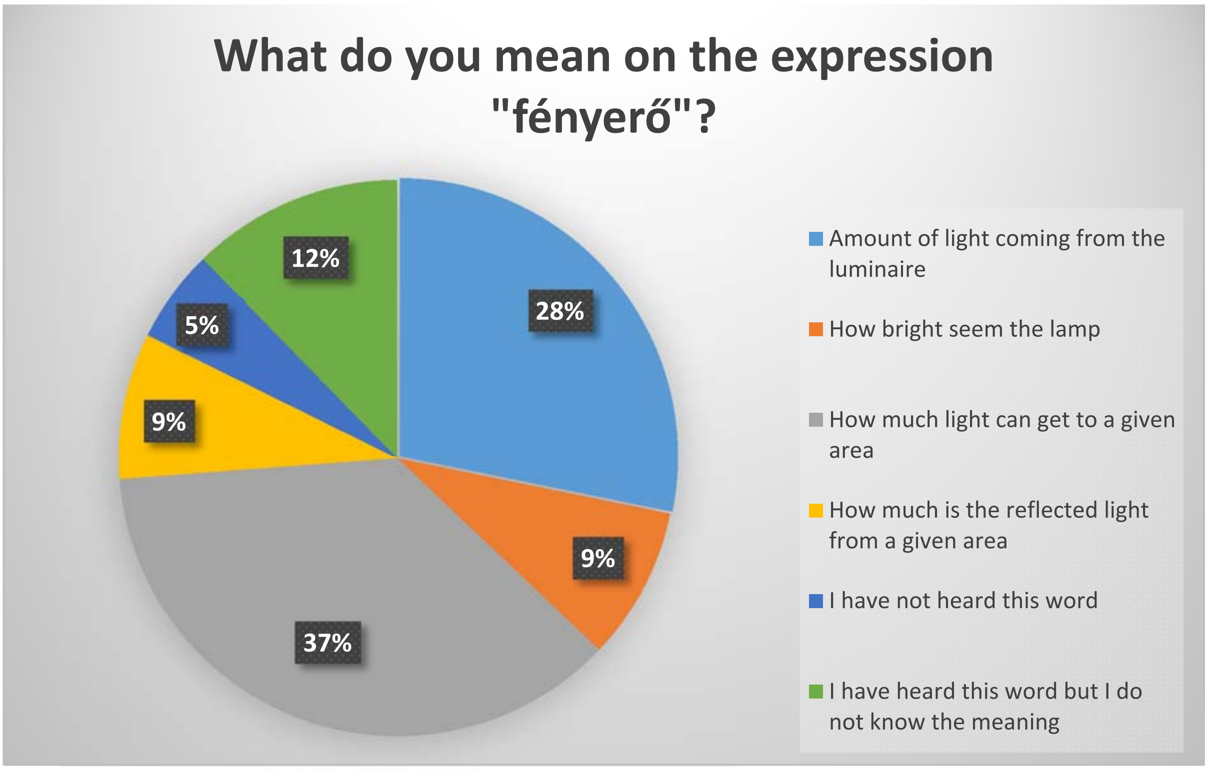

Figure 3. The common meaning of "fényerő" (light power)

Recognition of light sources

On the internet survey we show four figures for participants and we ask them to recognize them. We were very satisfied because most of participants could recognize all of the most popular light sources. Some of the participants (cca. 33 %) blended the halogen bulb and the filament LED light.

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Beleuchtungstechnik 4.0
The 4th Edition of a Lighting Education Book

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***Abstract* — The quick development of the LED has changed the overall field of lighting technology triggering the need for updating all sorts of documents and literature in the field of lighting. The German lighting association LiTG has initiated a project to work on a new, completely revised version of the book "Beleuchtungstechnik" by Roland Baer. This new 4th edition of the book was published in September 2016 and forms the result of the collaborative authorship of more than 20 individuals who are actively involved in lighting education. The book addresses the needs of lighting designers, educators and students from various fields of application. It serves as a source of information for the daily practice as well as study material to support efforts of students in Bachelor and Master programs.**

***Index Terms*— Daylighting, Education, Electric Lighting, Fundamentals, Lighting Control**

INTRODUCTION

The German Lighting Organization “Deutsche Lichttechnische Gesellschaft e.V.” (LiTG) initiated a working group of lighting educators in 2010. During their meeting at the Conference “Licht 2014” in Den Haag, NL, this group discussed a work item to contribute towards a new edition of the German book “Beleuchtungstechnik” (illumination technology). Back then, the third edition of the book had been sold out but the market still saw a huge need for it. “Beleuchtungstechnik” was initially published in 1990 by the authors Roland Baer, Dr.-Ing. Martin Eckert, Dr. sc. techn. Dietrich Gall and Reinhard Schnor.

The book led to a constant stream of sales throughout the various editions. This book is suitable for students who study lighting as well as professionals as a reference for their everyday work.

After the third edition was published in 2006, solid state lighting technology got introduced into the market and took off rapidly. It was clear to the LiTG working group that this disruptive technology change in the field of lighting needed to be reflected in a new edition. It became obvious that the 4th edition of this book would require a complete overhaul. The members of the working group got enthusiastic about the idea and initiated discussions with the editor.

More than 20 individuals who are all involved in lighting education have contributed towards the new edition. Among them were authors who provided content but also reviewers to ensure the quality of the outcome. Next to the initial editor Roland Baer, two co-editors were added to the team: Prof. Meike Barfuß and Dirk Seifert. The group set the ambitious target to complete their work so that the finished book could be presented at the next Conference “Licht” in Karlsruhe in September 2016.

THE PROCESS AND TEAM

Through active communication and thorough project management, the team of authors all agreed to take on parts of the book. Quite a number of sections required a thorough review which in some cases resulted in completely re-writing chapters and sections. Selected topics were elevated from being covered in a subsection to now having a dedicated section in the book. In addition, a completely new chapter on exterior lighting has been added to the table of contents.

The authors took on entire chapters or particular sections. To ensure the overall quality, each author as well as additional experts agreed to peer-review other chapters or sections. After the reviewers submitted their comments back to the authors, the authors updated their contributions accordingly. This process is nearly comparable to the standard peer review process applied by ISI journals. The one exception was the fact that the reviewers were known to the authors. This transparency allowed for direct communication between these two groups of people in the interest of accelerating the process to finalize the texts. This transparency is also reflected in the final version of the book – both, the authors and the reviewers of chapters or sections are mentioned.

Despite all efforts of streamlining the process, the set target date for publication remained ambitious. The timelines related to the necessary process of turning a finished manuscript into a printed book were fixed and defined the ultimate deadline for all authors. Subsequently, there were three major deadlines for the team of authors and reviewers:

1. Final draft to be submitted to the editors
2. Peer-review comments to be sent back to the authors
3. Final version to be submitted to the editors

While this is already difficult enough if there is only one author and one reviewer, the challenge increased by the fact that there were about 20 authors, i.e. 20 such processes that had to run and be completed in parallel. If only one of these parallel processes had failed to meet the final deadline, the entire project would have been at risk.

The team responsible for the creation of the new edition consisted of the following authors: Prof. Meike Barfuß, Dr. Hartmut Billy, PD Dr.-Ing. Peter Bodrogi, Dipl.-Ing. Wolfgang Cornelius, Dr.-Ing. Peter Flesch, Dipl.-Ing. Cornelia Fürst, Prof. Dr.-Ing. Roland Greule, Prof. Dr.-Ing. Tran Quoc Khanh, Dr.-Ing. Martin Kirsten, Prof. Arch. Werner Osterhaus, Prof. Dr. med. Dipl.-Ing. Herbert Plischke, Dipl.- Ing. Uwe Rabenstein, Prof. Dr.-Ing. Alexander Rosemann, Prof. Dr. sc. nat. Christoph Schierz, Dipl.-Ing. Hans-Georg Schmidt, Dipl.-Ing. Dirk Seifert, Dipl.-Ing. Stefan Söllner, Dr. Armin Sperling, Dr.-Ing. Cornelia Vandahl and Prof. Dr.-Ing. Stephan Völker.

The team got completed by the following peer-reviewers: Dr. Matthias Hessling, Prof. Dr. Paola Belloni, Prof. Dr.-Ing. Horst Riechert, Dr. Felix Serick, Prof. Mathias Wambsganß, Prof. Dr.-Ing. Paul W. Schmits and Dipl.-Ing. Christoph Heyen.

The initial editor, Roland Baer, remained a key player in this team and provided both, valuable guidance and leadership, to the other editors and authors.

Figure 1. Cover page of the book Beleuchtungstechnik [1]

BELEUCHTUNGSTECHNIK 4.0

The final result of the work, the 4th edition of the book Beleuchtungstechnik was available at the international conference “Licht Gemeinschaftstagung” of the lighting associations LiTG (Germany), SLG (Switzerland), LTG (Austria) and NSVV (The Netherlands) in Karlsruhe in September 2016. Figure 1 shows the cover page of the book.

The book is structured into the following chapters:

1. Fundamentals
2. Light Sources and Equipment
3. Luminaires
4. Illumination with Daylight
5. Illumination Systems in Building Interiors
6. Illumination Systems for Exterior Applications
7. Appendices

The book has 496 pages and aims at covering a thorough overview of the various topics. Its main purpose is to provide a good basis for those who study lighting as well as a good handbook for those who work in the field of lighting. In order to use the book for educational services, many efforts have been undertaken to keep its overall sales price low. This goal has been reached so that especially students of universities and universities of applied science can afford it. This new edition of the book is already in use in lighting courses provided by universities and universities of applied science in different countries.

Chapter 1 explains the relevant fundamental knowledge which has been expanded to consider the relevance to LED technology (e.g., optical lenses for LED applications). The topic colorimetry has also been extended and is now a section on its own. Figure 2 shows a picture from the colorimetry section.

Figure 2. Example figure on colorimetry, taken from [1]

The new edition of Beleuchtungstechnik also addresses the non-visual effects of light and points out the difference between the visual response and the melanopic response to visual radiation. This field represents a topic area in which still a lot of research is happening so it underlines the importance of considering non-visual aspects of lighting for lighting design. Figure 3 is an example of how the image forming and non-image forming effects of light are being processed in the human organism.

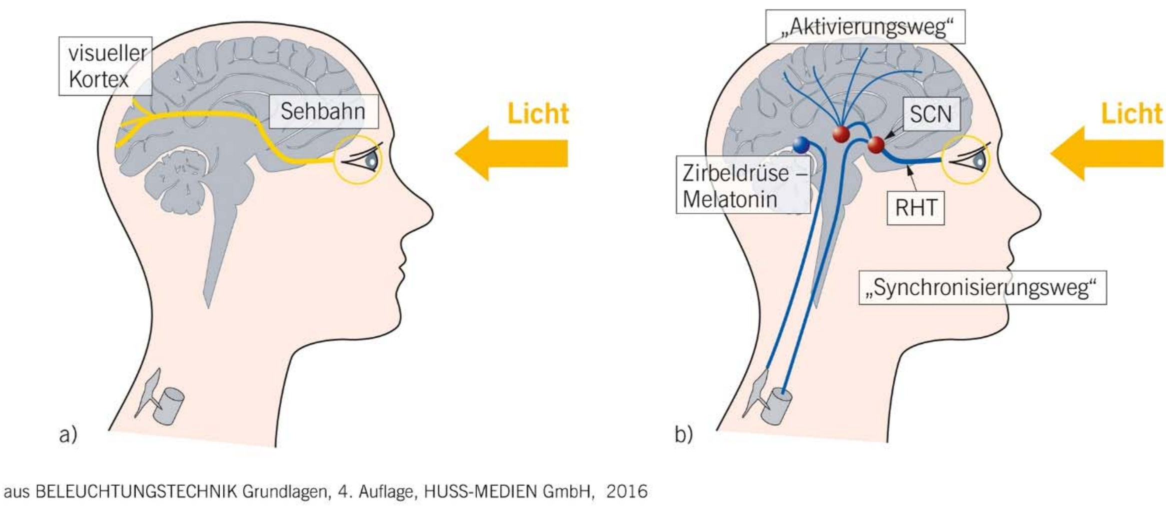

Figure 3. Example figure from the section light and health, taken from [1]

After introducing the fundamental knowledge relevant to light and lighting, chapters 2 and 3 look at the generation and distribution of light via lamps and luminaires. Both of these chapters address the conventional light sources but also introduce the solid-state lighting technologies. By this, they complete the overview and address the entirety of today's lighting technologies available on the market. As an example, figure 4 shows the variations of different LED spectra which shows the complexity of correctly applying solid state lighting technology.

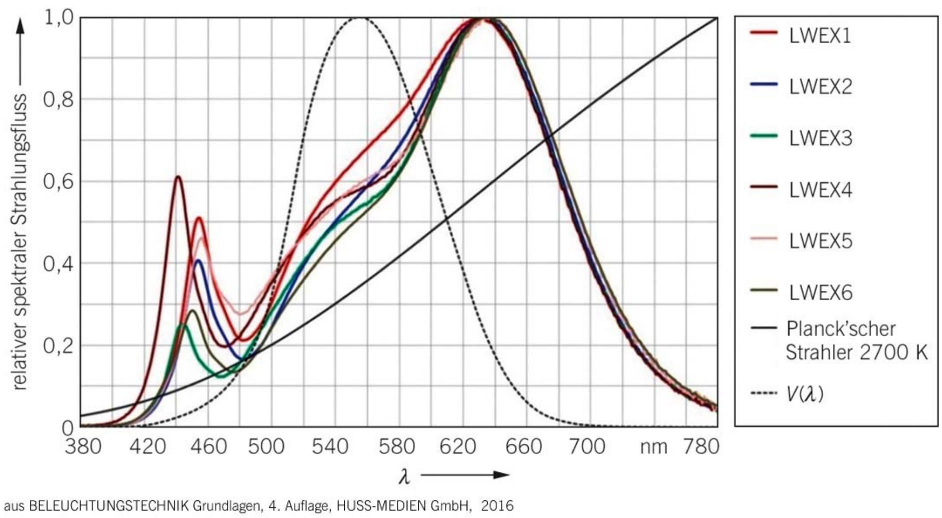

Figure 4. Example figure on the relative spectral radiant flux of LEDs, taken from [1]

Chapter 4 takes a look at the natural lighting available to us. Designing buildings with harvesting daylight in mind offers many challenges but can provide very rewarding results. The chapter provides an overview of key aspects of daylighting and explains means to control the amount of daylight entering a building such that an acceptable level of visual comfort can be maintained.

The last two chapters look at the application of lighting technologies introduced in the previous chapters. Both chapters follow the general line of introducing the recommendations in place followed by describing the design process.

Chapter 5 "Illumination Systems in Building Interiors" enhances the "traditional" set of quality criteria for lighting. Many of these additional items cannot easily be described or measured but yet form a means for comparing different lighting solutions. The chapter continues to describe the combined use of daylight and artificial light, the lighting design approach as well as economic considerations. Relatively new approaches like dynamic lighting and perception based lighting design are also touched upon.

Chapter 6 "Illumination Systems for Exterior Applications" forms a completely new chapter to the book and completes the application fields for lighting. Next to the applications street lighting and tunnel lighting, the chapter also focuses on outdoor work spaces, sports lighting as well as architectural lighting. Within the latter topic, the chapter underlines the need for a masterplan so that the lighting solution integrates in a harmonic way in the overall urban context.

Use for (continuous) professional development

There are two key target groups for this book: professionals and future professionals in the field of lighting. The book serves as both, a collection of knowledge as well as a reference to look up particular topics. These two uses correspond to the aforementioned target groups.

The structure of the chapters forms a sort of study guide that establishes a solid foundation by introducing the fundamentals. This knowledge is essential to understand the following chapters. Next to the chapters on generating and distributing electric light (lamps and luminaires), the chapter on daylighting introduces the natural light and means to control its utilization in building interiors. The last two chapters deal with the application of lighting systems in the built environment for interior and exterior applications.

To a large extent, this structure is aligned with most approaches of lighting courses taught at German universities and universities of applied science.

Lighting professionals use this book as a reference for refreshing their knowledge on particular topics or getting a quick overview on topics they are not yet familiar with. From that perspective, the book “Beleuchtungstechnik” supports the continuous professional development or similar efforts when preparing for the exam to achieve the qualification European Lighting Expert [2].

Summary

The new edition of the book Beleuchtungstechnik is a completely revised version of the book. It includes aspects for Solid State Lighting and forms an up to date fundamental book suitable for students and professionals interested in the field of lighting. It supports the education at universities and universities of applied science as well as continuous professional development such as preparation for the European Lighting Expert (ELE) exam offered by member institutions of the European Lighting Expert Association (ELEA).

The book Beleuchtungstechnik continues to be one of the top selling lighting education books in the German language. First steps towards checking the feasibility of publishing this book also in English have recently been taken.

Acknowledgements

The authors would like to thank the entire team of authors and reviewers for their contribution and dedication towards the completion of the book. Furthermore, we thank the publisher Huss-Medien GmbH for all the support provided all along.

Special thanks go to Roland Baer. Nearly 30 years ago, he published the first edition of Beleuchtungstechnik which has since formed the basis of the lighting education of many professionals who are now working and contributing towards the success of the lighting industry. His vision back then, his efforts along the way as well as his dedication towards this project have been inspiring for all of us and provided us with the energy required to complete this work!

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Visual Comfort Evaluation in Residential Buildings: a Simulation-based Study

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***Abstract*— Despite desirability of direct sunlight access in residential buildings, visual discomfort risks and the relevance of their evaluation methods for these building types are unknown. A simulation-based study was performed on typical residential buildings with heritage value in central Copenhagen in order to evaluate their daylight conditions and visual comfort characteristics using the existing methods. The visual comfort evaluations were done employing an immersive spatial rendering method where a range of view-directions was evaluated for each room type. After verification of existing methods' applicability, a new method for quantification of a relative contrast over the 360◦ span of field of view (FOV) was introduced.**

***Index Terms*—Daylighting, Gaze (View) direction, Residential buildings, Visual comfort, HDRI techniques**

INTRODCUTION

Visual discomfort caused by daylight has been observed in extend targeting commercial buildings with a focus on office buildings. These studies have proposed several metrics to describe discomfort caused by the luminance distribution in the field of view. These methods were developed to assess discomfort due to excessive or unbalanced luminous contrast within a fixed Field of View (FOV) with respect to a task-area [1]. Task-oriented visual comfort evaluation, however, does not seem to be as relevant in residential interior spaces where the classification of task and its position is less defined. Although several studies have explored the applicability of different daylight metrics to residential buildings [2] and daylight energy saving benefits [3], the visual comfort assessment methods in this building typology has not been addressed.

Visual comfort assessment methods are developed majorly in experimental set ups under electrical lighting with few exceptions that address this phenomenon under daylight conditions [4]. These methods rely on empirical models where subjective human response is correlated with a sophisticated relation of physical photometric quantities that represent perceived luminance contrast at the eye level. One of these models, which addressed daylight-induced visual discomfort, is the Daylight Glare Probability (DGP) index. The index is used to quantify the percentage probability of glare occurrence, developed for office rooms during daylight conditions [5].

The DGP formula consists of two main components. The first component of DGP formula is vertical illuminance at the eye level (E_V). This parameter shows a particular sensitivity when direct sun is a cause of visual discomfort. The second one, referred to as Glare Impact (GI) [6] is a summation of all the glare sources luminance weighted by their corresponding size in a solid angle and the sensitivity in the FOV measured by a position index [7], divided by Ev. The GI accounts for contrast-inducted glare, meaning the discomfort caused by high contrast between the center area of FOV and the surroundings. With the GI component, the contrast part of the glare is determined based on the intensity of the glare source, its size and location. Nevertheless, its contribution to the overall result for DGP is considerably smaller than Ev. As a result, the impact of contrast on the potential visual discomfort sensation is considered only to a limited extend when using the DGP index.

The chosen residential building type for this study represents a larger range of buildings in central Copenhagen, built in period from 1850 till mid 1950s, using the same principles. These buildings have masonry thick walls with smaller windows. The daylight levels are low and presence of daylight and direct sunlight during the majority of the occupied hours (7 a.m. – 10 a.m. and 4 p.m. – 6 p.m.) is rare. Therefore, almost no discomfort caused by excessive glare or higher illuminance levels at eye is detected when running the numerical simulations for the DGP index. However, our preliminary results on daylight availability shows high contrast between window area and the rest of the room. Knowing that contrast variations even in lower luminous environments can cause discomfort [8], in order to detect these conditions in these buildings, we have developed a new method based on relative illuminance contrast and applied for detection of potential visual discomfort in the case study building and determination of its view-direction dependency [9, 10]. The newly developed Relative Contrast model (RC) is based on relative contrast in FOV which shows the contrast variations in the FOV for the whole space.

In order to compare the view direction dependency and applicability of the DGP index components and RC, we ran a series of simulations. High dynamic range (HDR) images with angular fisheye perspective were rendered for an immersive range of view directions for different room types in the selected case study. These simulations were done for 4 time slots during the day within the chosen occupancy schedule relevant for the residential buildings and over 4 time points of the year representative of the sun path behavior for Copenhagen, Denmark. The images were then processed and the relevant photometric quantities were derived and compared. Our results show that, although high relative contrast situations exist within the observed period for view directions not only towards window direction, these situations are not captured by existing methods. High contrast variations within the FOV could cause certain unwanted behavior such as closing the curtains or shutters and excessive use of artificial light.

METHODOLOGY

Photometric behavior of a selected case study was observed using numerical simulations in Radiance. The selected case study is an approximately 100 years old multifamily, multistory building located in the northern part of the Copenhagen central area in a dense urban tissue. The building has 5 above ground stories – ground floor plus four floors. On each story there are 8 apartments - 6 of them with the E-W orientation, 1 facing N-S, both types consisting of living room, bedroom and kitchen and 1 apartment with the windows facing SW and NE, having one additional bedroom. The contrast in the rooms of case study building has been investigated based on the HDR rendering techniques using angular fisheye perspective images in the lighting rendering tool Radiance [11].

The contrast was calculated as a standard deviation of Illuminance values on the image. It was thus necessary to first derive the illuminance values of the images' pixels, bearing in mind that the image is a 2-dimensional perspective transformation of 3-dimensional space. For this purpose, Evalglare has been employed and furthermore the data obtained from Evalglare was used in Matlab to calculate the Relative Contrast (RC). The whole process is described in details in the following paragraphs.

Immersive Spatial Approach

In the further investigations for contrast assessment in the rooms of the case study building, the immersive spatial approach [12] has been applied. Instead of choosing one camera view direction for the simulation, a range of view directions were considered to create a set of images that could constitute a base for contrast analysis. For this purpose, the camera was placed in the center of each of 4 investigated room – Living Room and Kitchen in two apartments (LR2, LR8) at the height of 122 cm (the average height of a sitting persons eyes) and oriented towards 9 different directions. The rule for adjusting camera directions was the same for all the rooms investigated, despite their orientation – first view direction was perpendicularly towards the window, and the following ones were clockwise rotated 40° apart.

The HDR perspective images created for the 9 view camera directions in the 4 selected rooms have been produced for several specific points of time. The selected points in time are in equinox and solstice days, during the occupancy hours – 20th March, 21st June, 22nd September and 21st December at 7 a.m., 9 a.m., 4 p.m. and 6 p.m. During the simulation process it turned out not to be possible to render the images for 21.12 at 6 p.m. due to insufficient level of daylight at this time of the shortest day in the year. The resulting overall number of images for all the directions in all rooms selected for the investigation in the points of time listed above is 540.

Solid angle and Position index determination using Evalglare

The HDR images obtained as a result of Radiance rendering angular fisheye images, meaning that to generate them the angular (-vta) view type is used. The principle for fisheye projection is that the distance from the center of the image is proportional to the angle of the camera's view direction. As a result, half of the environment (in this case the room space) is projected onto a spherical image. Using the Radiance-based tool Evalglare [5], size of all pixels in solid angle values for the fisheye images were determined. Another parameter derived from Evalglare, which will further be used in the novel contrast assessment method is position index (PI) parameter for all pixel points. These two parameters were then used in RC for quantifying the relative contrast of each rendered image. Within the same processing workflow in Evalglare, DGP, Ev and GI components were also derived. The later was then calculated for all instances in Matlab.

Image Contrast Calculation in Matlab

Sets of images showing the 9 view direction perspectives of each room at one point in time were read in Matlab along with their pixels parameters derived from Evalglare. The first step in order to assess the contrast on each of the images was to calculate the illuminance values of image pixels. For this purpose, the RGB values of each pixel have been read in Matlab and the illuminance was calculated for each pixel based on (1).

$$\text{Illuminance} = 179*(0.265*R + 0.670 * G + 0.065*B) \qquad (1)$$

In order to account for the pixels' sizes, the calculated values of pixel's Illuminances were multiplied by corresponding solid angle values. The resulting pixels illuminance values weighted by the pixels' sizes were used to calculated the contrast on each image. The relative contrast (RC) was calculated based on the standard deviation of pixels illuminance values according to (2). This relative contrast was also calculated based on the pixels illuminance values weighted by the position index: RC_{PI} (3).

$$RC= \frac{1}{L_m}\sqrt{\frac{1}{N}\sum\left((L_i\,.\,\omega_i)-\mu_1\right)^2} \qquad (2)$$

$$RC_{PI}= \frac{1}{L_m}\sqrt{\frac{1}{N}\sum\left(\left({L_i\,.\,\omega_i}/{P_{index}}\right)-\mu_2\right)^2} \qquad (3)$$

Where
L_m = average luminance of the scene
L_i = luminance of the pixel
ω_i= Solid angle of the pixel
P_{index} = position index of each pixel
μ_1 = mean of all value corresponding to $(L_i\,.\,\omega_i)$
μ_2 = mean of all value corresponding to $\left({L_i\,.\,\omega_i}/{P_{index}}\right)$

DGP_c: The Photometric Relation of DGP

In order to determine whether the calculated contrast based on standard deviation of images' illuminance value shows more sensitivity to view direction than DGP, the photometric components of the DGP meaning Ev and GI were derived processing all the images. The sum of Ev and GI represents the photometric part of the DGP formula. This relation which is called DGP_c includes here only the photometric quantities of DGP without the weighting exponents which are determined by the empirical modelling process in accordance with the subjective responses from the study behind the formula. DGP_c allows for comparison of the results only based on photometric variations. The purpose of calculating Ev and GI for the images was to determine what DGP_c components has the main contribution to the overall result of DGP_c in the situation where glare is not detected by application of DGP – most of the cases in the investigated building.

RESULTS

The results from the study are shown in radar charts for each time point on rows and time of the year on columns, Fig.1 & 2. In each chart the values corresponding to DGP_c, GI, E_v, RC and RC_{PI} are shown for each of the 9 view directions. On each plot the windows orientation is specified (e.g. in Fig. 1 west is shown with W). Only the results from the two living rooms facing West and South are presented. The results are shown and compared using radar graphs, which is a two-dimensional chart for representing multivariate results, and the observations are described.

Living Room of Apartment 2 (LR2); West-facing windows

One of the rooms, where the visual comfort was investigated is Living Room of Apartment no.2 located on the 4th floor of the building. The apartment is West-East oriented and its area is 45 m^2. The living room has an area of 17 m^2 and its windows are facing west. The visual comfort parameters in the room are presented on the radar plots in Fig.1.

The graphs show that RC_{PI} has the most sensitivity to view direction. The shape of the RC_{PI} plot is never symmetrical in relation to the window, unlike the plots of other parameters for several particular dates. The values of RC_{PI}, however are higher in case of camera view direction 2 and 3 – to the right from the window in most cases, meaning that the relative contrast is much higher when looking to these directions. This is due to the relatively high brightness of the window in relation to the rest of the room and the location of the window in the FOV. The graphs also show that the Ev values are symmetrical in relation to the window, with the highest illuminance directly in front of the window,

gradually decreasing towards the back of the room. GI shows the same trend, however with lower values. In all graphs DGP_c and E_v are almost overlapping.
Despite the season of the year, the plots for all metrics have repetitive shapes for the morning hours. This is due to lack of direct sunlight in the West-facing room. It can also be observed in Fig. 1 that in the equinox days all parameters' values show similar trends both at 4 and 6 p.m., which is due to a similar angle of the sun in these days. Also on solstice day June 21. at 4 p.m. the Ev plot is similar for 7 and 9 p.m., whereas the RC and RC_{PI} show different view-direction dependent tendencies in the afternoon than in the morning. The same can be seen for December 22. – the plot of Ev at 4 p.m. has similar shape to 7 and 9 a.m., the shape of RC and RC_{PI} changes for different periods of the day, indicating that strongest contrast in the afternoon is detected for different view directions compared to the morning.

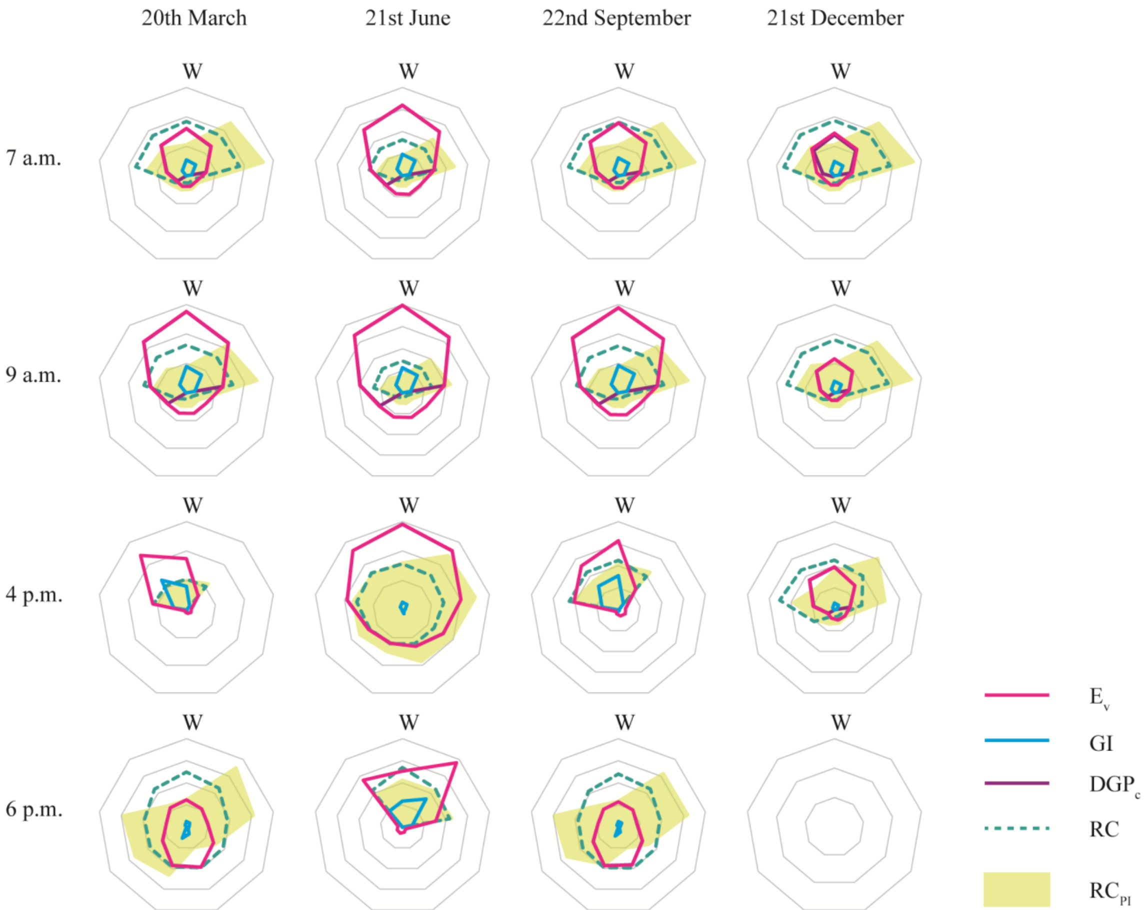

Figure 62 Radar plots of visual comfort parameters in solstice and equinox days at 4 specific hours during the occupancy in living room of apartment no.2

Living Room of Apartment 2 (LR 8); South-facing windows

The visual comfort parameters values were also calculated in Living room of Apartment no.8. Their radar plots can be seen in Fig. 2. This North-South oriented apartment is located on the 4th floor and has an area of approx. 44m^2. The living room has an area of approx. 17 m^2 and is oriented towards south. An overview of plots shows that the morning and afternoon hours of solstice and equinox days for both DGP_c components – E_V and GI, are less sensitive to the view direction than the RC and RC_{PI} parameters. The values of E_V and GI do not show large variations for different view directions, thus the plots have regular shapes and in most cases the highest discomfort glare was only detected in the direction towards the window. Similar to the previous results, RC and RC_{PI} indicate considerably higher view direction dependency of the parameters' values. Other interesting observations show when there is no direct sunlight expected in the rooms, e.g. 7 a.m. and 18 a.m., the shapes of RC and RC_{PI} plots are similar for all the solstice and equinox days. Both parameters values are lowest for the view direction towards the back of the room. RC contrast is slightly higher towards the left side from the window, whereas the RC_{PI} values are highest for the view directions towards the right side of the window. At 9 a.m. and 4 p.m. (both closer to midday, when the angle of solar radiation is highest) the shapes of both RC and RC_{PI} plots vary distinctively for different solstice and equinox days.

CONCLUSIONS

The results from the simulatin-based study on visual comfort asessments in the typical residentail building with heritage value in central Copenhagen showed that this type of building has façade typology that does not allow for sufficient daylight penetration over the year. Moreover, relatively dark interior spaces comparing to the bright window surfaces could lead to visually uncomfortable conditions. However, this is of course a subjective assessment and the same condition can be rated as cozy and appreciated in such building. Nevertheless, the results of the present study show that such conditions of high contrast can not be detected by the exisitng commonly used metrics for visual comfort assessments such as DGP. In cases with low Illuminance levels, DGP model only shows sensitivity when there is a diect and reflected sulight in the FOV. The reson is that the dominant component of DGP is E_V, whereas the GI (Glare Impact), that stands for the illuminance contrast has less contribution to the overall result of DGP index. In this study a newly developed relative contrast model $RC_{PI,}$ is presented as a new approach for visual comfort assessment based on contrast. It allows detecting and quantifying contrast in the room, despite the presence of direct or reflected sunlight in the FOV or lack of it. RC_{PI} values vary distinctively for different view directions in relation to window, unlike the values of DGP and its components that are mostly showing sensitivity towards the window.

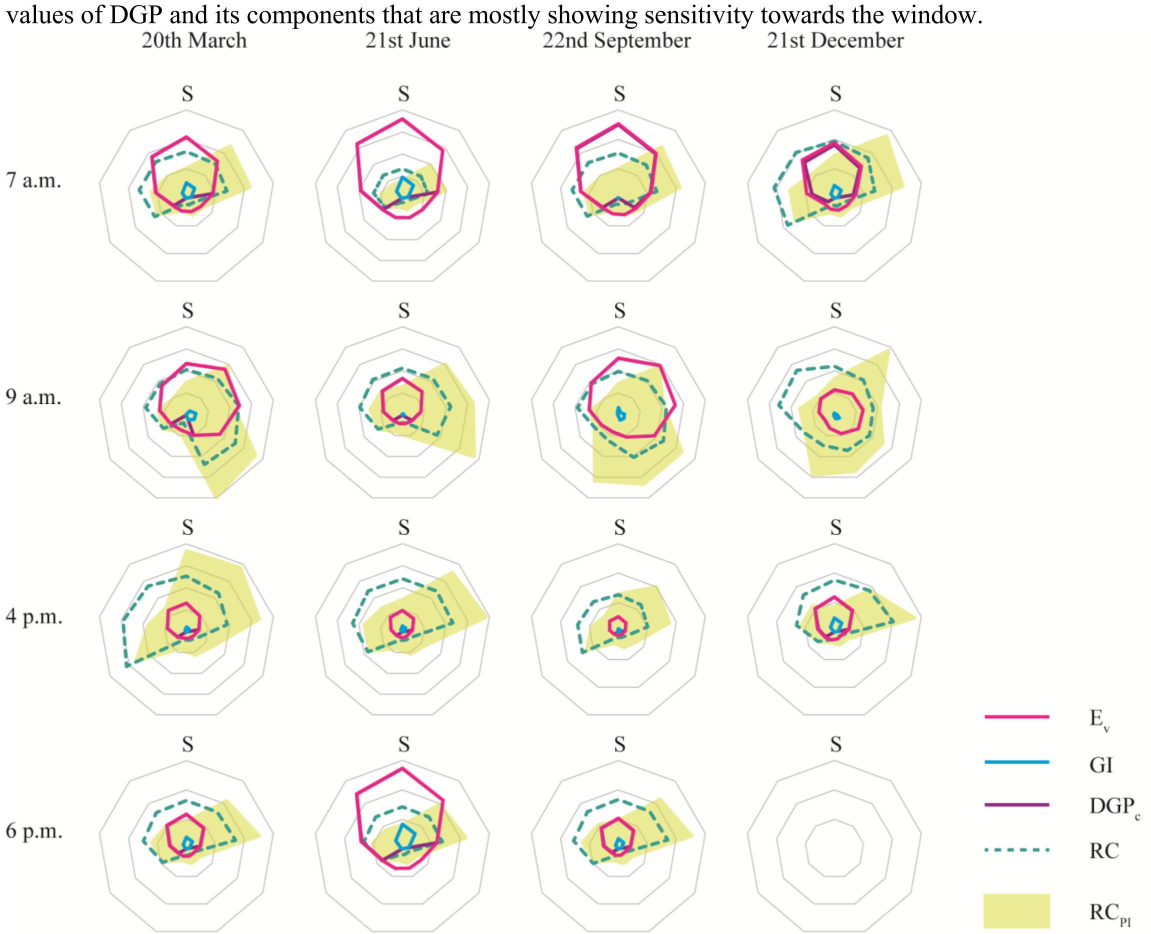

Figure 63 Radar plots of visual comfort parameters in solstice and equinox days at 4 specific hours during the occupancy in living room of apartment no.8

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First Outcomes of an Investigation about Daylighting Knowledge and Education in Europe

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***Abstract*—DAYKE (Daylighting Knowledge in Europe) is a project to investigate the daylighting knowledge and skills of Architecture students and practitioners from different countries within the European Union. This paper introduces the first stage of the research and provides results from a direct survey taken by 161 students from seven schools of Architecture: two in Italy, one in The Netherlands, two in Poland and two in Spain. The results indicate significant national differences in preference and perception of daylit spaces. They also show a lack of knowledge about daylighting metrics and regulations among the respondents. Although the research is undergoing, the preliminary data analysis indicates that there is a need for enhancing the daylight knowledge among future architects.**

***Index Terms*-- Daylighting education, Daylighting knowledge, Daylit spaces assessment, EU regulation, Surveys.**

INTRODUCTION

The European Union (EU) invests many resources in the dissemination of new energy saving strategies and policies [1], [2] and electric lighting design issues have been addressed in several architectural studies and framework programs. Until now, this does not seem to be the case for daylighting design, metrics and recommendations. But this is changing. The daylight evaluation method specified in the *EN 15193* [3] is a step in that direction. Moreover, the daylight assessment methods suggested in the draft of the new European *Daylight of Buildings* Standard [4], [5] will greatly influence the design of the building environment. Architects of today and tomorrow will have great responsibility in delivering the generations of energy efficient buildings to come. It is therefore important that they understand daylighting regulations and their implications on the design.

However, recent studies have revealed that there is a general inadequate knowledge about lighting retrofitting and energy performance evaluation of modern lighting systems [6], [7]. Other studies show that the use of the latest daylighting evaluation tools and metrics remains limited, with practitioners tending to rely on simplified methods and rules of thumb in the early design stages [8], [9]. At the same time, it has been highlighted that there is a need for a better daylighting education [10].

The DAYKE (DAYlighting Knowledge in Europe) research project aims at understanding the status of daylighting education and practice in the EU. The research is focused on investigating: (a) the level of preparation among architecture students and practitioners; (b) the relationship between national daylighting regulations and possible cultural/geographic differences. The project is currently being carried out in Germany, Italy, The Netherlands, Poland and Spain.

PROJECT DESCRIPTION

DAYKE structure

DAYKE is a project based on a system of questionnaires (paper and online-based, all ad hoc developed by the Authors) designed to give complementary information about daylighting perception, education and knowledge.

The first questionnaire is paper-based (Questionnaire A) and is used to evaluate the Architecture students' ability to observe and describe the daylight conditions within a given space as well as their knowledge about daylighting metrics/indicators and regulations. The suggested protocol includes a description of the confined space (a classroom), a photographic documentation and a series of illuminance measurements over the workplanes are taken in the room during the questionnaire.

The second questionnaire is an online survey (Questionnaire B) for the investigation of the differences between conceived and actual daylighting knowledge (on daylighting metrics, regulations, design tools and assessment techniques) and on the national existing daylighting design practice.

The third questionnaire is also an online survey (Questionnaire C) that focuses on the educational offer regarding lighting and daylighting design topics and on the practice of lighting and daylighting design in the Architecture profession in the different countries. The questionnaire is addressed to university staff of several faculties of Architecture for each participating country as well as to professionals.

The project is divided into three stages, corresponding to the three questionnaires.

- Stage 1, currently undergoing and based on Questionnaire A, aims at linking the daylighting topic to the education of European university students combining perceptual, cultural and general knowledge aspects.
- Stage 2 (Questionnaire B) aims at widening the investigation to designers (and other students) for a better understanding of the existing practical knowledge about daylighting.
- Stage 3 (Questionnaire C) is aimed at understanding the relationship between the previously obtained data and the daylighting educational offer in Europe.
-

Stage 1 - Questionnaire A (QA)

6) *Work plan*

The specific objectives of the first stage are: (a) to assess students' ability to describe the daylight conditions within a given space in comparison to the assessments done by two experts (university professors or DAYKE staff) and to measured illuminance levels; (b) to learn about students' preferences towards daylighting; (c) to assess students' general knowledge about daylighting; (d) to find which aspects of daylighting knowledge are missing in the architectural curricula.

the investigation on the perception (see next Section) was based on a benchmarking method that compares the judgments expressed by expert and non-expert respondents , consistent with already done in other studies about perceived environmental quality [11]–[13]. This first stage started in Winter 2017 and will be completed in Autumn 2017. It consists of collecting and evaluating 250 questionnaires taken by undergraduate and graduate students from universities in each country involved.

7) *Questionnaire A content*

Questionnaire A (QA) contains questions about: *Perception* (overall environment, luminous environment); *Preferences* (daylighting preferences) and *Knowledge* (daylighting knowledge). Questions had either an open-ended or a rating nature. For the rating questions, a 5-point rating scale was used. Data on the socio-demographic and daylighting education information of the participants is also collected.

STAGE 1 – FIRST OUTCOMES

This paper presents the results obtained from eight sessions of the first stage that took place between January and May 2017, involving 176 responses from the following faculties:

- Faculty of Architecture, Sapienza University of Rome and Faculty of Architecture, Roma Tre University, in Italy.
- Faculty of Architecture and the Built Environment, TU Delft, in The Netherlands.
- Faculty of Architecture, Poznan University of Technology and the Faculty of Architecture, Sopot University of Applied Science, in Poland.
- Barcelona School of Architecture (ETSAB) and Vallès School of Architecture (ETSAV), Universitat Politècnica de Catalunya, BarcelonaTech (UPC), in Spain.

The survey was completed by 40 students and 2 experts in each session.

Data analysis

The data analysis was performed using Excel and SPSS software v24. Descriptive statistics were plotted for each variable of interest. To check for any significant differences between the experts and undergraduate and graduate students a series of Chi square tests were performed for the categorical variables. For the ordinal variables, each variable considered in the study underwent Kolmogorov-Smirnov tests to control for any possible deviations from a normal distribution. As the test showed that many variables could not be considered normally distributed, the data was analysed by means of a series of non-parametric Mann-Whitney U tests. The following is a summary of the most representative results that were obtained.

8) *Perception: Comparison between experts' and students' reports*

The analysis showed that the ratings provided by the students and those given by the experts were overall quite similar. The only exceptions were found in:

- Spain, regarding the daylight quantity, with the students' evaluation of daylight being significantly poorer compared to the experts ($U=14.00$, $p<.01$);
- The Netherlands, regarding the daylight quantity, with students rating daylight significantly better than the experts ($U=12.50$, $p<.05$) and the possibility to control it, with students being significantly less satisfied compared to the experts ($U=12.50$, $p<.05$)

9) *Preferences: The best and the worst daylighting design example choices and reasons*

The students gave more "best" than "worst" examples of daylighting design. Approximately 2/3 (64.7%) gave a "best" example of daylighting design but not all of them could explain the reason for their choice (57.1%). "Worst" daylighting design examples were given by 59.0% of the students, while the reason for their choices was explained by 55.3% of them only. The Italian students were the least able to express their "best" daylighting design examples (60.0%) and in providing arguments to support them (22.5%). On the contrary, 88.1% of the Spanish students were able to provide "best" and "worst" daylighting design examples and the reasons for their choices.

a) Types of choice

Notably, a significant difference between the types of positive and negative examples given was observed, as one could expect (Fig.1a). As "best" examples, students focused on the function of the building (e.g. museums, libraries, greenhouses etc.) hereby called *general*, as well as on the significant features of exceptional architectural buildings, hereby called *exemplar.* Examples of the *exemplar* category include buildings like the Kimbell Art Museum or the Solomon R. Guggenheim Museum. For the "worst" daylighting designs, students have mostly provided examples drawn from their first-hand experience in their university buildings, houses or dormitories, hereby called *subjective*.

b) Reasons for choice

The responses regarding the reasons for the choices (open answers) were divided into eight categories: *Architectural quality, Quantity of light, Daylighting design strategy, Energy saving, Devices, Functional reason, Environmental and visual comfort reason,* and *Other* (Fig.1b).

The students reported *Daylighting strategy* (28.3%), *Quantity of daylighting* (25%) and *Architectural quality* (19.6%), as the first reasons behind their "best example" choices. The arguments provided vary by country:

- Spanish (50%) and Polish (33.3%) students reported more interest in the amount of incoming daylight.
- Italian (20%) and the Dutch (50%) students reported more interest in the daylighting design strategy.

The first arguments provided for the "worst" daylighting design example choices were: *Environmental and visual comfort* (29.2%), *Quantity of daylighting* (27%) and *Functional reasons* (14.6%).

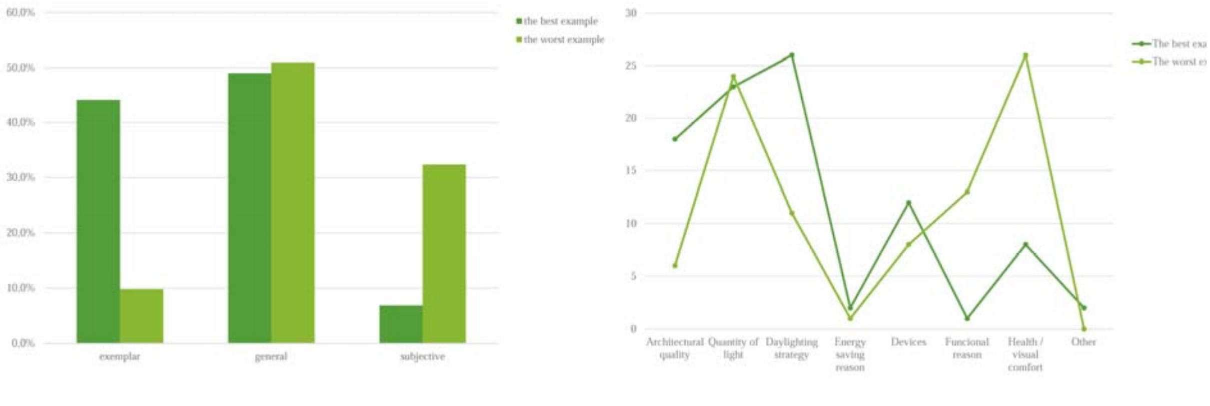

Figure 1. Preferences for the best and the worst daylighting design example: 1.a - (Left) Percentage of responses, grouped by type. 1.b - (Right) Reasons justifying the choices, by type.

10) *Preferences: greatest barrier to daylighting design*

This question was intentionally ambiguous to reveal the students' approaches to daylighting. The responses demonstrate a tendency to focus on a quantitative dimension and a propagation of daylight t (34.2%). Students also pointed out the difficulty in managing daylight due its seasonal and climatic variability (28.9%) and the risk of excessive solar gain/greenhouse effect (20.2%) as barriers to daylighting. It should be noted that only the Dutch students considered the financial cost (direct or indirect) as a barrier to daylighting design.

11) *Preferences: Expectations from daylighting design*

With regard to the expectations from daylighting, the Chi square tests showed that:

- Polish and Dutch students particularly expected the daylight to provide a view to the outside ($\chi^2(3)=27.74$, $p<.01$).
- Italian students expected daylight to replace electric light and to be energy efficient ($p<.05$ in both cases)
- Spanish, Dutch and Polish students expected daylight to provide a cosy and pleasant atmosphere ($\chi^2(3)=11.49$, $p<.01$)

In relation to daylighting regulations, the analysis pointed out that Polish students would welcome regulations significantly more than the students from other countries ($\chi^2(3)=12.66$, $p<.01$). It is worth noting that currently there isn't any standard or guidance on daylighting in Poland.

12) *Knowledge: Daylighting metrics/indicators*

Table I shows the results for the daylighting metrics knowledge questions. It can be seen that 43.5% of students claimed to know a daylighting metric or indicator. Interestingly, the analysis showed that only very few among them was able to correctly name them (65.2% gave 'false positive' answers). The number of 'true positive' answers revealed that 14.9% only of the students did actually know a daylighting metric. The Chi square did not show any significant relationship between country and the self-reported knowledge.

TABLE I. KNOWLEDGE ABOUT DAYLIGHITNG METRICS/INDICATORS AND INCIDENCE OF FALSE POSITIVES

Question	Answers	Country responses									
		Italy		*The Netherlands*		*Poland*		*Spain*		*Total*	
Knowledge about metrics/ indicators[a]	YES	20	50.0%	18	42.9%	18	52.9%	14	31.1%	70	43.5%
	NO	20	50.0%	21	50.0%	16	47.1%	31	68.9%	88	**54.7%**
	No answer	0	0.0%	3	7.1%	0	0.0%	0	0.0%	3	1.9%
Name of the metrics/ indicators[b]	true positive	6	28.6%	10	55.6%	2	11.1%	6	50.0%	24	34.8%
	false positive	15	71.4%	8	44.4%	16	88.9%	6	50.0%	45	**65.2%**

a. *Do you know any daylighting metrics/ indicators?*
b. *If yes, what daylighting metrics/indicators do you know?*

13) *Knowledge: Regulations concerning daylighting design*

Table II shows the positive responses concerning the knowledge of regulations. It can be seen that 3.7% only of the students declared to know a EU regulation concerning daylighting (but no one was able to name it). Only 19.9% declared to know the national regulation concerning daylighting design or an energy efficiency regulation. It seems that Polish and Dutch students are more informed concerning regulations, although the numbers are still too low to generate clear data.

TABLE II. KNOWLEDGE ABOUT REGULATIONS (POSITIVE RESPONSES)

Questions	Country positive responses									
	Italy		*The Netherlands*		*Poland*		*Spain*		*Total*	
Daylighting EU regulation[a]	2	5.0%	2	4.8%	2	5.9%	0	0.0%	6	**3.7%**
Daylighting national regulation[b]	5	12.5%	6	14.3%	9	26.5%	12	26.7%	32	**19.9%**
Energy-saving regulation[c]	7	17.5%	10	23.8%	7	20.6%	8	17.8%	32	**19.9%**

a. *Do you know any EU regulation concerning daylighting design?*
b. *Do you know any National regulation concerning daylighting design?*
c. *Could you please give an example of any regulation (building, energy-efficiency) regarding daylighting, solar gain or shading?*

Preliminary results

With reference to students' perception of the lighting conditions in the classrooms tested, the results show that a similar interpretation of the luminous environment is shared between the students and the experts.

It can be inferred from the results that there are divergences among students from different countries concerning daylighting preferences and expectations The following trends have been identified on this:

- The Dutch students denote a greater attention to light control (*perception*), visual comfort (the *worst example*), variability *(the greatest barrier*) which could be related to their preference for the design strategies (*the best example*). Those aspects are in line with their expectations for pleasantness and view to the outside (*expectations*).
- The Italian students pay more attention to architectural quality and daylighting design strategies (the *best example*) and the quantity of light for the negative aspects (the *worst example* and the *greatest barrier*). The latest may illustrate their expectations for the energy savings (*expectations*).
- The Polish students take notice of the quantity of light (the *best example*) and functional reasons (the *worst example*).
- The Spanish students show a greater interest on the quantity of light than on the qualitative aspects of daylight (*perception*; the *best example* and the *worst example;* the *greatest barrier*).

Distinct daylighting preferences between the faculties of southern of Europe (Italy and Spain) and of northern Europe (The Netherlands and Poland) were not found.

Regarding the daylighting knowledge, the results show deficiencies among all students, regardless the country. The high percentage of the ‘false positive’ answers to the daylighting metrics question can be interpreted in two different ways: either the students do not know the terminology or they did not understand the question. Either way, the results suggest that students are unfamiliar with the technical aspects of daylighting.

With respect to daylighting standards, all students were unable to name a European standard concerning daylighting. If a lack of knowledge regarding European regulations could be expected, the lack of knowledge about national regulations remains surprising. Less than one out of five respondents indicated to know a national legislation concerning daylighting or energy efficiency. The situation is slightly better in Poland and in the Netherlands, but the numbers are still very low.

CONCLUSIONS

As a summary, the first outcomes of the DAYKE project show that there are three major tendencies:

- The perception of quality of daylit spaces for students and experts is similar;
- Regarding cultural aspects (daylighting design know-how, preferences and expectation), students from different countries pay a different degree of attention to diverse aspects of daylighting design. There were no significant differences of interpretation found between South (Italy and Spain) and North of Europe (the Netherlands and Poland). A significant influence of the educational programmes on the responses of the students from the UPC Barcelona and from TU Delft was also noticed. In Italy and Poland, the students involved in the survey do not have any compulsory daylighting courses and the tendency is to consider daylighting from a non-technical viewpoint.
- Despite different educational offers, all the students have a low level of knowledge about daylighting metrics and standards. These findings confirm observations from previous studies and highlight the importance of considering its introduction in architectural curricula.

The complete results from the first stage of the DAYKE project will hopefully provide a better understanding of the differences regarding the daylighting education offer to the future architects of different European countries. It is expected this to help in formulating recommendations for a successful education in this field, in Europe.

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What's the Matter with Multi-Layers Facades?

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***Abstract*— It is observed that many recent buildings are equipped with multi-layer facades consisting in opaque exterior elements located in front of the glazed surfaces (fixed external lamellas, covered with grids, metallic fabrics, perforated plates, wooden claddings, etc.). These extra layers might sometimes be justified by protection issues but, in most cases, this choice is mainly motivated by aesthetics considerations. If their presence in front of opaque parts of the facade has a low influence on the building performance, however this implies a substantial weakening of the daylight availability and energy performance when those elements cover the windows. This paper discusses the main impacts associated with this architectural trend and shows its limitations in terms of performance.**

***Index Terms*—Daylighting, User's comfort, Energy efficiency**

INTRODUCTION

Today's techniques and technologies enable to build very energy efficient buildings. High insulation, suitable glazings and effective shading devices lead to very low heating loads, good coverage of daylight requirements and control of summer overheating risks. All these demands can be met with a conventional envelope, which means composed of a single layer façade alterning opaque surfaces and glazed area equipped with movable shading device.

However, observation of recent architectural production shows that many new buildings are built today with an additional outer layer. Beyond the aesthetic aspects that we are not in a position to judge, the presence of these external elements results in a certain change of the interior spaces, both in terms of energy performance and visual comfort. This paper aims to examine the impact of these external elements on daylight availability, energy balance in winter, overheating risk in summer and view to the outside. Thus this paper proposes to compare three *representative* multi-layers facade systems (see figure 1), and to compare their performance with the one of an efficient single layer facade equipped with external automated blinds.

SELECTED CASE-STUDIES

The selected case studies are supposed to be representative of existing buildings. However, the examples mentioned in this study are merely illustrative and the conclusions of the article can in no case be applied stricto-sensus to these buildings. The comparative approach relies solely on simulations (without survey / monitoring).

Main features

The room used for comparison is a medium size open space office (width: 18.30m, depth: 7.75m, height: 2.88m). The building is located in an urban environment of medium density (outdoor masks altitude = 25°, reflection coef. 0.25, albedo = 0.10). The indoor reflection coefficients are as follows: floor: 0.30; vertical walls: 0.50; ceiling: 0.70. The room is equipped with 15 standing LEDs luminaires with the following characteristics: 93W; 12'505 lm (luminous efficacy: 134 lm/W; specific power: 9.8W/m^2); automated dimming and absence sensors. Simulations are run with DIAL+ [1] software with the climatic data of Lausanne. The occupied period is 8AM to 6PM.

Reference case (REF)

The reference case is equipped with standard double-glazing (τ = 0.80, g = 0.62, U_{glass} = 1.1W/m^{2}K). The windows are fitted with automated external venetian blinds (ρ = 0.50).
(Analogy with EPFL Innovation Park (EIP), Lausanne, Switzerland, arch. Richter Dahl Rocha 2011).

Case Study 1 (CS1): Fixed horizontal blades

The external layer is composed of horizontal blades in ultra-high performance fiber-reinforced concrete (UHPC) with the following characteristics: Width: 20 cm; Thickness: 3 cm; Spacing: 25 cm, Reflection coefficient: 0.15.
(Analogy with Pavillon 52 building, Lyon, arch. R. Ricciotti 2016).

Case Study 2 (CS2): Fixed tilted lamellas

The additional external layer is composed of tilted aluminum blades with the following characteristics: Width: 17 cm; Spacing: 38 cm; Tilting angle: 40°; Reflection coefficient: 0.40.
(Analogy with Ecotox Building, Valence, France, arch. Brunet Saunier, 2016).

C. ***Case Study 3 (CS3): Perforated metal sheets***

The additional outer layer is composed of perforated sheets with an average perforation rate estimated at 0.56.
(Analogy with "Cube-Vert" building, Lyon, France, arch. Jakob MacFarlane, 2014).

REF: Analogy with "*EIP*" CS1: Analogy with "*Pavillon 52"* CS2: Analogy with "*Ecotox*" CS3: Analogy with "*Cube-Vert"*

Figure 64: External views of 4 emblematic buildings showing an analogy to the selected cases studies. Photos Estia.

In all three cases, the external system has the same appearance regardless of the orientation of the facades, as shown in Figure **45** above.

DAYLIGHTING

Dynamic simulations were run using the Radiance three-phase method [2] and the results are shown in Figure 2. The limit value of illumination was set at 300 lux for this analysis. For the reference case, the shading devices are assumed to be down when incident radiation exceeds 200 W/m^2. For CS1, CS2 and CS3, there is no movable shading device, which leads to clearly overestimate the results (in reality, the need to install interior curtains to avoid glare is more than likely and it is highly probable that their use by the occupants will not be optimal).

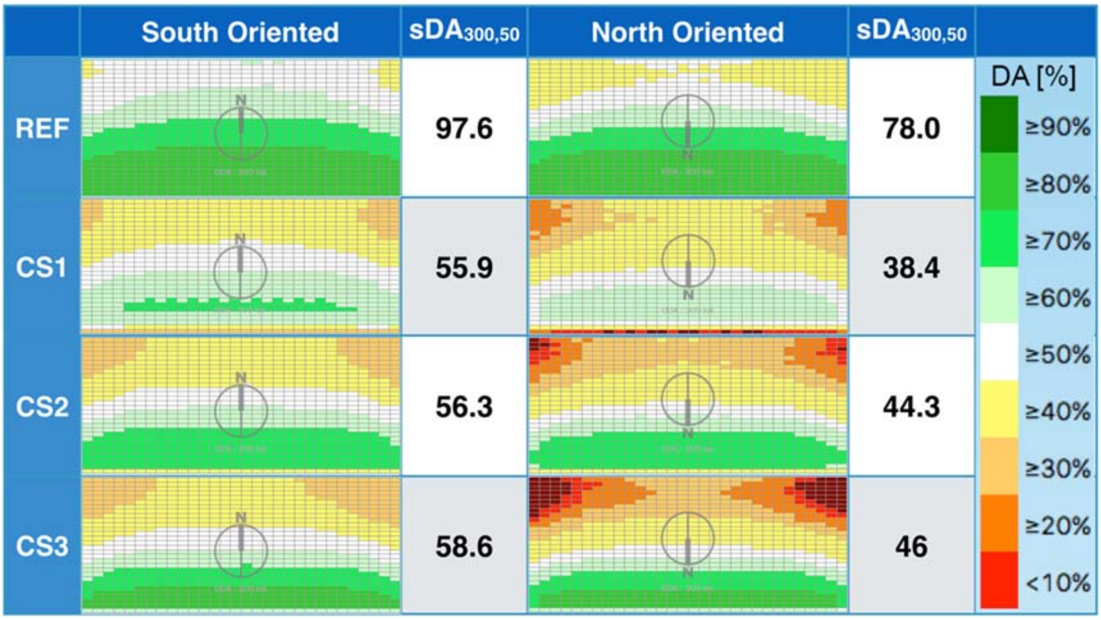

Figure 65: Daylight autonomy and $sDA_{300\text{-}50}$, for the 4 configurations, according to the room orientation. DIAL+ simulations.

D. South orientation (Cf. left part of Figure 65)

- Ref: Daylight availability is very high and almost all the room surface reaches 300 lux during 50% of the occupied hours ($sDA_{300\text{-}50}$ = 97.6%).
- CS1: The horizontal lamellas lead to a 42% reduction of the spatial daylight autonomy ($sDA_{300\text{-}50}$ = 55.9%).
- CS2: sDA is very similar to case CS1 ($sDA_{300\text{-}50}$ = 60.9%). However, the daylight contribution is higher near the window but lower in the back part of the room.
- CS3: The contrast between front and back zones of the room is further accentuated ($sDA_{300\text{-}50}$ = 58.6%).

E. North Orientation (Cf. right part of Figure 65)

For north-oriented rooms, the daylight contribution is even more affected by external layers.

- Ref: Daylight availability is still very high and a 300 lux illuminance level is reached over the largest part of the room surface during 50% of the openig hours ($sDA_{300\text{-}50}$ = 78.0%).
- CS1: The horizontal lamellas block and absorb a large proportion of daylight wich leads to a division by 2 of the spatial daylight autonomy ($sDA_{300\text{-}50}$ = 38.4%).
- CS2: Compared with Ref, the daylight contribution is nearly halved ($sDA_{300\text{-}50}$ = 44.3%).
- CS3: The gap between front and back zones is very high ($sDA_{300\text{-}50}$ = 46.0%).

Not surprisingly any additional layer, regardless of its shape, absorbs a significant part of the natural light and leads to a very substantial reduction in the coverage potential of the lighting needs.

VIEW

It is clear that none of the fixed protection systems studied here can guarantee the blocking of solar penetrations in all circumstances. This is all the more true as their geometry has identical characteristics on all the orientations. Although we were unable to make in-situ measurement of the visual comfort conditions, we had the opportunity to get some pictures from inside two of the studied buildings. Figure 66 highlights some of the characteristics of the impact of the external layers.

The picture on the left was taken on August 11 at 4:45 pm. It is observed that the spacing of the blades does not allow blocking the sunrays while the facade is oriented to the South. As a result, the area near the façade is not protected against glare. This image confirms the fact that a glare protection device should be offered to the occupants (when the photo was taken the building was not yet in service).

The picture on the right was taken on September 7 with overcast sky conditions. The landscape that faces the opening is the left bank of the Rhône river in Lyon (East façade). It can be seen that the presence of perforated sheets greatly reduces the legibility of the landscape. We believe that this "barrier effect" is detrimental to the quality of perception of the external environment and leads to penalize the satisfaction with the amount of view [4] as well as the environmental quality credits that could be allocated to these buildings [5]. The color of the perforated metal plates might have effects on the perception of the occupants but simulations cannot approach this effect.

CS2, Ecotox building Valence, Photo ©Estia.

CS3, Cube-Vert, Lyon, Photo ©Paule.

Figure 66: View from inside of two buildings equipped with an external layer:

ENERGY ASPECTS

A. Electric lighting

To estimate the annual energy consumption due to electric lighting, we used the diffuse daylight autonomy [3] and assumed that the continuous dimming only complete the amount light to provide 300 lux on the workplane. Figure **67** shows that any of the solutions that include an external layer lead to a significant increase of energy consumption due to lighting. The most unfavorable case corresponds to CS1 due in particular to the thickness and the dark color of the lamellas. This graph corresponds to a south-oriented façade, but the conclusions are similar for other orientations.

B.Cooling loads

We also used DIAL+ software to estimate the cooling and heating loads in the different configurations (DIAL+*Cooling* module). The rooms are equipped with radiators and fan coil units. The minimum temperature has been fixed to 20°C and the maximum to 26°C. The ventilation strategy is based on mechanical ventilation ($36m^3$/h per person).

Figure **67** shows that the cooling demand of CS1 and CS2 is slightly higher than the one of the reference case (respectively 17% and 27%). These additional layers actually limit the solar gains in summer (when the sun is high) but does not prevent sun penetration in mid-season.

CS3 shows a 77% increase of the cooling loads which is mainly due to the fact that the perforated metal plates do not offer any selectivity with respect to solar radiation, which leads to significant gains whatever the season.

The comparison is made here on the basis of the analysis of the thermal behavior of the south facade. On the eastern and western façades, the cooling loads would be even higher insofar as the low incident angles of the sun would increases the portion of the rays passing through the fixed blinds.

C. Heating loads

The reference case is the one that can best benefit from solar gains and therefore has the lowest heating consumption. CS1 shows an increase of 14.5% for the heating loads. CS2 is slightly less penalizing (+11.5%) insofar as the distance between the blades is relatively large, which allows the sun to reach the façade in winter. CS3 has a higher global energy transmittance and thus lead to increase the solar gains (heating loads +9%). On this subject too, it is observed that fixed systems are less efficient than an automated mobile shading system.

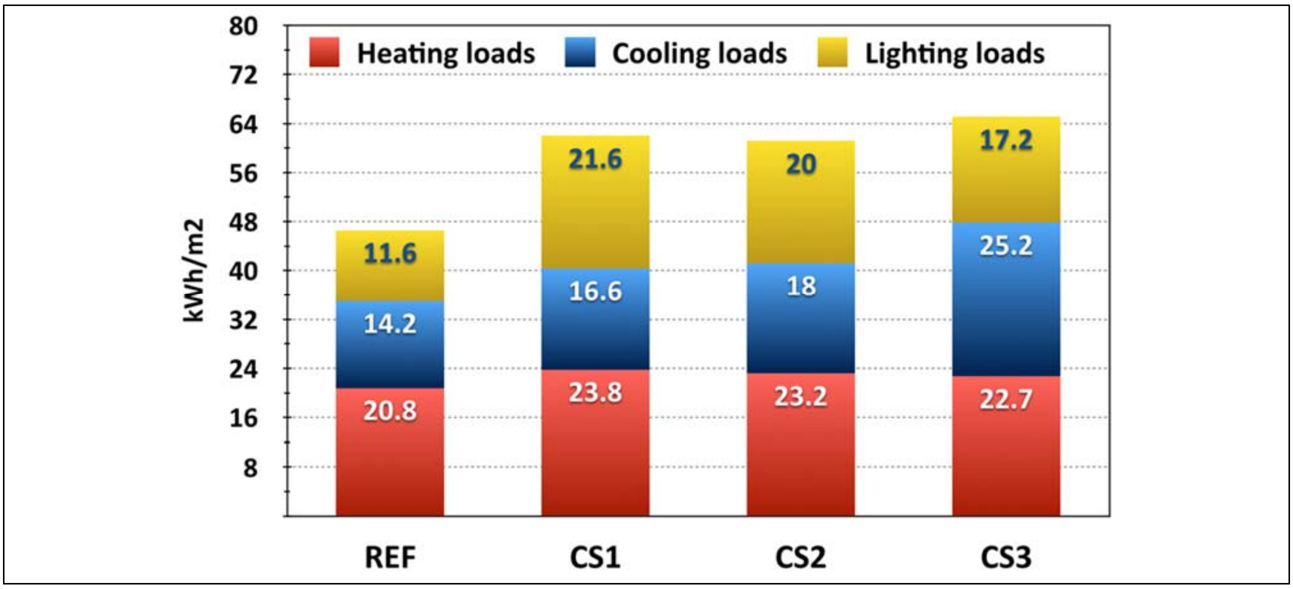

Figure 67: Estimation of the energy demand for south oriented rooms.

OTHER IMPACTS

A. Primary energy

As a simplified approach, the embedded energy contained in the additional layers can be estimated from the approximated weight of added material per square meter of façade.

We considered that CS1 is made of ultra-high performance fiber-reinforced concrete (UHPC) with an average weight of 50 kg per m^2 of façade.

CS2 and CS3 are made of aluminum with an average weight of 2.7 kg per m^2 of façade for CS2 (tilted lamellas) and 4 kg per m^2 of façade for CS3 (perforated plates).

For REF we applied the same value as for CS2 to take into account the movable blinds, but we considered that this value has to be applied only for 55% of the global surface of the façade (glazed areas only). We assumed that the height between two storeys is 3.30 m and that the lifespan of the systems is 30 years for movable blinds and 40 years for the outer layers.

Table 7 shows significant differences between the 4 configurations. Despite of the heaviness of the lamellas, CS1 is the solution that requires the less primary energy (23% less than REF). This is due to the fact that compared with UHPC, the energy content of aluminum is quite high (27 kWh/kg vs. 0.77 kWh/kg for UHPC [5]). On the other hand CS2 and CS3 show a significant additional amount of primary energy compared with REF (+36% for CS2 and +103% for CS3). A more detailed study would have probably resulted in different conclusions for CS1 insofar as the structure required to support the UHPC lamellas lead to a significant increase of the primary energy of this solution. Whatever the case, the building sector is a heavy user of resources and the use of additional materials must be assessed in the light of the actual utility of the proposed solutions.

	Weight of the system per square meter (kg/m²)	Primary energy per kg (kWh/kg)	Primary energy per m² of Façade (kWh/m²)	Percentage of facade covered by the system (%)	Primary energy per lineal front meter (h = 3.3m) kWh/m	Primary energy per year (lifespan: REF = 30y CS1 CS2 & CS3 = 40 y.) (kWh.y)
REF	2.7	27	73	55%	132	4.4
CS1	50	0.77	39	100%	127	3.2
CS2	2.7	27	73	100%	241	6.0
CS3	4.0	27	108	100%	356	8.9

Table 7: Estimation of the embedded energy of the four configurations (sources primary energy KBOB [5]).

B.Maintenance

The maintenance of facades constitutes a non-negligible part in the maintenance budget of the buildings. The implementation of additional layers can result in an increase in the complexity associated with this topic, in particular, cleaning of the outer face of the glazings. Field observations (CS3) confirm this (soiled glasses).

C. *Fire safety*

Concerning fire safety, the presence of an outer layer requires defining specific fire-accesses in the event of outside intervention, which constitutes a point of additional complexity depending on local regulations.

CONCLUSIONS

We have seen that the implementation of additional external layers on the facades of buildings poses a number of problems with regard to the energy performance of buildings and their functioning. The aesthetic attractiveness linked to this artchitectural trend is probably associated with a temporary economic advantage (flattering image) when renting or reselling the building.

However, we recommend that designers carefully measure the consequences of this trend and, at least, we think that building owners should be aware of the concrete negative impacts that this can create for the daily use of buildings.

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Advances in Daylight Simulation – Validation and Applications

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***Abstract*—The Radiance Five-Phase method was developed as an extension to the Three-Phase method to allow a more accurate calculation of the direct sun component. We present a further refinement to the Five-Phase method that also allows to accurately simulate luminance images with an improved representation of the fenestration system itself. This extension now also allows to perform daylight glare evaluations from the rendered images. The new algorithms are validated against field measurements taken in a testbed with different façade systems. The comparison shows a good agreement between measurements and simulation results and thus proves the suitability of the method for predictive daylight simulations.**

***Keywords*— Daylight, annual simulation, Five-Phase method, complex fenestration system, validation**

INTRODUCTION

Climate-based daylight modeling has found its way from academics into the practice over the past few years. The Radiance Three-Phase method enabled time-efficient annual daylight simulations with complex fenestration systems for the first time [1]. The Three-Phase method algorithms form the basis for many annual daylight simulations (e.g. OpenStudio, DALEC, Honeybee, Fener, TypeDLT, Artlight, …). The method was also validated against field data by McNeil and Lee [2].

With the Three-Phase Method significant errors can occur in situations with direct sunlight, particularly in the assessment of visual discomfort. With the Five-Phase method, McNeil [3] proposed a refinement to overcome the issue of direct sunlight illumination for sensor calculations, but did not resolve the issue for renderings. However, the latter are necessary to derive evaluations of visual comfort, e.g. luminance based glare evaluations such as DGP [5].

THE FIVE-PHASE METHOD

A. The Three-Phase method

The Three-Phase method [4] allows efficient annual daylight simulations by splitting up the flux transfer from the sky to an interior surface or sensor point. The calculation of the flux transfer from the sky onto the exterior of the façade, the flux transfer through the fenestration system and the flux transfer from the interior of the façade onto an interior surface are separated.

$$I = VTDS \tag{1}$$

where **I** is the resulting (il)luminance vector or matrix, **V** is the view matrix that connects the sensor point with exiting directions of the façade system, **T** is the bidirectional transmission distribution function (BTDF) of the façade system, **D** is the daylight matrix that connects incident directions at the façade system with sky areas, and **S** is the discretized sky distribution vector or matrix.

B. The Five-Phase method

The caveat of the Three-Phase method is that the direct sun component is treated as part of the overall sky distribution and averaged over a large solid angle. The Five-Phase method [3] improves that by removing the direct sun part from the Three-Phase method and substituting it with an improved calculation using the façade system's geometry or a high-resolution BSDF.

$$I = VTDS - V_dTD_dS_{ds} + C_{ds}S_{sun} \tag{2}$$

where $\mathbf{V_d}$ is the direct view matrix that directly (without interreflections) connects the sensor point with exiting directions of the façade, $\mathbf{D_d}$ is the direct daylight matrix that directly (without interreflections) connects incident directions at the façade system with sky areas, $\mathbf{S_{ds}}$ is the discretized sky distribution vector or matrix that only includes the sun contribution (no sky), $\mathbf{C_{ds}}$ is the direct sun coefficient matrix that represents direct (without interreflections) contributions to the interior sensor point from sun positions, and $\mathbf{S_{sun}}$ is the discretized sun contribution vector or matrix.

C. Extension of the Five-Phase method for renderings

The Five-Phase method in equation (2) works for illuminance sensors and luminances on interior room surfaces, but does not correctly represent the direct sun contribution to window luminance in renderings. To overcome this, we further extend the calculation.

$$I = VTDS - V_dTD_dS_{ds} + (C_{R\text{-}ds}+C_{F\text{-}ds})S_{sun} \tag{2}$$

where $\mathbf{C_{ds}}$ is replaced by the sum of two matrices: $\mathbf{C_{R\text{-}ds}}$ is the direct sun coefficient matrix that represents direct (without interreflections) contributions to the sensor point on interior room surfaces from sun positions and $\mathbf{C_{F\text{-}ds}}$ is the direct sun coefficient matrix that represents direct (without interreflections) contributions as directly seen at the interior side of the façade.

Fig. 1 shows the schematic workflow of the Five-Phase method, Fig. 2 shows an exemplary comparison of results obtained with the Three-Phase method and the Five-Phase method, respectively. Notice the improved representation of the luminance highlights seen at the façade.

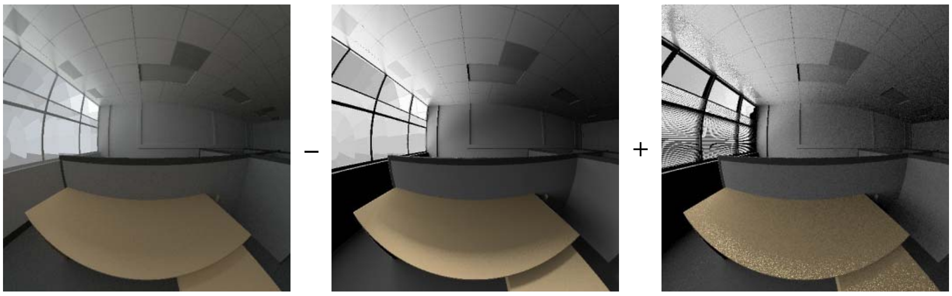

Figure 1. Schematic workflow of the extended Five-Phase method: Three-Phase method result **VTDS** (left), subtracted direct sun component of Three-Phase method $\mathbf{V_dTD_dD_{ds}}$ (center), and added detailed direct sun component $\mathbf{(C_{R\text{-}ds}+C_{F\text{-}ds})S_{sun}}$ (right).

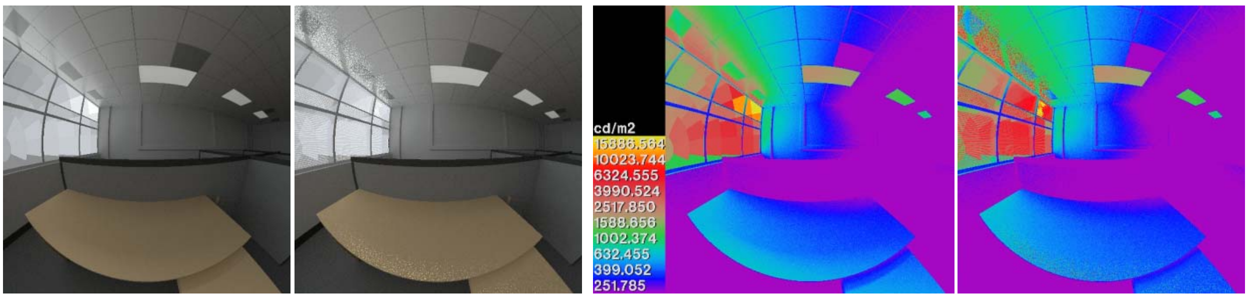

Figure 2. Comparisons of results with Three-Phase method and Five-Phase method. Each pair (renderings left and falsecolor results right) shows the Three-Phase result left and the Five-Phase result right.

FIELD MEASUREMENTS

Full-scale field tests were conducted around equinox 2015 in the LBNL's FLEXLAB testing facility. Two adjacent 6.1 m wide by 9.1 m deep by 2.7 m high south-facing rooms (reference and test room) were configured with the same interior finishes and low-height workstations to emulate open plan perimeter offices. The south facing façade of the test room was equipped with a shading system with 2.54-cm wide, indoor horizontal venetian blinds lowered over the entire window with a fixed slat angle set to block direct sunlight. Three alternate daylight systems were tested sequentially in the test room:

- DL-L1: a 1-mm thick daylighting film (Lucent Optics) with embedded microscopic reflectors designed to reflect light with maximum efficiency for profile angles between 45-65° (the remaining light is transmitted specularly);
- DL-L2: a 375-micron thick daylighting film (SerraGlaze) with micro-replicated prisms designed to redirect sunlight with maximum efficiency for profile angles between 42-55° (for angles lower than 42° sunlight is transmitted specularly); and,
- S-L: a light-weight solar screen (SmartLouvre Technology Ltd, MicroLouvre) consisting of 1.25-mm wide, 0.22 mm thick, matte black horizontal slats spaced vertically to produce a cut-off angle of 40°.

The first two daylight-redirecting films were installed indoors in the upper 0.6 m clerestory portion of the window with an indoor venetian blind in the lower 1.2 m vision portion of the window (similar to the reference room). The third solar screen was installed outdoors against the face of the window frame and covered the entire window (with no indoor blind).

Interior measurements were taken for horizontal and vertical illuminances at several positions inside both rooms. Additionally, field-of-view luminances were captured by taking images with a digital camera (Canon EOS 5D with Sigma Fisheye lens) for a typical user perspective. Using the vertical illuminance measurements at the camera position, the exposure sequences were converted to HDR images using the *hdrgen* tool. Glare evaluations were performed with the *evalglare* tool [6]. The exterior conditions were captured vie measurements of global and diffuse horizontal irradiances.

SIMULATIONS

The FLEXLAB was virtually rebuilt and simulated utilizing the Five-Phase method in Radiance. The measured global and diffuse horizontal irradiance values were used as input to the simulations. The direct horizontal irradiance (difference between global and diffuse) was converted to direct normal irradiances using hourly sun positions. Together with the diffuse horizontal irradiances a climate data file in the Daysim format with values for every 5 minutes was generated. Using the Radiance tool *gendaymtx* this climate data was then transformed into discretized Perez sky representations $\mathbf{S}$, $\mathbf{S_{ds}}$ and $\mathbf{S_{sun}}$.

The daylighting systems were characterized by BSDFs measured with a scanning goniophotometer and resampled to high-resolution tensor tree BSDFs. Thus, the spatial transmission properties of the façade components were reproduced at high detail, which was necessary to realistically simulate interior luminance values. Both, a Klems representation (145 directions) for the Three-Phase method calculations and a tensor tree representation (option -t4 7 for a maximum resolution of 1.4°) for the advanced direct sun calculations were created.

BSDFs for the venetian blinds in the reference room were generated with *genBSDF* using a geometrical model of the shading system and a measured reflectance value (ρ = 0.733). Again, a Klems representation for the Three-Phase method calculations and a tensor tree representation (-t4 6 for a maximum resolution of 2.8°) for the advanced direct sun calculations were derived.

Figure 3. Indoor photograph of the FLEXLAB test room (left), angular fisheye image representing a user's perspective in the office mockup (center), and simulation model of the same perspective (right).

RESULTS

The simulations were performed for the weekly periods with the different systems installed. All sensor values and images were simulated in 5 minute intervals, i.e. 1728 time steps for the 6-day periods (systems DL-L1 and S-L) and

2016 time steps for the 7-day period (system DL-L2). The evaluations were performed for the times between 9am and 5pm representing working hours with adequate daylight provision.

Tab. 1 shows the frequency of deviations between the simulated and the measured values for all four investigated metrics (horizontal workplane illuminance, vertical illuminance at the eye, daylight glare probability, and daylight glare index). Summarizing, the Five-Phase method clearly outperforms the Three-Phase method in terms of prediction of these metrics. For most situations, the Five-Phase method is able to predict vertical illuminances with deviations from the measurement within 20%, for the DGP glare evaluations the deviations for most situations are below 10%.

TABLE I. Frequency (% of measured period) of deviations between simulation results and measurements (Δ%). Sensor on desk close to the façade for horizontal illuminance, sensor and camera position and direction according to typical user perspective in an office scenario for vertical illuminance and glare evaluations (DGP and DGI).

Metric	Monitoring Period	Set-Up	Three-Phase method			Five-Phase method		
			Δ < 5%	Δ < 10%	Δ < 20%	Δ < 5%	Δ < 10%	Δ < 20%
Horizontal workplane illuminance	October 08 - 13	Test room (DL-L1 & venetian blinds)	16.8%	33.5%	58.3%	29.0%	53.9%	85.0%
		Reference room (venetian blinds)	15.7%	42.7%	94.9%	31.9%	73.0%	94.3%
	October 01 – 07	Test room (DL-L2 & venetian blinds)	26.7%	55.2%	86.9%	28.2%	61.3%	92.9%
		Reference room (venetian blinds)	17.9%	46.9%	95.1%	44.5%	85.7%	94.5%
	October 20 – 25	Test room (S-L & venetian blinds)	28.2%	55.1%	78.7%	25.0%	50.9%	74.1%
		Reference room (venetian blinds)	22.7%	49.4%	88.1%	35.2%	70.2%	88.3%
Vertical illuminance	October 08 - 13	Test room (DL-L1 & venetian blinds)	16.3%	35.6%	75.9%	20.6%	52.1%	92.0%
		Reference room (venetian blinds)	14.8%	30.8%	81.2%	40.0%	74.0%	87.5%
	October 01 – 07	Test room (DL-L2 & venetian blinds)	18.2%	47.0%	89.4%	33.1%	75.5%	96.3%
		Reference room (venetian blinds)	22.0%	45.5%	89.7%	49.8%	77.9%	90.9%
	October 20 – 25	Test room (S-L & venetian blinds)	22.7%	45.2%	67.7%	21.9%	41.0%	65.1%
		Reference room (venetian blinds)	14.2%	29.5%	72.8%	23.6%	54.9%	75.8%
Daylight Glare Probability (DGP)	October 08 - 13	Test room (DL-L1 & venetian blinds)	16.7%	32.7%	84.4%	36.6%	74.5%	99.7%
		Reference room (venetian blinds)	39.2%	91.7%	97.1%	76.5%	97.5%	100%
	October 01 – 07	Test room (DL-L2 & venetian blinds)	23.9%	75.9%	94.2%	62.7%	94.8%	99.4%
		Reference room (venetian blinds)	60.2%	99.2%	100%	76.7%	100%	100%
	October 20 – 25	Test room (S-L & venetian blinds)	83.8%	93.1%	97.7%	82.4%	93.1%	98.1%
		Reference room (venetian blinds)	29.8%	80.6%	90.6%	68.0%	81.8%	97.6%
Daylight Glare Index (DGI)	October 08 - 13	Test room (DL-L1 & venetian blinds)	3.9%	6.6%	11.3%	14.7%	28.7%	48.5%
		Reference room (venetian blinds)	16.5%	30.9%	56.2%	14.8%	25.2%	68.7%
	October 01 – 07	Test room (DL-L2 & venetian blinds)	4.1%	10.3%	18.3%	8.6%	16.5%	53.9%
		Reference room (venetian blinds)	21.3%	41.8%	75.8%	15.9%	32.6%	72.4%
	October 20 – 25	Test room (S-L & venetian blinds)	37.7%	56.5%	78.2%	36.1%	56.6%	78.2%
		Reference room (venetian blinds)	9.2%	15.7%	33.9%	16.5%	36.3%	64.6%

Fig. 4 shows an exemplary result for a single day of measurements. The Five-Phase method closely matches the measurement and outperforms the Three-Phase method. Although the venetian blind slats are positioned to block direct sunlight, the coarse Klems representation used in the Three-Phase method inferior to the geometric representation used in the Five-Phase method. This behavior is clearly pronounced in the afternoon hours in Fig. 4 where the Three-Phase method predicts a strong peak where there is none.

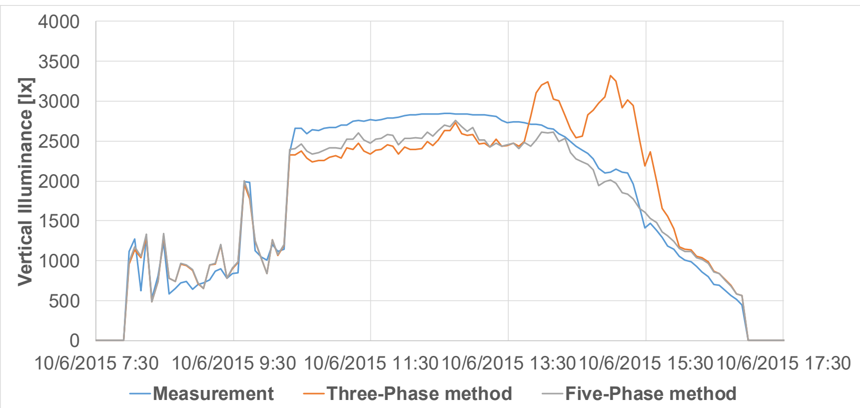

Figure 4. Examplary result for one measurement day (October 6th): comparison of vertical illuminances in the test room (DL-L2 in upper section, venetian blinds in lower section of the façade) from measurements, Three-Phase method, and Five-Phase method.

CONCLUSION

The Five-Phase method for simulation of complex fenestration systems with Radiance was further extended to accurately represent the direct sun contribution also in renderings where the façade is in the field of view. The adapted Five-Phase method was then validated against field measurements in terms of workplane illuminances, vertical illuminances and glare evaluations. Measurements were performed in LBNL's new FLEXLAB testbed facility for four different daylight systems.

The extended Five-Phase method clearly outperforms the Three-Phase method for predicting horizontal and vertical illuminance sensor values as well as glare metrics derived from rendered images. For all metrics and all investigated systems, the results from the Five-Phase method show lower deviations from the values obtained in the field measurement. Even with input from global and diffuse horizontal irradiance data only, DGP values could be predicted to within 10% error for most situations.

This validation shows that the Five-Phase method can predict interior daylight illumination at high accuracy. With this method at hand, lighting designers are able to evaluate buildings precisely already in the design phase, and researchers and developers can accurately quantify the performance of new complex fenestration systems. The validated high precision for the prediction of luminance images and vertical illuminances provides not only the possibility to predict visual comfort (e.g. glare) metrics, but also light dose and thus even non-visual lighting effects.

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Tubular Light-Guide under Broken Cloud Array – Working Plane Illumination

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***Abstract* — The numerical modelling of the light-guide efficiency is highly preferred in situations when mass calculations are required in order to test different daylighting technologies, to identify basic features of light field below a pipe and/or to find an optimum properties of light-pipe installations accepting prevailing sky types in a given territory. An analytical ray-tracing approach we have developed allows for more realistic and fully reproducible predictions of illuminance patterns on the bottom interface of the straight light pipes. This paper is to introduce a unique solution that links two numerical tools, HOLIGILM and UNISKY, both developed by a team of the Slovak Academy of Sciences. The first one is to compute the light beam trajectories in a straight light pipe, while the second one is to model the sky radiance/luminance distribution under heterogeneous cloud cover. The latter can even model the clouds that are formed into random arrays and drift through a part of sky from/to preferred direction. The main goal of this paper is to analyse the working plane illumination below the light-guide under partly cloudy skies.**

***Index Terms* -- broken cloud array, cloud cover, light-guide, sky luminance distribution, working plane illumination**

INTRODUCTION

Effective energy utilization in buildings requires novel technologies such as cylindrical light-guides that transport the natural light to interior spaces and thus increase visual comfort and save the electricity otherwise consumed for artificial lighting. It is difficult to determine the effectiveness of a hollow light-guide experimentally under controlled conditions because exterior illumination changes continuously. This is why numerical modelling is highly preferred as it allows for systematic computations for wide range of input/scaling parameters. The luminous efficiency is a complex function of both light pipe characteristics and actual illumination scene outdoors. Today's modelling tools largely focus on homogeneous skies, because it is extremely difficult to determine sky radiance patterns under broken cloud arrays. However, the homogeneous skies represent only a small fraction of all sky types, while partly cloudy sky is very often observed in many locations worldwide. Note that no one homogeneous sky (see e.g. [1], [2], [3]) can approximate fractional cloud coverage with a ripple structure of sky luminance that is typically observed at the interface between cloud and cloud-free atmosphere. In addition, the luminance gradient near a cloud edge depends on the angular distance from the hemispherical position of sun disk. Therefore no simple empirical model can simulate all situations that realize in nature. There is a lot of numerical and experimental studies addressed to light-guide behaviour under homogeneous skies (see e.g. [4], [5], [6]). Up to now, no comprehensive work has been published that models light-tube behaviour under broken cloud arrays. This paper is to present a unique solution that links two modelling tools Unisky [7] and Holigilm [8]. The numerical results are obtained for a set of skies with various cloud coverage.

THEORETICAL BACKGROUND

A. Modelling sky luminance patterns with broken cloud array

Modelling the sky radiance/luminance patterns under different meteorological conditions has a key role in prediction the radiative flux reaching the upper interface of the passive light transporting systems. The modelling of cloud arrays requires a special attention because cloud sizes, shapes and spatial distributions vary over wide range while all being characterized as a random stochastic system. Our modelling of the radiative transfer in such complex environment is based on the method of Successive Orders of Scattering (SOS), in which single-scattering radiances from broken clouds and a cloud-free atmosphere are well separated, while their non-trivial superposition determines a second order approximation to the radiative field. The radiance can be formulated as a finite series. However, it is usually sufficient to confine infinite series to the first two terms, thus minimizing CPU requirements significantly while keeping the computational error small. The main objective is to obtain luminance of an arbitrary sky element and determine its contribution to the irradiance/illuminance on a working plane after light transmission through the straight light guide. The first-order sky radiance normalized to the extra-terrestrial radiance of the sun *(F_0/π)* can be expressed as follows

$$\pi\frac{L^{+}_{1,S}}{F_0}=S_e(0,M_Z,0)\{P(z_S)[S_e(M_Z,M_S,0)-S_e(M_Z,M_S,h_C)]+(1-\delta_{0,z})[S_e(M_Z,M_S,h_C)-1]\}\times$$
$$\times\frac{\overline{P}_0(\theta)}{4}\frac{M_Z}{M_Z-M_S}+H(h_C-h_1)\delta_{0,z}S_e(M_Z,M_S,h_C)S_e(0,M_Z,0)[a_C\overline{r}_F+\exp(-M_S\tau_C)] \quad . \tag{1}$$

Here z_S is the solar zenith angle, H_S the scale height of a turbid atmosphere, M_Z the optical air mass at the zenith angle z, and M_S the optical air mass measured toward the sun. *H(x)* is Heaviside function, a_C is the cloud albedo, τ_C is the cloud optical thickness, and $\tau_0=\tau_0^a+\tau_0^m$ is the total optical depth of a cloud-free atmosphere. A bulk scattering phase function can be approximated by the Henyey-Greenstein function

$$\overline{P}_0(\theta)\approx\frac{1-g'^2}{(1+g'^2-2g'\cos\theta)^{3/2}} \quad . \tag{2}$$

The second-order scattering was derived only recently in [9] and it is defined as follows

$$L^{+}_{2,S}=M_Z\frac{\tau_0F_0}{16\pi^2}\int_0^1\frac{S_e(0,x,0)}{x(x-M_S)}I^{+}_{p2}(z_S,z,z'_x)B(x)dx+$$
$$+M_Z\frac{a_C\tau_0F_0}{4\pi^2}\left(1-e^{-hc/Hs}\right)\int_0^1\frac{\overline{r}_F(x)\delta_{0,z'}}{x^2}I^{+}_{p1}(z,z'_x)S_e(0,x,0)S_e(x,M_S,h_C)dx \tag{3}$$

where the term h_C represents the altitude of a cloud-base. For the detailed explanation see [10]. The visibility of clouds from the ground is approximated by Zuev's and Titov's model [11]

$$\delta_{0,z}=1-(1-C_F)\exp[C_F\beta(\sec z-1)] \tag{4}$$

with C_F being the cloud fraction. The aspect factor β is computed as the ratio of cloud base diameter to the cloud height and typically varies from 0.75 to 2.5. The C_F is identical to the so-called nadir-view cloud cover. It is the ratio of a horizontal cloud area as viewed from the nadir to the total area of a selected zone. Alternatively, the hemispherical sky cover can be also used that depends on C_F Using an approximate formula defined in [12], we can write

$$C_{F,hemisf}\approx\frac{C_F}{\left[1-\beta\frac{arctg\left(\frac{R_c}{H_c}\right)}{\alpha^*}\right]} \tag{5}$$

where R_C is a cloud radius, H_C is a cloud-base height, $\alpha^*=80^o$ and β is the cloud aspect ratio introduced above. The random cloud distribution is based on a simplified cellular statistical model of the broken cloud field. In the Eq. (1) and (5) it is expressed as r_F defined as follows

$$r_F=\frac{1+\cos^3(\varepsilon)}{2}\frac{(1-C_F)^2}{C_F} \tag{6}$$

where ε is angle contained by the direction to the sun and direction to a sky element. The direct normal illuminance is the product of the normal extra-terrestrial illuminance E_V and the optical transmission function (i.e. atmospheric transparency)

$$E_{V,S} = E_V \exp\{-\tau_0 / \cos z_S\} \tag{7}$$

where the turbidity factor τ_0 predetermines the atmospheric transmission. Based on the theory developed we can model luminance of a non-homogeneous atmosphere. The diffuse irradiance is obtained by integrating the sky luminance over the upper hemisphere, while the radiance of a sun is determined from Eq. (7) taking into account the angular radius of a sundisk.

B.Modelling light transmission through the light-guide

The passive lighting systems, such as light-guides, typically collect exterior skylight and sunlight and transport them into building interiors via high-reflecting tubes. The key objective of a 3D light transmission modelling through the light-guide is to determine its optical performance and find out correct illuminance distribution on the working plane below the pipe. The expected luminance at the light-tube base is proportional to the sky luminance reduced primarily due to the multiple reflections in a tube as well as due to the attenuation by the hemispherical top dome. The light beams propagate through a light-pipe with multiple internal reflections until reaching the base of the pipe and illuminate the infinitesimally small surface of the diffuser:

$$E_i(\phi_0, r_0) = \int_{\theta=0}^{\pi/2} \int_{\varphi=0}^{2\pi} j(\theta,\varphi,\phi,r) \cos\theta \sin\theta \, d\theta \, d\varphi \; \cdot \tag{8}$$

Because the diffuser lies in the horizontal plane and we consider vertically oriented straight pipes, the exit angle always corresponds to the entrance angle, and thus the zenith angle of a beam is conserved. Now, let us consider a diffuser-free light guide installed above the working plane. Illuminance of any selected point of a working plane with coordinates X', Y', Z' is determined as follows

$$E_W(X',Y',Z') = \frac{t_D}{2\pi} \int_{r=0}^{R} r\, dr \int_{\phi=0}^{2\pi} \frac{\cos^2\Theta}{R^2(\Theta,\Phi,r,\phi)} d\phi \int_{\theta=0}^{\pi/2} \sin(2\theta) d\theta \int_{\varphi=0}^{2\pi} j(\theta,\varphi,\phi,r) d\varphi \quad , \tag{9}$$

where R is the distance between a selected point on the light-tube base and arbitrary point. In previous equations, luminance $j(\theta,\varphi,\phi,r)$ is a function of the zenith and azimuth angles of a light beam and also depends on the point in which the beam intersects the upper interface of a light-pipe. When the sunlight is absent, we can write

$$j(\theta,\varphi,\phi,r) = L_a \, \rho^N \, t_C \quad , \tag{10}$$

where L_a is a luminance of a sky element with the specific azimuth and zenith angle. In our model it is a product of the first and the second order of the light scattering in the atmosphere and it is given by Eq. (1) and (5). A parameter ρ is a reflectance of the interior surface of the light-tube which we consider as a constant and t_C is a transmission coefficient of a hemispherical cupola. A variable N corresponds to the number of reflections within the interior of light-tube and can be expressed as the Eq. (28) in [8]. In general, the direct sunlight also contributes to the illuminance on elementary surfaces of the diffuser as well as on the working plane in the building interior. When the angular distance of the sky element from the center of the sun disk is smaller than the radius of the sun-disk, we have to use total luminance defined as

$$j_T(\theta,\varphi,\phi,r) = j(\theta,\varphi,\phi,r) + j_S(\theta,\varphi,\phi,r) \tag{11}$$

where

$$j_S(\theta,\varphi,\phi,r) = \frac{L_{V,S}}{\cos z_S} \rho \, N_{Sun}(\varphi) \, t_C \tag{12}$$

for the term N_{Sun} holds the same Eq. (28) in [8], when the zenith angle of the incident beam is substituting with solar zenith angle.

NUMERICAL EXAMPLES

The numerical implementations of the theoretical approaches described in the previous sections were developed as the C++ software packages called UNISKY [7] and HOLIGILM [8]. The first mentioned tool allows creating the maps of zenith normalized spectral sky radiance or luminance with respect to the atmospheric and meteorological conditions. Some of these parameters only slightly change over the time, while others depend on both time and place. The second one is used for modelling light transmission through the tubular light-guide with hemispherical top dome and different types of diffusors. In our work, we prefer a transparent glazing at the bottom of the tube to demonstrate light distribution directly coming from the sky vault and the sun. Afterwards, a simple application was developed to connect two simulation tools for mass calculations using a large scale of external conditions.

A. Sky luminance distribution

The sky luminance distributions were calculated in accordance with the approach described in Section II.A, considering various nadir-view cloud fractions. As the examples demonstrating Unisky Simulator outputs, three different sky conditions are shows on the Figure 1; (a) C_F = 0.15, (b) C_F = 0.30 and (c) C_F = 0.45. Note, that for the cloud-base altitude H_C = 1 km and cloud radius R_C = 0.5 km, the hemispherical sky cover corresponds to (a) $C_{F,hemisf}$ = 0.22, (b) $C_{F,hemisf}$ = 0.45 and (c) $C_{F,hemisf}$ = 0.67. Thus, the ground view sky cover on the figures seems to be higher than the input parameter for Unisky Simulator. Solar coordinates are set to A_S = 180°, z_S = 60° while the position of the sun is depicted as a white cross on the figures. An interesting phenomenon can be observed when the solar altitude is low enough; the clouds with the albedo a_C = 0.5 or higher located opposite to the sun position are illuminated “from below” and reflect much more light than the clouds on the solar part of the sky vault. This effect can significantly influence the total amount of light falling on the light-guide top dome from a given direction.

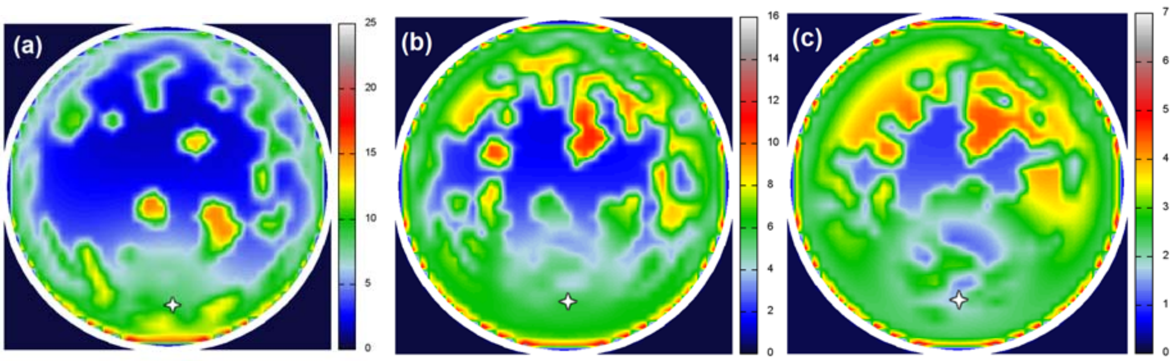

Figure 1: Sky luminance distribution under broken cloud array generated by Unisky Simulator for various cloud fractions: (a) 0.15, (b) 0.30, (c) 0.45. Solar altitude equals 30°.

B. Working plane illumination

Different values of the cloud fraction concurrently with changing solar altitude affect the behaviour of the light-guide and produce interesting illumination effects on the working plane if transparent glazing is used at the bottom of the light pipe. At first, random cloud distribution without preferred cloud direction is modelled with predefined aerosol parameters and light-guide technical specification, such as light guide length l = 0.5 m, radius r = 0.26 m, internal reflectance ρ= 0.94 and the transmittance of the cupola t_C = 0.92. The testing room dimensions are x = 6 m and y = 4 m and the position of the light-guide centre with respect to the testing room coordinate system is x’ = 1.5 m, y` = 2 m. Working plane illuminations for various cloud fractions and solar altitude equals 45° are plotted on Figure 2. Zero cloud fraction (2a) shows only a typical ring caused by the multiple reflection of direct sun beams in the tube interior. As it is evident lower cloud fractions (2b), (2c) cause slight brightening below the centre of the light-tube. As high is the cloud fraction as marked is the central brightening (2d).

Low solar elevation has more interesting consequences for the working plane illumination as it is shown on Figure 3. It is caused by the higher number of internal reflections of the sun beams as well as high reflecting randomly distributed clouds illuminated by the sun. There are significant brightening below the centre of the light-tube as it is depicted on Figures (3c) and (3d) if the cloud fraction is high enough. In these cases the sun disk is shaded by the clouds thus the typical ring caused by direct sunlight is absent.

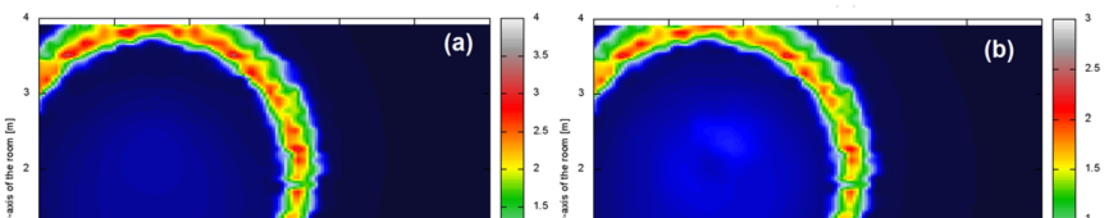

Figure 2: Working plane illumination below the light guide with radius of 0.26 m and length of 0.5 m under randomly distributed clouds with various cloud fractions: (a) 0.0, (b) 0.15, (c) 0.30, (d) 0.45. Solar altitude equals 45°.

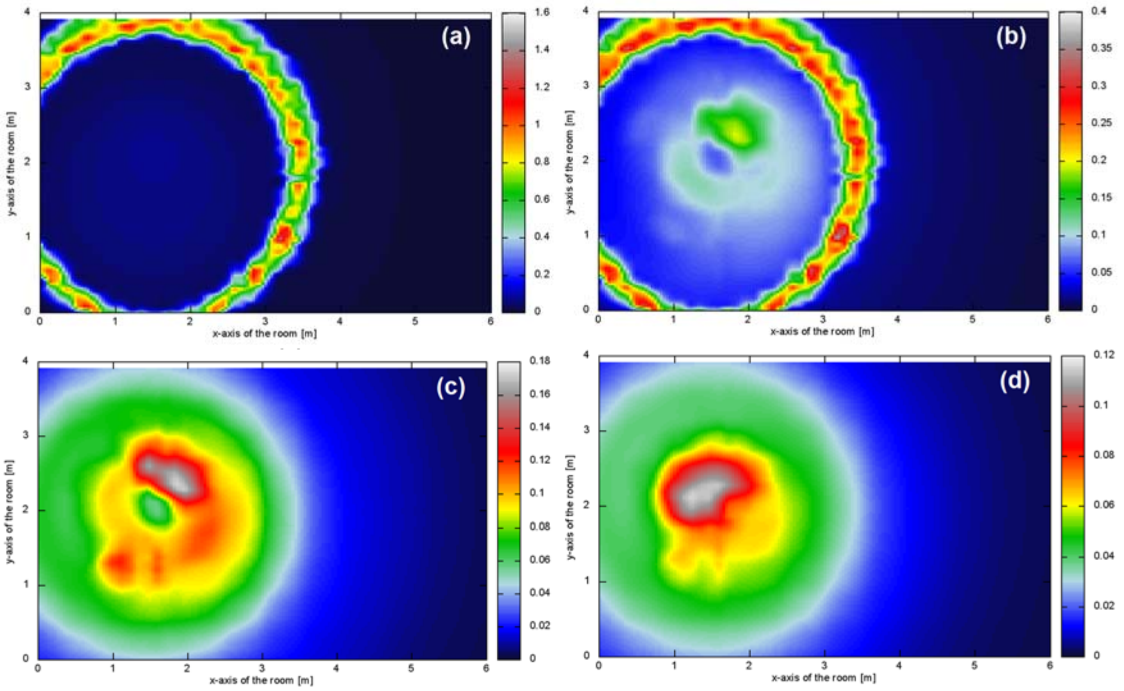

Figure 3: Working plane illumination below the light guide with radius of 0.26 m and length of 0.5 m under randomly distributed clouds with various cloud fractions: (a) 0.0, (b) 0.15, (c) 0.30, (d) 0.45. Solar altitude equals 15°.

C.Cloud shifting from preferred direction

An interesting behaviour of the working plane illumination occurs when the cloud field is concentrated in a given direction, or the clouds are shifted to a given azimuth. We focused on the cloud shifting from the solar and anti-solar direction. Figure 4 show sky luminance distribution as well as cloud field position on the sky vault. The sun is depicted as a white cross with position $A_S = 180^o$ and $z_S = 20^o$.

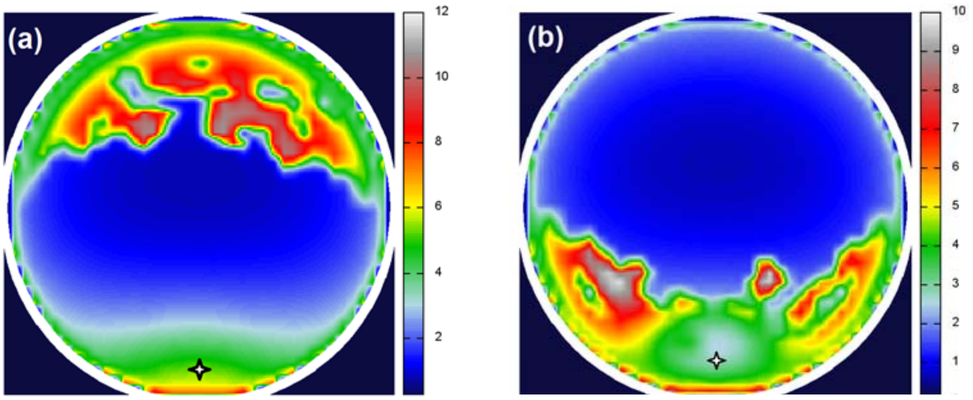

Figure 4: Sky luminance distribution under broken cloud array with cloud fraction = 0.3. Clouds are cumulated in a preferred azimuth: (a) 0º and (b) 180º with the offset of 2.0 km. Solar altitude equals 20º.

The working plane illumination differs significantly if the clouds are concentrated in one part of the hemisphere. As it is evident form Figures 5, the clouds cause remarkable illuminance increasing on the on the opposite side (azimuth in local coordinate system) than the clouds are located (compare with the Figure 4). Otherwise, if clouds are shifted to the anti-solar direction, the brightening on the "solar side" is much higher than on the opposite side. Of course, we are considering transparent glazing at the bottom of the light-tube for better recognizing of the broken cloud effect. This knowledge can help in more effective diffuser proposing in regions with low solar elevations and frontal weather behaviour.

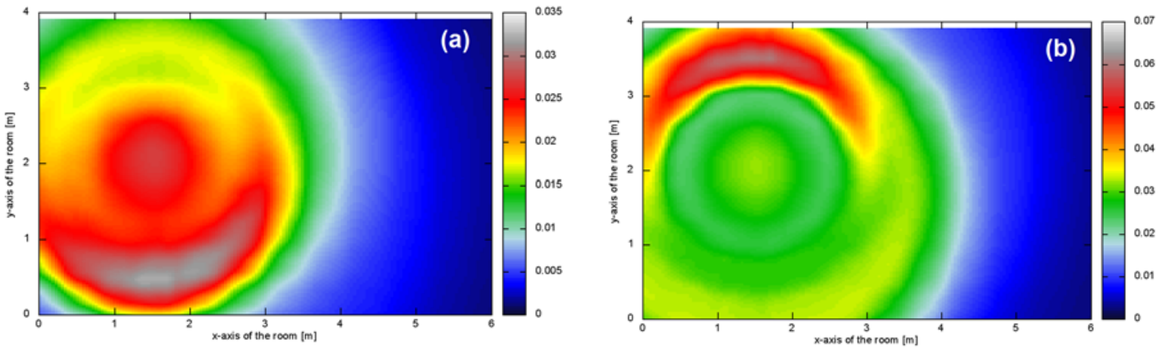

Figure 5: Working plane illumination below the light guide of radius 0.26 m and length 0.5 m under the sky conditions depicted on Figure 6.

CONCLUSIONS

This paper concentrates on a theoretical study of the tubular light-guide behaviour under more realistic outdoor conditions. Two unique simulation tools UNISKY and HOLIGILM developed at Slovak Academy of Sciences were linked together with a simple application for modelling light field with the broken cloud array with a tool for simulating light transmission through the straight light-guide. A hemispherical dome with the given transparency at the top of the tube and a transparent glazing at the bottom was considered. Various randomly distributed cloud fields were simulated with different cloud fractions. Shifting of the clouds from preferred solar and anti-solar direction was also examined.

Two interesting results were obtained:

- A light field on the working plane below the light-guide is different if low solar elevation and higher cloud fractions are considered in comparison with the sky condition with high solar altitudes.
- If the cloud field is concentrated around the given azimuth, e.g. in cases of frontal systems, the working plane illumination shows remarkably brightening on the side opposite to the azimuth of the cloud field.

The following results on light-tube efficiency, luminous flux and asymmetry parameter will be published in the near future.

ACKNOWLEDGEMENT

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Measuring Daylight Properties with Five TCS230 Sensors

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***Abstract*— Replicating light from outside. Colors are all around us. Everywhere we look, everything is drenched in colors. Light affects us (our behavior and wellbeing) more than we may acknowledge. In the morning, the lighting is different than during the day or in the afternoon. Here, we are going to take a look at the visible specter of colors and how they affect us. In order to do so, we used a dark room, TCS230 sensors, a radiospectometer specbos 1200, Microsoft's Excel program and Python. Our goal is to find out how well certain low-cost sensors pick up colors. By calibrating the sensors and calculating the CCT we were able to compare the measurements from the sensors with the ones from the spectrometer.**

***Index Terms*-- calibration, CCT, RGB, sensor, spectrometer**

INTRODUCTION

As we all know, our most important source of light is the sun. Up until today, most of the living creatures on our planet have adapted to sunlight.

Light isnt only a neccesity for us to be able to see, but it also triggers a chain of activites which enable us to achieve better mental and pyshical health, enhance our concentration skills and boost creativity. Most of us can agree, that a sunny summer day makes us feel a lot better than a gloomy autumn one does. The visibile spectre of light is actually quite narrow, wavelenghts ranging from 380 to 750 nm. On the other hand, when talking about frequency, the numbers are somewhere in between 400 and 790 THz.

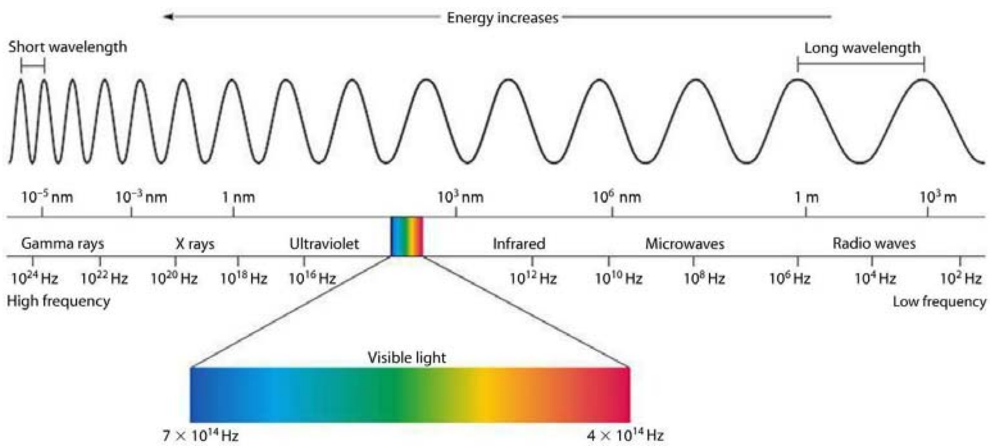

Figure 68: The Electromagnetic Spectrum [6]

TABLE 8: VISIBLE LIGHT SPECTRUM WAVELENGTH AND FREQUENCY

Color	*Wavelength*	*Frequency*
Violet	380 – 450nm	668 – 789 THz
Blue	450 – 495nm	606 – 668 THz
Green	495 – 570nm	526 – 606 THz
Yellow	570 – 590nm	508 – 526 THz
Orange	590 – 620nm	484 – 508 THz
Red	620 – 750nm	400 – 484 THz

Throughout history humanity has evolved to the points, where we require more light than we currently have in our homes. In general, we require the most light in the first half of our day as the need for it greatly diminishes the longer the day goes on. As a result we are motivated to stay outdoors during this period and go indoors when the sunlight begins to fade. Indoor light control systems are an important factor when it comes down to our lifestyle and our wellbeing. They allow of sleeping much better, which results in us feeling a lot more rested than we usually do. Many individuals today suffer from issues such as lack of sleep. In the long run sleep deprivation leads to a number of psychological issues such as: stress, poor judgement, loss of memory and concentration, creativity barriers as well as many negative physical effects such as diabetes, cardiovascular disease and cancer. Considering the fact that most people need on average about 8 hours of sleep it is worrying that the average individual only gets about six and a half.

Scientific research done in the last 20 years discovered certain photoreceptors located in the human eye [2][3][4] which greatly affect our quality of sleep and sleep schedules/cycles. These cycles have an enormous impact on our wellbeing. Disorders in this field are usually accompanied with things like depression, schizophrenia and bipolar disorder. [1]

The price of the lamp depends on its rated power, current THD, PF, life, efficiency, efficacy, CRI and environmental effects. When comparing two lamps of same rated power (10W), 82 CRI, 2700 CCT, 520 lumens output may cost around $9-10 for 8000h life, high current THD and low PF for $40-50 for 12.000h life, low current THD and high power factor. There is no question that CFL and LED lamps save energy but we should take into consideration that factors projected by the manufacturers are often overstated. [5]

As mentioned before the light lamp is characterized by the power required to operate, current THD, PF, output luminous flux,efficacy, efficiency, CRI, CCT and market price. Overall techno-economic study recommends to advise public to use LED or low current THD (<10%) high PF (>0.95) CFL lamps. [5]

PROBLEM DESCRIPTION

In order to set up conditions for the right amount of daylight in a space, we first need to measure the color of the source and then apply that to the LED lights. In today's market we can already find devices called radiospectometers which can give us a reading of the temperature of the light source measured in Kelvins. The human eye is quite sensitive to changes in color temperature in the range from 3000 to 6000K, which represents the visibility span when it comes to color temperature of sunlight. These devices usually carry a pretty hefty price tag that is why we wish to design a system, which will be available to the broader audience.

MATERIALS AND METHODS

A) Raspberry Pi

In order to see the system up, we require a Raspberry Pi 3 model B device and some TCS230 sensors. In general we can divide them into three models: A, B and zero. The B model is a bit more expensive than the A model but is also more powerful. Due to its simplicity when saving and working with data, as well as its affordable price, we decided to go for the mini-computer the size of a credit card called Raspberry Pi. The developers intent of this device was to construct a affordable version of a computer for tech enthusiasts, as well as students and others.

In our case, we used a Raspberry Pi 3 model B with a 4-quad processor ARM Cortex A53, 4 x 1,2 GHz. For storing the operation system and data we used a microSD card with space up to 32 GB. Besides the standard in/outgoing connection options such as 4x USB and HDMI, we can also find other less common ones. The DSI connector for connecting a display and a CSI connector for connecting a camera. It also includes a BCM43438 unit for wireless and Bluetooth 4.1 (Low energy). For the matter of power supply we decided on a unit with a Micro USB connector, with a 2, 5 A outputs current.

B) TCS230 Sensor

We then used a color recognition sensor called TAOS TCS230. It is made out of a group of 8x8 photodiodes with four different filters. A photodiode is a semi-conducting device which transforms light current into a square wave. It is made out of 16 diodes with a red filter, 16 diodes with a green filter, 16 diodes with a blue filter and 16 diodes without a filter. All of the abovementioned photodiodes with their filters are intertwined in a chessboard like fashion. This reduces the effect of inequality of irradiation.

Figure 69: 64 photodiodes [7]

. The output from se sensor is a square wave (50% duty cycle) with frequency directly proportional to light intensity.

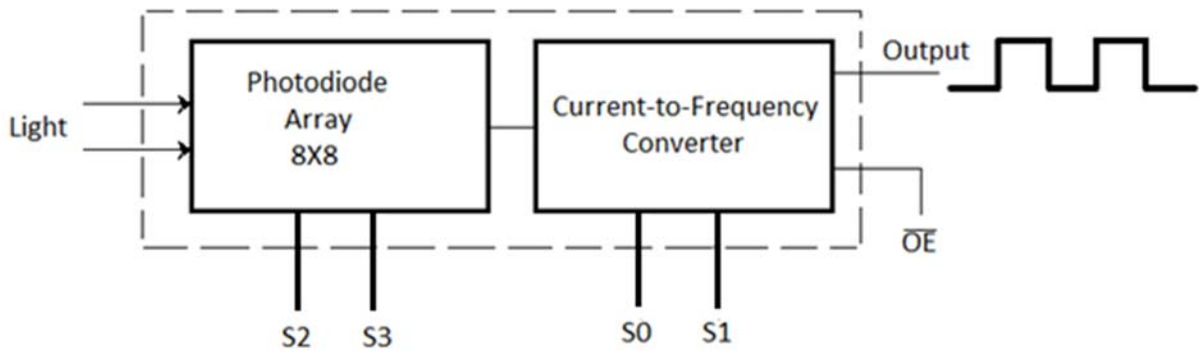

Figure 70: Functional Block Diagram

The sensors work very well when it comes to color recognition, although they still need to be calibrated. In order to calibrate them we used a Jeti Specbos 1200 spectoradiometer and calculations.

C) Spectrometer

The Specbos 1200 is a spectroradiometer, which is made by JETI, a German based company. Its use is quite simple: with the help of an USB cable, we connect it to our computer and control it through the Specbos program. The device captures readings of wavelengths in between 380 and 780 nm. It falls under the category of more expensive spectometers. It is able to measure many other variables such as: xy coordinates, CCT and CRI. [8]

D) python:

Python is a scripted programming language. We decided to use it, due the fact that it was already integrated on the Raspberry Pi.

E) Sensor Calibration

The sensor calibration took place in a dark room laboratory for illumination and photometric at the faculty of electrical engineering in Ljubljana. To start it all of we had to connect all of the sensors with the Raspberry Pi and write the code. Measurements were done based on a warm white LED, cool light LED and a blue LED. The blue diode is coated with a luminescent coating[8]. The before mentioned LED light are powered with different currents of 50mA per step. We try all possible combinations for all of the three LED lights with the following currents: 0mA, 50mA, 100mA, 150mA, 200mA and 300mA. We made total of 216 different measurements.

TABLE 9: CURRENTS USED FOR MEASUREMENT COMBINATION

Current (mA)
0
50
100
150
200
300

F) Software And Excel Calculations

In order to get the data from our sensors, we used an existing solution written in Pyhton and upgraded it to suit our needs. First of all, we had to upgrade the code for it to be able to save measurements from all five of the sensors. The next step involved data processing, transferring the measurements into an Excel file and then analysing them. For each individual sensor, considering the possible combinations of current, we then got 5 x 216 different measurements from which we then calculated an average value for the initial five different measurements. This resulted in 216 aquarate readings.

All the results were needed to normalize to sRGB (0 – 1). From sRGB we made an inverse sRGB Companding

$$v = \begin{cases} V/12.92 & if\ V \leq 0.04045 \\ ((V + 0.055)/1.055)^2 & otherwise \end{cases}$$

after that we multiply the results with a matrix D65 2 degrees, therefore we got XYZ.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} [M] = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$M = \begin{bmatrix} 0.4124564 & 0.3575761 & 0.1804375 \\ 0.2126729 & 0.7151522 & 0.0721750 \\ 0.0193339 & 0.1191920 & 0.9503041 \end{bmatrix}$$

From XYZ we had to convert to xy

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

and finally we used the McCamy formula to get CCT out of xy.

$$CCT(x, y) = -449n^3 + 3525n^2 - 6823{,}3n + 5520.33, where\ n = ((x - 0.33320)/(0.1858 - y))$$

From this we received all the necessary data, required for the upcoming calibration

The xy values received from the sensors were compared to the xy value from the radiospectometer. We noticed a deviation, so we decided to reverse the procedure in order to find an adequate matrix, which will yield similar if not identical results to the ones measured with the radiospectometer.

G) Matrix Optimization And Deviation

To begin with, we took all of the gathered measurements and divided them up per sensor. For each individual sensor we then divided the measurements on to a learning multitude, which involved random (80%) measurements and a test multitude, which involved the remaining measurements (20%). In the case of the learning multitude, we optimised the matrix for each sensor. We then got an M matrix, where the deviation of the xy from the xy received from the spectrometer was as small as possible. We optimised the matrix by minimising the function, which was defined as a squared difference between the forecasted x and y with their actual values from the measurements. This ended with us taking the test multitude for each sensor and comparing the forecasted values of x and y with the actually ones measured. We then calculated the RMSE (root-mean-square error) in MAE (Mean Absolute Error).

Mean Absolute Error (MAE)

$$MAE = \frac{1}{n}\sum_{j=1}^{n} |y_j - \hat{y}_j|$$

Root mean squared error (RMSE):

$$RMSE = \frac{1}{n}\sqrt{\sum_{j=1}^{n}(y_j - \hat{y}_j)^2}$$

TABLE 10: SHOWS THE DIFFERENCE BETWEEN RADIOSPECTOMETER AND SENSORS AFTER CALIBRATION

Sensor	RMSE (x)	RMSE (y)	MAE (x)	MAE (y)	MAX error (x)	MAX error (y)	MIN error (x)	MIN error (y)	Average error (x)	Average error (y)
9	0,00437	0,00384	0,00354	0,00324	9,22%	2,82%	-3,16%	-3,77%	1,55%	1,32%
10	0,00419	0,00311	0,00321	0,00232	10,66%	2,42%	-3,45%	-3,15%	1,40%	1,10%
23	0,00376	0,00456	0,00266	0,00344	2,94%	2,67%	-4,97%	-7,90%	1,03%	1,33%
24	0,00396	0,00361	0,00289	0,00293	2,59%	2,98%	-4,31%	-1,88%	1,08%	1,05%
25	0,005	0,0039	0,004	0,00249	10,00%	2,18%	-5,06%	-8,03%	1,63%	1,08%
Combined	0,00754	0,00702	0,0062	0,00525	10,04%	12,11%	-8,38%	- 10,62%	2,43%	2,25%

CONCLUSION

The color temperature of light has a significant effect on an individual wellbeing. By measuring the CCT we are able to get natural lights, which are then transferred into a space using LED lights. The process of calibrating a single low cost sensor usually has an average error below 2%. This shows that even low cost sensors can be quite useful and accurate. CCT is then calculated by the formula (McCamy) mentioned above.

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The Effect of Daylight on the Elderly Population

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***Abstract*— A study was completed among 9 participants, 3 housebound and 6 non-housebound, to identify whether the relationship between daily activities including light exposure, and sleep disorders in the elderly population, reveal any patterns worth further investigation. Participants were invited to take part in a semi-structured interview. Questions regarding their daily activities, ability to go out, or not, and sleep patterns were asked. Building orientation, room dimensions, window positions, room wall-reflectance and illuminance levels were recorded. This study supports evidence that suggests that people over the age of 60 spend most of their "indoor" time under low illuminance levels. Also, a notable difference in the health and sleep condition between housebound and people able to go out was observed. This means daylight availability is particularly important for housebound elderly with limited access to outdoors.**

***Index Terms*—elderly, health, lighting, well being.**

INTRODUCTION

The world population is ageing. In 2014, according to the Office for National Statistics, 17.7% of the UK population was aged 65 and over and this figure is expected to grow to 23.3% by 2034. This implies a potential increase in the demand for healthcare service provision. A prevalent condition that comes with age is sleep disturbance, which is associated with alterations in the circadian system [1]–[3].

Light is a powerful cue to entrain the circadian clock [4]–[10] and it is also important for vision, however, requirements for the good functioning of circadian entrainment are different from the requirements for vision[11]. There have been numerous studies focused on the benefits or disadvantages that light might have on people's physical and mental health[12]. When it comes to sleep disorders a similar conclusion arises, if people are exposed to light during the night or if they are not having enough light during the day, their sleep can be disturbed.

Research has shown that, due to our daily patterns and designed environments, people may be less exposed to daylight than in the past[9], this affects health and wellbeing, especially in the population aged 65 and more. The visual system of older people is diminished due to changes in the physiology of the eye and therefore appropriate lighting requirements are needed.

A study was completed in 2001 by Bakker, Iofel & Lachs[13] in New York City. Illuminance measurements were taken in dwellings of housebound people over 65 years, and participants were asked for their perceptions of lighting. The results were compared to the IESNA standard minimum illuminance levels and found to be below those recommended. Despite this, participants were satisfied with their lighting condition. All participants mentioned that their main light source was daylight. Another qualitative study was recently completed in the Netherlands[14]. The focus of the study was the experience of old people in the house as a *home*, even though it was not focused on light, it turned out that people made modifications to their home relating to the orientation towards the sun and the amount of daylight it might gain. One of the participants decided to create a full-height glass façade in order to have more daylight in his living room.

The aim of the present study was to analyse the relationship between daily activities, the ability to go out and be exposed to daylight and sleep patterns.

PILOT STUDY

A.Method

A qualitative study design was performed to comprehend the relationship between daily behaviour patterns and the impact those might have on the elderly populations' sleep patterns. Interviews enquired about the time spent indoors and outdoors by the participants, as well as their sleeping habits. The study was carried out in locations with different orientations across London.

i. *Participants*

Nine participants, 6 females and 3 males, over 60 years were interviewed in their homes. All participants were currently living alone. From the 9 participants, 1 was semi-housebound and 2 were completely housebound, see Table I. The criteria needed to take part in the study was to be above 60 years of age and willing to be interviewed in their own homes. Additionally, taking photographs of their non-personal spaces and site measurements were agreed in advanced. Participants were compensated for the time invested in the interview. This study was approved by the UCL's BSEER Chair of the Departmental Ethics Committee. Eight of them provided written consent and one verbal consent due to her visual impairment. Data were collected between April and May 2017.

TABLE I. CHARACTERISTICS OF PARTICIPANTS' LIVING ALONE

Name(not real)	Gender	Age Range	House Type	Illuminance (lx) At sitting spot	Non-housebound/ housebound	Sleep Conditions
Nancy	F	60-65	One bedroom flat	~253	Housebound	Naps. Sleeps 3-4 hours at night
Betty	F	65-70	3 bedroom house	~138	Non-housebound	Four night of good sleep, one night interrupted sleep.
Brian	M	65-70	One bedroom flat	~279	Non-housebound	Naps during commuting. Four hours of sleep at night
Marco	M	65-70	One bedroom flat	~2,368	Non-housebound	Eight hours of sleep at night. No naps
Nell	F	65-70	Studio flat	~233	Non-housebound	Eight hours of sleep at night. No naps
Tony	M	70-75	One bedroom flat	~180	Housebound	Naps. No sleeping schedule
Rachel	F	80-85	One bedroom flat	~129	Non-housebound	Sometimes no sleep at all. Otherwise 8 hours sleep
Diana	F	90-95	Studio flat	~582	Semi-housebound	Sleeps 3-4 hours at night
Stephanie	F	90-95	One bedroom flat	~580	Non-housebound	Naps. Eight hours sleep at night

ii. *Data Collection*

A semi-structured interview was designed to gain an insight into older people's perception of their living conditions, their needs and the influence that the environment might have on their health and overall well-being. The aim of this study was to find a relationship between exposure to daylight and the consequences this might have in their sleeping habits. To reduce bias during the interview none of the questions were directly related to the concept of "light" or "daylight". The interview focused on their daily routines, including the amount of time spent indoors and outdoors; whether they require help to accomplish any activity; their home, including preferred room and sitting spot and also their opinions about their living surroundings. They were asked to describe how they begin and finish an ordinary day, what they normally eat and if they had a regular schedule to do so. Finally, questions related to their sleep schedule were asked. All questions formulated were open ended and because of the different characteristics within the sampling, questions were excluded or added in response to participants' specific conditions.

At the end of each interview, photographs and measurements of the living room, kitchen and hall/stairs were taken. Only one person declined this section of the study. Both photographs and measurements provided evidence of their existing living condition. Location of the dwelling and measurements facilitated a broad impression of how much daylight participants receive in their preferred room. In addition, illuminance was measured (using an illuminance meter-Konica Minolta T-10M) inside the room where the interview took place, in most cases the participant's preferred room was where the interview was held.

iii. *Data analysis*

The recorded interviews were transcribed verbatim. Theme coding and deductive analysis were used.

RESULTS

In order to identify any differences among them, participants were classified into two groups (house bound and non-housebound) depending on their ability to go out and carry out physical activities.

A. Non-Housebound Elderly

i. Dwelling Perception

One aspect considered is sitting preference and what they consider when choosing a sitting spot inside their home. Preference inside their home was asked, which also led to questions related to the perception of the place, surrounding and how they deal with them. Apart from Nell, who lives in the studio flat, all of the non-housebound mentioned that the bedroom is only used for sleeping. One interviewee, Marco, has a conservatory room, adapted to accommodate a working table. He prefers this room because it is "sunny". Also, he mentioned that the living room is "only to watch TV", but he did not spend a lot of time watching TV. Three female interviewees had a similar response regarding their preferred room, all of which were facing the garden. Also, each of these 3 rooms faced south. Betty mentioned she enjoyed spending time in there because it was "nice and bright"; Rachel said that "there (the room) is sunnier so I would probably (…) spend more time there, it looks out to a small garden". Brian's and Nell's rooms faced east. Nell, who lived in the studio flat, did not have a choice of internal rooms, nonetheless her preferred sitting spot was near the window. Brian spends most of his time in the living room, where he has the TV and karaoke equipment.

Different aspects were revealed when people were asked about their surroundings: the importance of the neighbourhood; people living nearby; the convenience of local shops and public transportation. All participants made positive comments related to their neighbours and the importance of having "friendly" ones. Brian commented, "They really look after (me), not just like a simple neighbour, they really treat you as family". Interaction with neighbours is an accessible way of being socially active.

ii. Daily patterns

When people were asked about their daily routine, most of them emphasised going out and keep by themselves "active". In the group, all subjects were engaged in recreational activities, such as "morning coffee", yoga, going to church, to libraries, etc., and two of them were active members of the Chinese Centre, located in North London.

Besides one person, interviewees wake up early in the morning, around 07:00, without any clock alarm. The average hour-time to go out and return to their homes is 10:00 and 18:00, respectively. In relation to eating habits, all mentioned having breakfast before going out. All interviewees described their breakfast in similar tone, one of them, Brian described it as having a "light breakfast". The only similarity this group have regarding eating habits was the type and time of breakfast. Otherwise eating patterns with the group were different, depending on their resources, time and habits.

As people age, sleep problems are more present[1], [2], [15]. From the 6 interviewees, at least 4 had a self-reported sleeping problem, however this was not supported by the amount of sleep they had, typically from 23:00 hours to 07:00 hours. Two female participants mentioned having a bad sleep pattern and that they needed to take sleeping pills, when necessary. One of them, Rachel, responded, "sleeping is not very good, I'm not good at sleeping. Sometimes I don't sleep…I really do have problems sleeping"; she was aware that the problem worsened when she didn't go out or do any activity. While Nell responded "I have to take a sleeping pill at night, and some nights I skip it…", the reason for her to skip pills was because she wanted to feel healthier. The other two females, have different medical conditions which somehow disturb their sleep. Stephanie solved her condition easily without taking any medication and now she could sleep eight hours at night. Betty mentioned that discomfort in her arm kept her awake some nights. Her response was, "my sleep really works for four nights then I have a night where I can't sleep, I don't know why". In her case, she mentioned it was worst when she felt stress about a situation she could not control.

Brian responded "…is very strange…sometimes I can sleep very early about 22:00 hours but only 4 hours basically…I sleep 4 hours". Although, it is only 4 hours, he never mentioned it was a problem. He is used to sleeping that amount of time. Marco was the only interviewee with no sleep disturbances. He responded, "I need a lot of sleep, I usually need eight-hour sleep to be fully energise". He pointed out that, in order to get a good sleep, he needs a complete dark environment, and in summer he does not need to set the alarm clock, because light wakes him up. Stephanie and Marco were the ones with more weekly activities and with less sleep disturbances. One of them was the youngest of the group and the other the oldest.

B. Housebound Elderly

Two people were classified as totally housebound; they cannot go out unless escorted to the hospital by an ambulance. The other person was semi-housebound; she could go out but she has visual deficiency in both eyes.

i. Dwelling Perception and Weekly Pattern

The three participants were living in their flats for more than 15 years. Two of them live in a one-room flat and the other on live in studio flat. Diana, has been living in a third-floor studio flat for twenty-seven years. Her room/living room has a large window facing south and she likes to sit next to the window on daily basis. Once a week she uses the "transport support" service. This service picks her up and take her to the grocery store, the service waits up and returns her to the flat. She mentioned, because of the time she has living there, she knows her way around the flat and she is satisfied with it. Although she commented that she would like to do some changes in the kitchen to feel "more safety" when she needs to clean up. What she does on a weekly basis is listen to music, clean her flat, ring her acquaintances or brother, cook 2-3 times a week and go shopping when necessary. Regarding her sleeping habits, she responded "I don't think I have problems to sleep, I think I sleep what I'm supposed to…", she only wakes up at night when she needs to go to the toilet, which is a prevalent situation in old people.

Tony is completely housebound as he requires twenty-four-hour supplementary oxygen, he also has anxiety and mental problems. "Because I'm always connected to it, it limits what I can do…" His daily activity is to sit down in the living room, next to the window facing west, watch TV, read, and fall asleep in the chair. He only goes out when he needs to go to the hospital, normally once every 3 months. As a result of his regular naps during the day, he does not have a defined sleep pattern. "I hate to go to sleep at night…I feel tired but I fall asleep on the chair".

Nancy, has living in a ground floor one-bedroom flat for fifteen years. She needs help to accomplish any activity, she is entirely dependent on her 4 carers. She spends all day sitting next to a window facing north. Her activities are praying, watch TV, and spending time at her computer. Like Tony, she only goes out when she needs to visit a doctor, which is once every 3 months. She mentioned she can sleep 3-4 hours in a row, then fall asleep again until the morning carer wakes her up and helps get her out of bed. During the interview, she showed memory and breathing problems.

The last two interviewees had a similar cluttered room condition which appeared gloomy. Windows were blocked in order to reduce glare on the TV screens. All three participants mentioned that because of their condition, they do not meet with other people, therefore feel alone.

DISCUSSION

As people get older their frequency of sleep disturbance increases due to various reasons[1], [16],which can have repercussions on their health and well-being. The results in this study, as it was expected, showed a difference between the groups regarding their daily activities and how this might affect their sleep, mood and health condition[17]

In the first group, composed of people who can go out, it can be assumed that they are exposed to sufficient levels of daylight and their circadian system should be normally entrained[18]–[20], hence, they should have less sleep problems. One of them, which is the youngest of the group, reported to have 8-hours of sleep. He likes to spend most of his time working in the conservatory and when it is time to go to bed he blocks all the light in the room. On the other hand, the oldest participant from the same group mentioned that she notices her sleep worsen when she does not have enough exercise or go out. She likes to spend time in the room facing south, although, her preferred sitting spot was near the window, it is blocked by a tree and does not receive direct sunlight. These are two people with more than fifteen age gap, and with different levels of activities, however, it can be noted that exposure to daylight might be a factor in improved sleep quality.

In the second group, despite the sample size, comparisons were made. There were more sleep problems with the two completely housebound than with the semi-housebound who is still able to go out, move around and sit next to her facing south window. Participants' health condition in this group is a significant variable to consider and sleep disorder cannot be only related to the lack of light and dark pattern in their daily pattern, however, it might enhance their mood[21]–[23] and have some benefit on their health and wellbeing

Regarding preferred rooms and ambient light, as Sörensen and Brunnstom indicate in their study[24], is difficult to measure non-standard situations, nevertheless, illuminance was measured inside their preferred room. It was noticed that, without exception, rooms of the housebound participants appeared gloomy. This was related to the colour on the walls, floor, the number of personal belongings in the room and the distance between the location where illuminance was measured to the nearest window. There was an average illuminance of ~290 lux in most of the rooms which is a little less than recommendations for residential buildings in the US [25]. There are no general requirements in the UK for minimum illuminance in domestic dwellings. Regardless, participants did not appear to have a problem with light. This might be due to the ability to adapt to their current living conditions without making adjustments. People are restricted by the architecture of their home, and it can be noted that all participants' preferred room was one with windows having outdoor view. Additionally, when the rooms were facing south, participants made positive comments about sunlight and the brightness that they perceive in the room. Finally, the study revealed the importance of all participants being able to be independent by going out and accomplishing simple activities unaided.

The evidence shows that people who are able to go out and spend time under daylight might reduce their sleep disorder. In this study, it was evident that people that could not go out have more sleeping problems, however it was clear that their health condition had an impact on their sleep pattern, perhaps more than the dark-light pattern. In order to fully understand and propose what could be the best quality of light for elderly population to enhance their sleep pattern, more research is needed; and it is also important to bear in mind the existing differences between elderly peoples' physical and social living situations.

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Gender- and Age-Related Preferences of the Lighting Conditions for Activity and Recovery

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Abstract—**In recent years, LED lighting became an indispensable alternative to conventional lighting systems. Sophisticated solutions offer not only comfortable white light with a high color rendering index. They also provide the possibility of changing illuminance and color temperature values. Such systems are supposed to have a positive effect on well-being, performance, sleep-quality and health. We investigated the subjective preferences of men and women regarding light-settings for activation and relaxation. More than 80 individuals – belonging to four groups differing in gender and age – were asked to imagine activating and relaxing situations for which they should adjust suitable and pleasant lighting by tuning the illuminance and the color temperature. With the correlated color temperature as an example, we show that there are clear differences in the lighting conditions preferred for these two situations. Also some gender- and age-specific differences become apparent.**

***Index Terms*—Human Centric Lighting, Gender and age related preferences**

INTRODUCTION

The last years have witnessed the rapid progress of light-emitting diodes (LEDs) as the base elements of future lighting solutions. While the success story of LEDs initially was mainly triggered by the aspect of energy efficiency, nowadays attributes of LEDs beyond efficiency become more important. Their compact size favours the nearby arrangement of individual LED dice and therefore the combination of dice covering different wavelength ranges. In combination with ongoing improvements of driver technologies more and more sophisticated luminaries that allow for dynamic modifications of either the luminous flux and/or the color temperature enter the market. Based on this it is for example possible to fabricate luminaires that mimic the natural run of the sun. Such dynamic light can support the psychophysiological, biological and emotional requirements of the people. This so-called "Human Centric Lighting" therefore gains more and more importance both for customers and developers since it is supposed to have positive effects on well-being, performance, sleep-quality and health [1].

Generally, aspects of light and their impact on human beings have been studied for many decades. A well-known study in this regard was reported by Kruithof in the 40´s of the last century. As a result of this study, combinations of illuminance and correlated color temperature (CCT) value ranges that are voted as comfortable or pleasing by humans are defined. However, there are a lot of debates on the usability of these results and there are also some concerns on the experimental design that is reported to be insufficiently described [2]. Still, this is also true for a lot of other studies in this regard. From a comparison of the reliable studies in this regard, Fotios [2] concludes that a variation in CCT has a negligible effect on ratings of pleasantness and that it are low illuminances (< 300 lux) that may be perceived as unpleasant. Therefore, he proposes that the Kruithof graph should rather be a straight horizontal line at about 500 lux (independent form the CCT value), indicating pleasant conditions above that line and unpleasant conditions below.

The impact of the CCT value has been studied also with respect to psychophysiological effects of light. However, even in this case the results reported in scientific literature are divergent. For example, McCloughan et al. 1999 [3] investigated the mood of men and woman in dependence of the CCT values and deduced that the mood of females is better in warm light than in cold one, while the mood of males is similar in both situations. The latter is in contrast to Knez 1995 [4] who concluded that also the mood of males is influenced by the CCT.

As evident from these examples, there is still no consensus in the scientific literature regarding the effects of light on human beings. The results regarding the effect of CCT seem to be more diverse than the results regarding the illuminance.

Therefore, we designed a laboratory study to gain a better understanding on the influence of illuminance, CCT and the deviation from the Planckian locus (Δu'v') on activation and relaxation in dependence of gender and age of human beings, this means of younger and older men and women.

EXPERIMENTAL

All in all, 85 persons agreed to take part in the studies. These persons were assigned to one of the four investigated groups: young men (age from 18 to 30 years, 20 persons), young women (18 to 30 years, 20 persons), old men (50 to 80 years, 22 persons) and old women (50 to 80 years, 23 persons). Generally, during the study, the persons were asked for tuning illuminance, CCT and Δu'v' values for envisioned situations of activation and relaxation and to fill some questionnaires.

The laboratory where the studies were performed consisted of an anteroom and two white coloured rooms with grey colored bottoms (see the sketch of the laboratory set-up in the left side image of Figure 1). Two small light cubes were placed in the anteroom (see "1" in the left side image of Figure 1) of the laboratory and each of the two white coloured rooms were also equipped with such a light cube. The cubes in the anteroom were used for the initial training of the persons and for testing the sensitivity of the individual persons to changes in the CCT value. For this, the persons were asked to look inside the cube and to see the undisturbed light. The light settings for the cubes (each of them containing one lamp from LUMITECH Production and Development GmbH [5]) could be tuned via twist dimmers on the left and on the right side of the cube, see the right side image of Figure 1. The lamps used in this study are based on the PI-LED technology that allows for tuning illuminance, colour temperature and Δu'v' in a wide range. In our experiment, illuminance could be set from about 350 lux to 5500 lux, CCT could be set from 2500 K to 7000 K, and Δu'v' from -0.02 to 0.02. Twist dimmers were chosen as the most promising method to cope with the most pleasant technology for tuning of the light settings for all 4 groups of participants.

The whole study took about two hours: After the arrival, the subjects had time to become accustomed to the situation while filling some general questionnaires in the anteroom that was illuminated with a custom standard light setting. After introducing the participants into the handling and the tuning of the light settings of the light cube and testing their sensitivities to changes in the CCT value, they were asked to enter one of the two white rooms. Each room was equipped with 12 lamps from the LUMITECH Production and Development GmbH. The rooms were furnished with a white table and a white chair. On the table, a light cube of similar type to the ones in the anteroom was placed (see Figure 2).

When the light settings in the cubes were modified, the light in the white rooms changed in the same way. For the tests in the white rooms, the participants were asked to imagine situations of activation and relaxation and to tune (with the twist dimmers) either illuminance, CCT, or Δu'v' (with two of these parameters fixed), or they could change all of those variables simultaneously, while looking into the cube, until they feel comfortable with the light in the cube for the envisioned situation. This setting was finally locked with the help of a button placed on the twist dimmer. For a better statistical analysis and to evaluate consistency from one phase to the other (e.g., activation 1 and activation 2), the persons were asked to repeat the light settings within four phases: two imagined activation phases and two imagined relaxation phases that were permutated, starting either with activation or relaxation (e.g.: 1. activation, 2. relaxation, 3. activation, 4. relaxation). This permutation and repetition allows for comparison of the light settings and to assess the consistency and reliability of the light settings in a statistically solid manner. In addition to the light settings, the subjects were asked to fill some questionnaires about their satisfaction with the light settings and about their actual mood, in each of the four phases.

RESULTS

From the tests in the white rooms and the light cubes, we collected plenty of data regarding preferred light settings locked by the subjects for the two envisioned situations of activation and relaxation.

Regarding activation and relaxation, the semantic differential showed a clear trend in the amount of separation between the activating and the relaxing light situations. Young subjects distinguished verbally stronger between activation and relaxation than did older subjects.

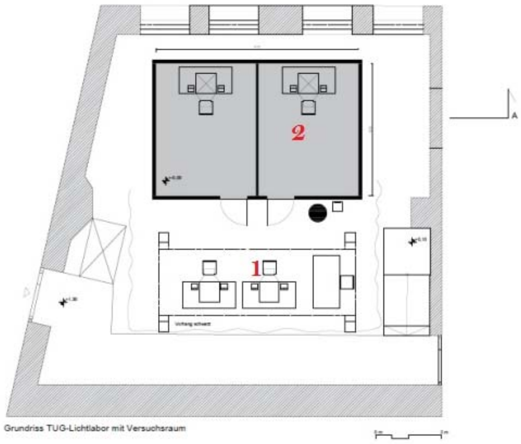


Figure 1: Left side: Sketch of the laboratory: In the anteroom (1) two light cubes are placed, that were used for training of the subjects and also for testing the sensitivity of the subjects to changes in the CCT value (see right side image showing one of the authors upon fine-tuning of the set-up). The light settings of the cube could be tuned via two twist dimmers on the left and on the right side of the cube. Afterwards, the participants were asked to enter one of the two (to be able to test 2 persons parallel) white rooms installed in the laboratory (see (2) in the left side image).

Figure 2: Laboratory environment. The white rooms were equipped with 12 lamps and were furnished with a white table and a white chair. On the table, a light cube of similar type to the ones in the anteroom was placed.

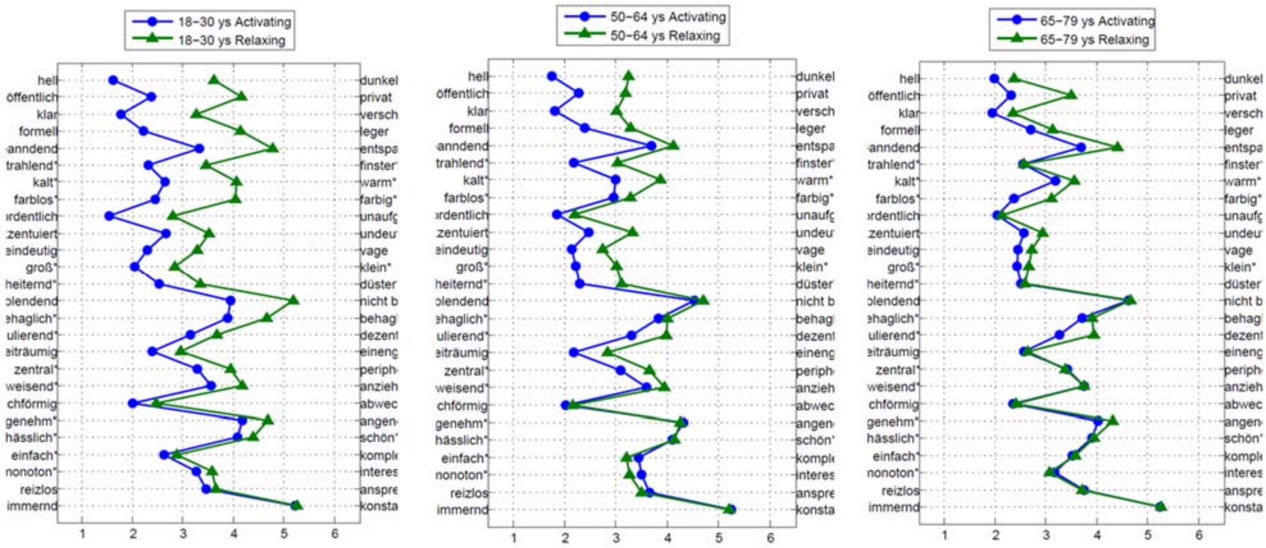
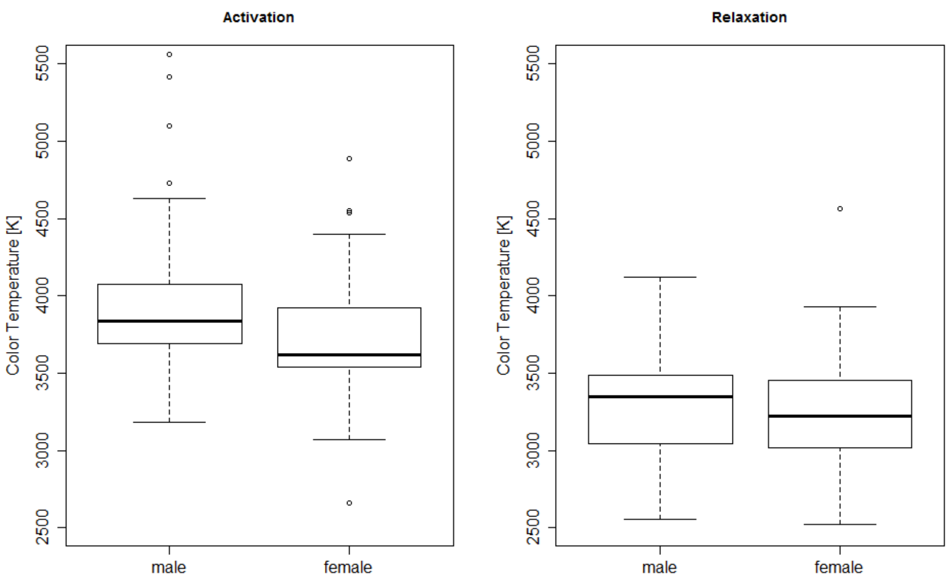


Figure 3: Semantic differential as gained by the evaluation of the light settings by the test persons. The blue line shows the mean value for activating situations and the green line for relaxing situations. The results are shown for 3 groups of age. Left side: 18-30 years, Middle 50-64 years, right side 65-79 years. With increasing age the differentiation decreases. For a more precise presentation the verbs are given in German, which was the language of the questionnaire**.**

A look at the data shows that the test persons (men and woman, elder and younger persons) generally tend to prefer more bluish light with higher CCT values in case of activation, while they prefer more yellowish light with lower CCT vales in case of relaxation.

A main point of our design was to look at gender and age differences in the preferences of illuminance and CCT values. In general, our data show that there are some differences with respect to gender and age for the preferred settings of illuminance and CCT.

As an example, Figure 4 shows the preferred settings for the CCT values with respect to gender and age. Generally, the meaning about the influence of CCT on humans reported in the literature is quite diverse [6, 7-10]. Our studies show that there are some differences in this regard that should be considered in sophisticated lighting solutions. For activation male persons as a whole tend to prefer a little bit higher CCT value than female ones. This is in accordance with [11]. Although the significance is very low, there is also some tendency that younger persons as a whole prefer lower CCT values for activation than the older ones, however, the results for the younger persons show at least a lower spread. For relaxation, all groups prefer lower CCT values as in case of activation. Again, male persons as a whole tend to prefer a higher CCT value than female ones while the preference of older persons as a whole for higher CCT values than younger ones again is of low significance.



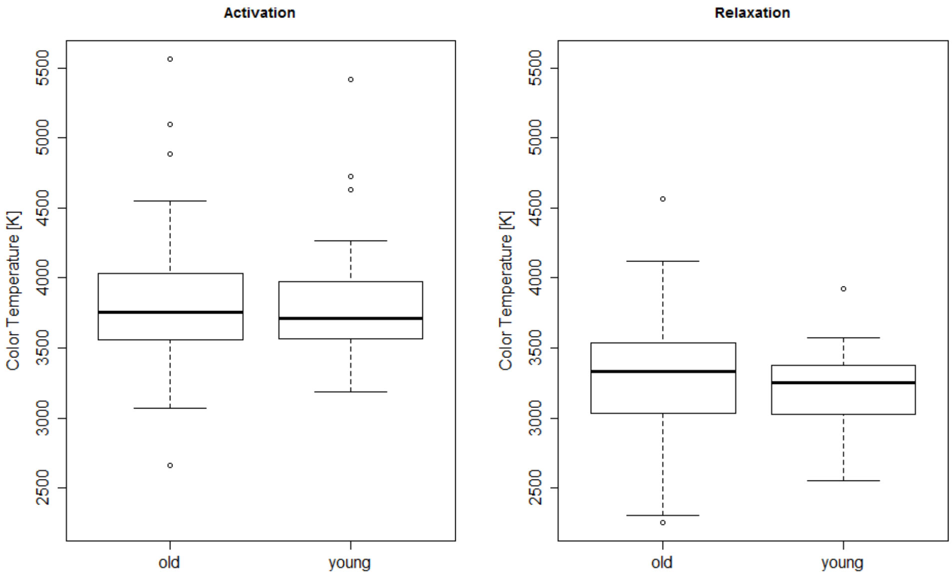


Figure 4: Boxplots of preferred color temperature settings of male and female subjects for activation and relaxation (upper chart) as well as old and young persons (lower chart).

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Daylight-Dependent, Seasonal Patterns in Industrial Incident Data

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***Abstract*—This article illustrates the close connection between daylight, the circadian system and safety at the workplace. It is initially explained that safety-related behaviour outcomes such as fatigue, alertness, cognitive performance and sleep are influenced by the circadian system. This influence is then reflected in practice in case of accidents, wherein circadian lows are associated with an increased risk of accident. The role of daylight is then addressed as an important zeitgeber (time cue) for the internal clock and the circadian system, and – with regard to incident analyses – it is illustrated that daylight-dependent, seasonal patterns can arise in industrial incident data.**

***Index Terms*—Circadian, Daylight, Incident, Safety, Season**

Introduction

Many studies indicate that a link exists between circadian-controlled performance parameters and accidents. The influence of the circadian system on fatigue, alertness, cognitive performance and sleep is particularly significant. These are safety-related behaviour outcomes which can be linked to incidents or accidents.

The influence of the circadian system on fatigue and alertness can be verified in particular by using instruments for the assessment of the subjective condition (e.g. sleepiness scales) [1]. With continuous recording over the whole day, circadian rhythms show marked alertness lows [2].

With regard to cognitive performance parameters, objective tests in laboratory investigations have shown that performance in specific standardised tests, such as the psychomotor vigilance task, search and detection tasks, sorting tasks, logical thinking and the reading accuracy of instruments is correlated to markers of the circadian phase [1]. These findings are supported by neuroimaging studies, which show that brain responses are influenced by the circadian system [3].

The relationship between sleep and the circadian system is also explained by the „two-process model of sleep regulation“ [4], [5]. The model describes the overlap of the circadian rhythm of sleep propensity with the homeostatic sleep pressure which linearly increases with elapsed time awake. The model has been used in many laboratory studies on fatigue and performance and could be verified in field investigations.

The statements of the previous sections should illustrate that the circadian system and safety at the workplace are closely linked. Along with the influence of the circadian system on fatigue, alertness, cognitive performance and sleep in laboratory investigations, a possible link between the circadian system and safety is also reflected in practice. The effects of these safety-related behaviour outcomes are particularly significant on incidents in work environments where short attention deficits can lead to direct damage (e.g. railway transport, transport in motor vehicles, aviation, healthcare). Retrospective analyses illustrate that accidents in the mentioned areas occur especially at times of circadian lows (e.g. at night, in the early morning and in the early afternoon) [6]. Various authors were able to establish marked circadian rhythms in accident frequency rates [7], [8]. Furthermore, studies that have researched the effects of daylight saving time on incidents point towards a fatigue-related increase of accident risk after the changing of the clocks in the spring [9].

So far, the role of light has not been considered in the outlined connection between the circadian system and safety. Light is the most important zeitgeber for the internal clock. The circadian system synchronises with daylight even in the modern world [10]-[12]. The influence of the above described behaviour outcomes is therefore evident through daylight changes. Particularly noticeable changes in the photoperiod arise with the change of the seasons. Strong changes occur in particular for sunrise times, day length and loss or gain of daylight. Figure 1 shows seasonal changes of the listed parameters, wherein the loss or gain of daylight is calculated with the difference of day lengths of previous and following calendar weeks.

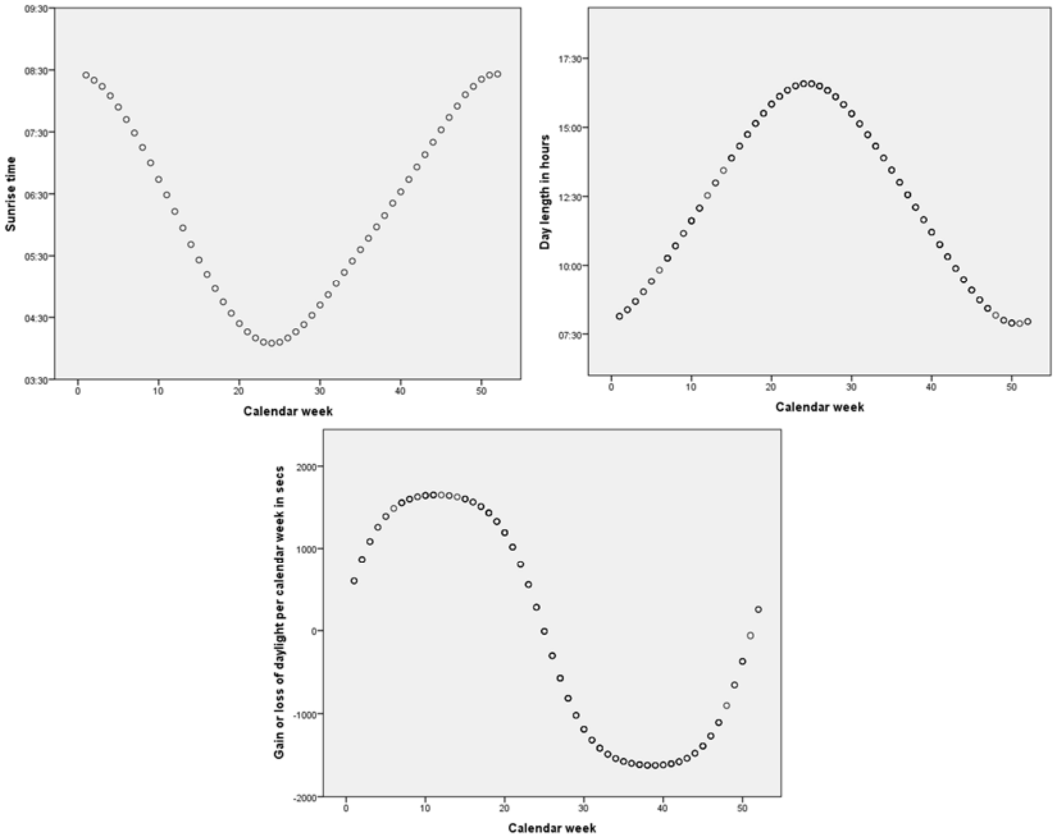

Figure 1. Changes in the seasonal photoperiod (exemplary for Central Germany)

The studies illustrated below indicate that adaptations of the circadian system to seasonal changes of the photoperiod effectively take place. Investigations on the seasonal adaptation of the circadian system date as far back as 180 years ago [13]. Seasonal rhythms could be observed particularly in sleep and in body temperature [14], [15]. Paul [16] and Kantermann [17] point to other indications of seasonal sleep rhythm; they determined significant differences in sleep duration between the seasons, wherein sleep duration is reduced in the summer in comparison to the winter. Furthermore, Cajochen was able to demonstrate that subjective and objective sleep parameters vary in an analogous manner to the moon phases [18]. A more recent neuroimaging study even suggests that cognitive brain functions such as sustained attention and working memory performance are subjected to seasonal changes [19].

Against the backdrop of the illustrated connection between daylight, the circadian system and safety at the workplace, the following hypotheses were formulated and verified according to an incident data set of the German Federal Environmental Agency:

1. The time of man-induced incidents varies between the seasons.
2. The time of technically-induced incidents does not vary between the seasons.
3. The median time of man-induced incidents shifts in an analogous manner to the seasonal changes of sunrise times.
4. The frequency of man-induced incidents shows an annually recurring seasonal effect.
5. The frequency of technically-induced incidents shows no annually recurring seasonal effect.
6. The annual frequency distribution of industrial incidents is correlated with changes of day length over the course of the year.

METHOD

In a retrospective analysis of 3,000 incidents reported to the German Federal Environmental Agency in the period between 1990 and 2015, the influence of the circadian system on the occurrence of incidents was examined. The statistic models for the analysis included factors such as date, time, geographical location, season and cause of incident. Furthermore, interfering factors such as daylight saving time, shift work and the amount of workforce were considered.

For the identification of possible influencing factors of the circadian system, various filter criteria were applied to the incident data set. Due to the fact that changes in daylight not only depend on the season, but also on the geographical location, only incidents within Germany were considered. The cause of the incident was further classified according to man-induced and technically-induced incidents. This separation is based on the assumption that only man-induced incidents can be influenced by the circadian system. In another step, the time of the incident was adjusted to normal time. The effects daylight saving time were hereby removed. The time adjustment was carried out with the aim of establishing a higher correlation between the natural daylight period and the time. Furthermore, all the incidents that did not occur between 8 a.m. and 4 p.m. were excluded from the analysis. The reason for the exclusion of night and early shift data is shiftworkers' frequent lack of adjustment to natural daylight. In particular, night shift work is associated with a decoupling of natural daylight and circadian desynchronisation [20]. By limiting the times, it can further be ensured that an almost constant number of employees was working in the mentioned time period. By contrast, it is for example known that less employees work during night shifts. If these differences are not considered in the number of working employees in relation to daylight, this can lead to erroneous interpretations in the analysis of incident frequency. After using the listed filter criteria, about 10% of the reported incidents remain for further analysis.

RESULTS ON INCIDENT TIMES

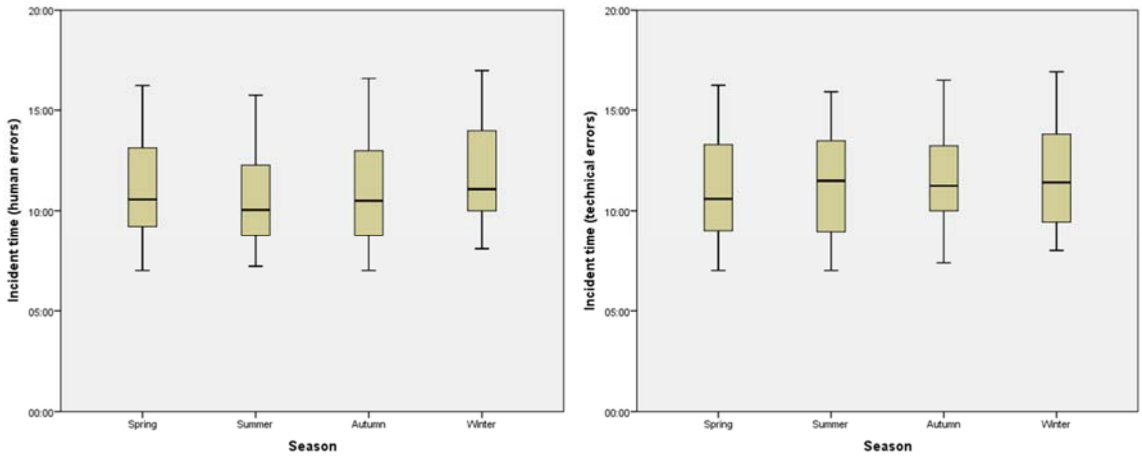

Figure 2. Box plots of incident times for human and technical errors

Figure 2 shows a shift of the median time of man-induced incidents to an earlier time in the summer (10:02 a.m.) and to a later time in the winter (11:05 a.m.). This pattern occurred in an analogous manner to seasonal changes in the photoperiod (earlier sunrise in the summer, later sunrise in the winter). In line with our hypothesis, this daylight-dependant, seasonal pattern does not appear in technically-induced incidents (figure 2).

By means of variance analysis, significant differences could be proven between the average values of incident times in man-induced errors ($F(3.251)=3.47$ $p=0.017$). Bonferroni post hoc tests for the paired comparison of the seasons resulted in a significant difference between the incident times in the summer and in the winter ($p=0.007$). In conformity with hypothesis 2, the statistics show no seasonal effects in technically-induced incidents ($F(3.336)=0.60$; $p=0.62$).

RESULTS ON INCIDENT FREQUENCY

For the analysis of incident frequency, cross tabulations of incident frequency were inspected as a first step in relation to the season. The chi² test showed a significant difference of incident frequency between the seasons $\chi^2(27,N=236)=167.82$ $p<0.001$ (Cramers $V=0.49$). A Poisson regression with the season as a factor and the incident frequency as a dependant variable also resulted in a significant effect (Wald-$\chi^2(3,N=236)=22.00$ $p<0.001$). The results suggest that the number of incidents varies between the seasons.

In an in-depth analysis, it was attempted to further restrict the seasonal difference in incident frequency. The visual inspection of the histogram on incident frequency (figure 3) over the calendar week suggests a certain similarity with the annual course of the day length (figure 1). A moderate correlation between the annual change of the day length and incident frequency could be determined ($r(236)=0.33$, $p<0.001$).

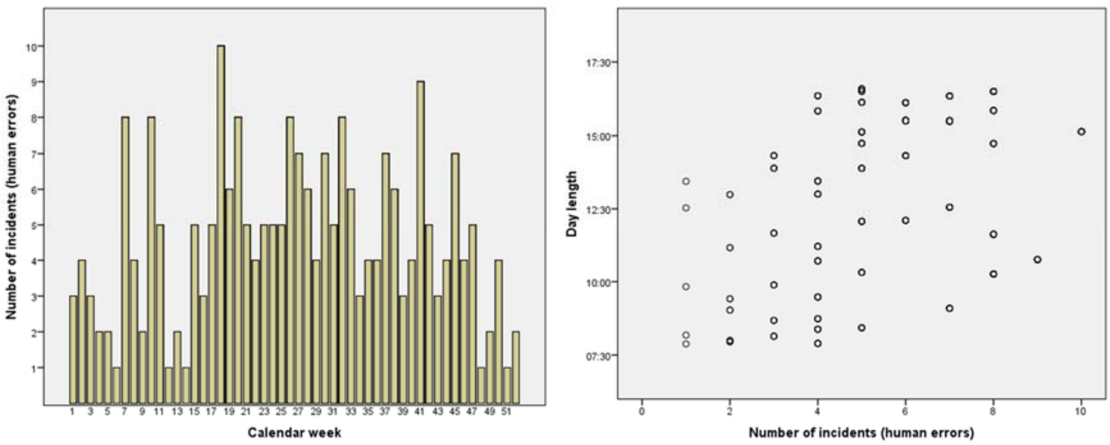

Figure 3. Histogram of incident frequency and scatter plot on the number of incidents in relation to day length

Contrary to the above illustrated hypothesis 5, technically-induced errors showed the same significant effects of a man-induced error. Even the technical error is significantly dependant on the season and shows a moderate correlation with day length ($r(321)=0.44$, $p<0.001$). For the man-induced error, against the backdrop of the above illustrated relations between the circadian system and work safety, the effect can be easily interpreted. For the technical error, the significant effect cannot be explained.

Discussion

Looking back on the hypotheses formulated in the introduction, the seasonal effects are reflected in the time of the incident as well as in the development of incident frequency. Except for hypothesis 5, none of the hypotheses to be tested had to be rejected. The results indicate an influence of the circadian system on incident occurrence which should not be ignored. Other non-significant results of our analysis support this assumption. For instance, an increase in incident frequency in the first week after changing the clocks in the spring or in the autumn appeared in in-depth analyses on the influence of time change.

Regression analyses further showed a geographical shift of incident times from east to west of 30 minutes. Surprisingly, the difference of sunrise times between east and west Germany amounts to 36 minutes, and therefore varies merely by 6 minutes from our result. In line with our results, Roenneberg found a shift of the chronotype from west to east to an earlier point in time [10], which indicates an adaptation of the circadian system to daylight.

Due to the fact that, in the retrospective analysis of the incidents, it could only be referred to data from the incident notification form, the represented results should be evaluated critically. Significant confounding variables, whose influence on the events cannot be excluded, are not recorded in the incident documentation and could not be considered in the analysis. These include for example:

- time elapsed since getting up
- time elapsed since starting work
- shift system
- break times
- differences in working conditions and type of work duty
- differences in lighting conditions
- individual factors such as chronotype or level of sleep deprivation

Despite not considering the listed confounding variables, some parallels can be drawn when comparing the results illustrated here with studies of other research groups on work and road accidents. Other research groups discovered similar seasonal patterns, however they were not able to provide an explanation for it [21]-[23]. For instance, Pierce researched seasonal patterns in work accident data and found an annually recurring pattern with higher accident figures in the summer and a drop in end-of-year months [24]. Pierce discusses various influencing factors, such as the weather, the length of the working day or methodical causes in the recording of accidents. In the end, Pierce concludes that none of the factors examined provide an explanation, and suspects a physiological mechanism to be the cause.

Against this backdrop, our analyses indicate a so far little observed influencing factor for safety at the workplace. Circadian factors should therefore be given greater consideration in accident analyses or in accident prevention in the future.

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Age Difference in Comfortable Lighting Evaluation of Lighting Environment in Real Space

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***Abstract*— The purpose of this study is to propose a comfortable lighting environment for a broad age group ranging from young to elderly people. Today, many developed countries including Japan are confronted with an aging society, and it is predicted that the average age of the population will continue to rise. Therefore, we should take visual properties into account and plan lighting with regard to illuminance, light colour and temporal change for all age groups of people. So, we set a condition of various illuminances and correlated colour temperatures in real spaces and conducted a subjective evaluation experiment. We analysed the results of the experiment and considered a proper lighting condition in addition to the results of previous experiments in the laboratory. On an impression evaluation of the lighting environment, it is clear that both age groups of people are affected by a usual lighting environment.**

***Index Terms*—Age, Comfortable Lighting, Illuminance, Lighting Environment Evaluation, Relative Correlated Colour Temperature**

INTRODUCTION

Currently, many developed countries, including Japan, are confronted with an aging population, whose average age is estimated to rise in the future. Since visual function decreases with age, we should take visual properties, such as illuminance, light colour, temporal change, etc., into account while planning lighting for elderly as well as young people.

Before now, the evaluations of illuminance, correlated colour temperature (CCT), and adjustment speed are considered mainly for the young people [1]. The recent development of solid-state light sources such as light-emitting diodes (LEDs) and organic LEDs has enabled us to propose lighting methods that consider temporal changes and plan for a comfortable and an energy-efficient lighting environment for daily life.

However, there are limited data that considers age factors. When planning a lighting environment, we should consider the visual performance of various age groups of people and accordingly provide for their visual requirements. It is necessary to ensure that they are comfortable in the lightning environment. Therefore, we have clarified the relationship between illuminance and CCT for various activities and the proper adjustment speed between the two aspects for both young and elderly people with the help of our findings in the laboratory [2][3]. We also conducted an evaluation experiment in a real space for the purpose of confirming the results of our experiments. In this paper, we compared these experimental results of impression evaluation for the lighting environment for both real-space and experimental rooms.

EXPERIMENTAL METHODS

Table I shows experimental outlines of a real space and the experimental room. Fig. 1 shows the combination of illuminance and CCT in those experiments.

A. Experimental Environment of a Real Space (Subjects' Living Space)

The LED ceiling light is set in a living room or a private room at a home of the subject or a nursing home. The light can be adjusted for illuminance and CCT. The range of the lighting condition is from 220 to 850 lx (4 levels), and the range for CCT varies from 2700 to 5100 K (4 levels). Accordingly, we set eight conditions. Note that "2700 K" is a colour of Sakura (cherry blossoms, light pink). Illuminance and CCT are set points of 80 cm from the floor under the apparatus.

A total of 26 people (10 young subjects aged 19-32 years; 6 middle-aged subjects aged 50-61 years; 10 elderly subjects aged 75-87 years) without colour blindness were included in the study. Among the elderly people, three were scheduled for a cataract operation, and one has an upper side of visual field defect.

The experimental procedure is as follows: 1) Subjects evaluate the usual lighting environment (fluorescent light); 2 The lighting equipment is changed to LED ceiling light; 3) The lighting condition is set, and they evaluate the lighting environment (first, the illuminance and the CCT are in the same condition as the fluorescent light); 4) They stay under the circumstances for five to seven days and evaluate the lighting environment again. Thereafter, steps 3 and 4 are repeated. They evaluate the light environment on a scale of one to four, i.e., whether they liked it, they could concentrate, they were free from stress, they could sleep or get up easily, and they felt good.

B.Experimental Environment of the Experimental Room

The interior colour of the experimental room is white (reflectance: 0.8), and the size is W2.7 m×D2.9 m×H2.8 m (Fig. 2). A ceiling light is used as a real space experiment. We set 90 conditions; the horizontal illuminance is set 3.0 to 1100 lx, and the horizontal CCT is set from 3000 to 5700 K.

39 young people (19-24 years old) and 26 elderly people (69-82 years old) without defective colour vision were included. In the elderly group, two subjects had a cataract removed or had a slight cataract.

The experimental procedure (Fig. 3) is as follows: 1) Subjects stay in the experimental room for 10 minutes; 2) Subjects adapt to the lighting condition for 3~5 minutes and evaluate the lighting environment (Evaluation 1); 3) An illuminance or a CCT is changed for the next condition by the experimenter; 4) Subjects evaluate the change of light environment (Evaluation 2). Thereafter, steps 2, 3 and 4 are repeated. In this paper, we handle the evaluation of the lighting environment (Evaluation 1).

D. Evaluations

In various impressions of the evaluation items for a lighting environment of the experiments, there are 2 common items: *like or dislike* and *concentrate or distract* in a real space and a laboratory. In this paper, we show these two items.

Evaluation scale on a real space is 4 levels and on the experiment room is 7 levels. Table II shows evaluation scale for lighting environment. The lighting conditions to be avoided (grey area) are defined as *the ratio of negative evaluation*; they are called two ratios of *disliked* and *distracted*. Evaluation scales are different for both experiments; however, we considered that the relation of an evaluation category and a ratio is equal for each age group and accordingly calculated the ratios.

TABLE I. EXPERIMENTAL OUTLINE

Experimental Space	***Real Space (Subjects' Living Space)***	***Experimental Room***
Experimental Environment	Living room or private room in each subject's home or private room in a nursing home	W2.7 m×D2.9 m×H2.8 m All walls are white
Experiment Period	3.5 months between 2012-2014	2010 - 2012
Lighting Equipment	LED ceiling light	LED ceiling light
Lighting Condition	Illuminance: 220-850 lx CCT : 2700-5100 K	Illuminance: 3.0-1100 lx CCT : 3000-5700 K
Subjects	26 people 10 young people (19-32 years old), 6 middle-age people (50-61 years old) and 10 elderly people (75-87 years old)	65 people 39 young people (19-24 years old) and 26 elderly people (69-82 years old)
Subjective Evaluation	whether they liked it, they could concentrate, they were free from stress, they could sleep or get up easily and they felt good	brightness, colour, whether they liked it, they could concentrate, they could they have calmed, they felt secure and comfortable

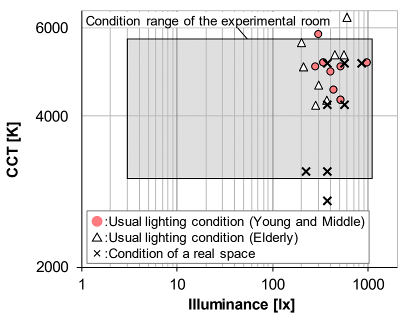

Figure 1. Experimental Conditions

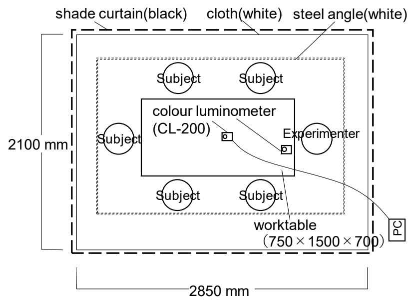

Figure 2. Experimental Room

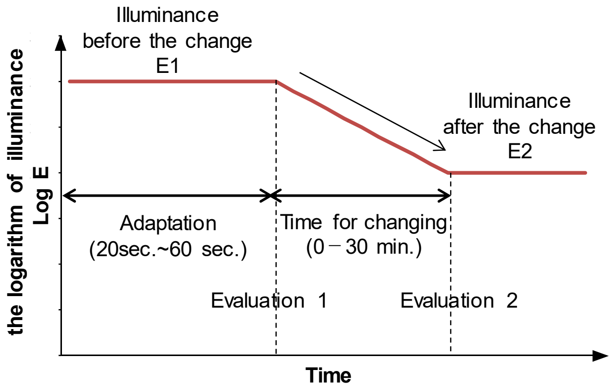

Figure 3. Experimental Procedure (the case of an illuminance control)

TABLE II. EVALUATION SCALE (DISLIKED⇔LIKED)

Real Space	*Experimental Room*
Disliked	Really disliked
	Disliked
A little disliked	A little disliked
A little liked	Neutral
	A little liked
Liked	Liked
	Really liked

RESULTS AND DISCUSSIONS

A. Examination Method

We compared and examined the results of the evaluations of various lighting environments on a real space and the experimental room. Fig. 4 shows the ratio of negative evaluation for each illuminance and CCT by age group. The range of lighting conditions in ordinary life (usual lighting environment) is indicated by grey colour in the figure.

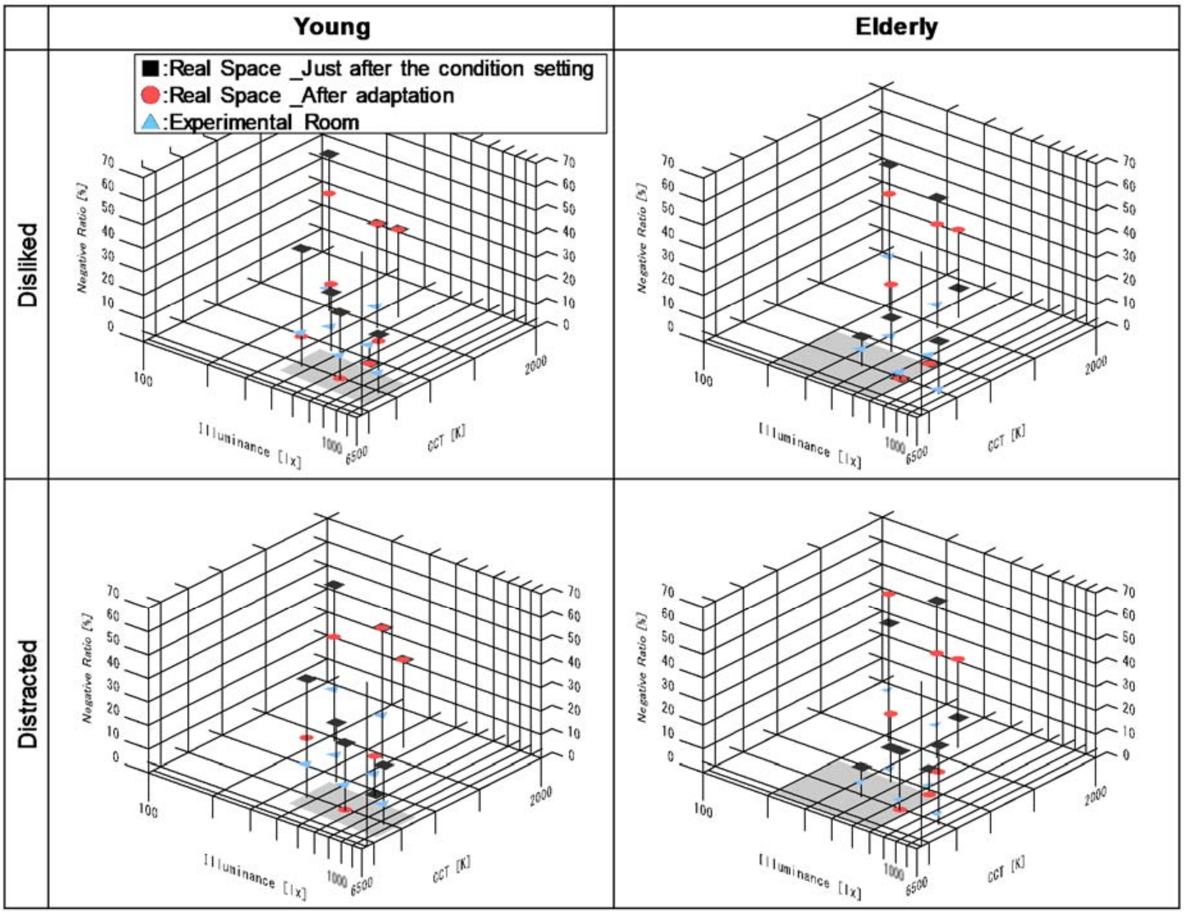

Figure 4. Comparison between a real space and the experimental room (ratios of negative evaluation)

B.Results

Fig. 4 shows that the ratio of negative evaluation in a real space is higher than that in the experimental room when separated from usual lighting environment. This tendency is common in both the young and elderly people.

Since we examined the influence of experiment variables on each evaluation, Fig. 5 shows the relations between ratios of negative evaluation and CCTs, and Fig. 6 shows the relations between ratios of negative evaluation and illuminances. In this paper, due to the presence of few subjects, we did not include differences less than 20%.

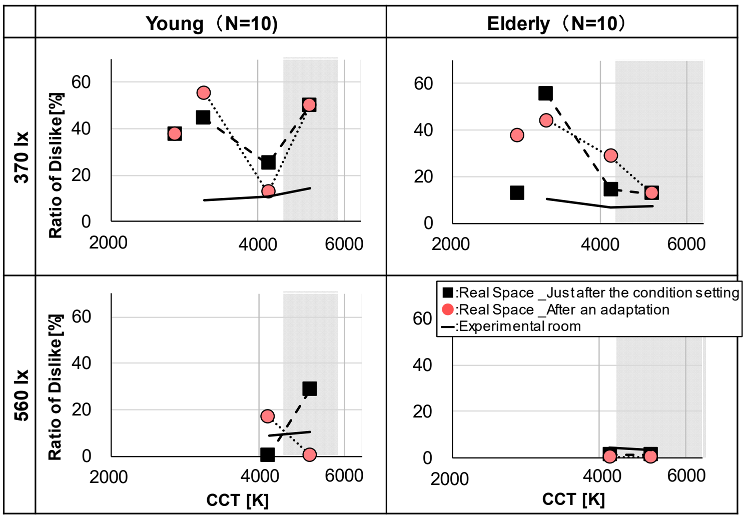

Figure 5. The influence of CCTs

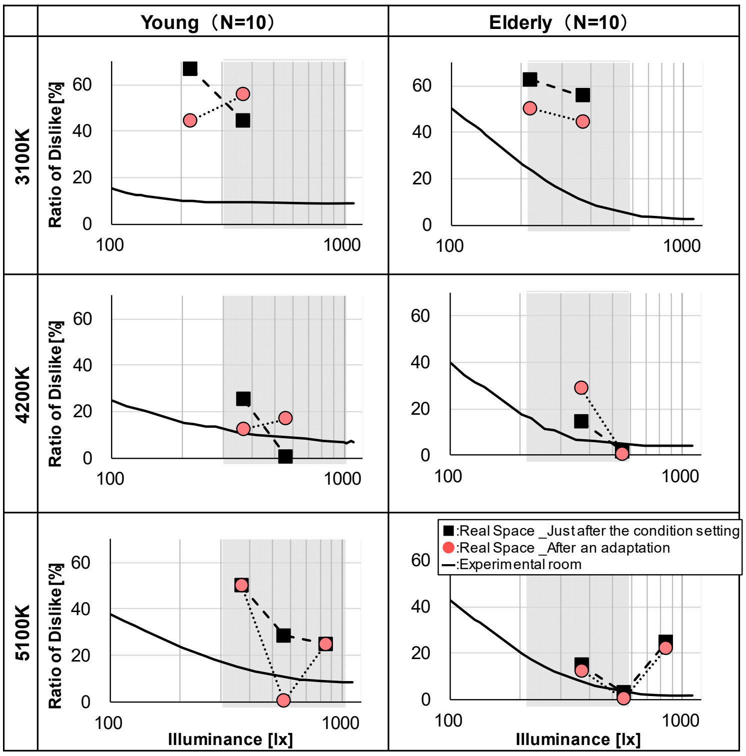

Figure 6. The influence of illuminances

i. *The influence of CCTs (Fig. 5)*

We can confirm that a ratio of negative evaluation is high in the condition of *3100 K*, which is far from the usual lighting condition in both age groups.

When the CCT condition is 5100 K near a usual lighting of elderly people's home, the ratio of negative evaluation is under 20 % regardless of illuminances. In elderly people, the lower is the CCT, the higher tends to be the ratio of negative evaluation except for 2700 K. In young people, the ratio of negative evaluation on the condition of 5100 K is higher than that of 4200 K. Both experiments (a real space and the experimental room) have these tendencies in common. But there is a difference in the ratio between a real space and the experimental room. It is necessary to consider an application method to a real space of the experimental rooms' results. This tendency is similar to the ratio of distracted evaluation.

ii. The influence of illuminances (Fig. 6)

When the condition is lower than 560 lx, we found that with increasing illuminance, the negative ratio decreases. However, when the CCT condition is 5100 K, the ratio of 850 lx after an adaptation is higher than that of 560 lx for both age groups. This may be because the subjects look for a source of light in daily life on a real space experiment, whereas the experimenter directed them not to watch for the source of light in the experimental room. This tendency is similar to the ratio of distracted evaluation.

CONCLUSION AND FUTURE PLAN

Through the impression evaluation for a lighting environment, it is clear that young and elderly people are influenced by usual lighting. Therefore, it is necessary that we consider usual lighting to fix the recommended lighting environment. Since there is a mutual interaction between illuminance and CCT, it is necessary to examine a heaviness charge account when we predict a room space evaluation. Also, we should consider the room type in such evaluations.

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An Investigation on Lighting Matter in Design Guides of Educational Buildings

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***Abstract*—The school design guides, one of the activities aimed at improving the education and space quality of the schools, aim at constructing energy efficient schools which are in compliance with the national education system, standards and regulations of the countries and to adapt old schools to the requirements of today's conditions. These design guides include information intended to guide many designers such as room features and dimensions, design recommendations for spaces, comfort conditions to be achieved (visual, acoustic and thermal comfort) and energy use.**

This paper analyses the design guides of the various institutions and organisations in 14 different countries toward the structures of education from 2000's to today. Guides were analysed and compared the information contained in the basic parameters' aspect toward its quantitative and qualitative features.

***Index Terms*—Design Guide, Educational Buildings, Lighting.**

Introduction

The features of the physical environment have a significant effect on the maintenance of the education and training in an effective manner as well as the personal qualifications. It is inevitable that environmental-physical environment conditions are supervised and some specific values have to be ensured to establish a healthy communication between the individuals. When the necessary conditions are failed to be provided, the students have physical, physiological and psychological negative effects such as difficulty in understanding, perception errors, distractibility, quick fatigue, frequent sickness, nervousness, and headaches [1]. The necessary comfort conditions have to be provided for "all building physics elements (light, heat, noise etc.)" in the education buildings to prevent such negativities.

The contribution of visual perception during the throughout education is more than the other senses. The required visual comfort conditions have to be provided to protect the eye health of the students, improve their visual performances, maximise their learning performance, to be contending with their environments in a psychological manner in the school buildings, of which the main users are students.

The design guides, one of the activities aimed at improving the education and space quality of the schools, aim at constructing energy efficient schools which are in compliance with the national education system, standards and regulations of the countries and to adapt old schools to the requirements of the times. These design guides include information intended to guide many interior designers such as room features and dimensions, design recommendations for spaces, comfort conditions to be achieved (visual, acoustic and thermal comfort) and energy use.

This paper provides the preliminary results of the research, which has been carried out on the school design guides in terms of lighting. 70 design guides about the education buildings from 2000's to today by 14 countries have been studied. The artificial lighting information involved in the guides has been examined as well. Thus, this study aims to create a source that will provide data to the institutions and organizations that will prepare guideline and education building designers and users on lighting.

Lighting In Education Buildings

The research and studies toward education buildings clearly indicate that learning capacity and performance of the students do not only depend on the personal factors such as motivation, psychological condition and intelligence but also physical conditions of the space that they are in. In order to provide complete, accurate and tireless and effortless learning, the good visual conditions, that is to say, visual comfort has to be provided in terms of light and lighting, which is one of the elements of the physical environment.

The school lighting not only affects the performance of the student but also the energy consumption. Studies on lighting indicate that heating-cooling and lighting are the most energy consumption elements in the schools. For example, the total energy cost of the primary, secondary and high school (K-12) in California, which is the most populous state of the USA (~ 35 million) is 700 million USD and it is almost equal to the budget for books and other needs [2].

Taking the energy consumption used in the artificial lighting into account, it is inevitable that what is necessary for the sustainable lighting must be done. The sustainability concept on lighting design is defined as "meeting the quantitative needs of the visual environment with the minimum effects on the natural environment" by IES (Illuminating Engineers Society) and IALD (International Association of Lighting Designers). Sustainable lighting design requires consideration of lighting performance, energy performance, and environmental impact criteria as of the preliminary design phase of the building. It can be summarised as effective use of energy on lighting, implementation of technological innovations, researching renewable energy resources, and also not compromising on the requirements that may enable the visual performance of the users.

Lighting design in schools should be in a way to enable the students and members of staff to carry out their actions in a cosy, comfortable and safe manner. In designing lighting, the possible flexibilities and restrictions have to be considered. The applicable standards and regulations in many countries contain information about the required lighting conditions in the schools. One of these standards is "EN 12464-1 Light and Lighting - Lighting of work places - Part 1: Indoor workplaces". This standard specifies the minimum values for artificial lighting parameters (*illuminance-E; glare-UGR; illuminance uniformity-U_0; colour rendering index-R_a*) according to the different functions (Table 1). The standard also includes information on inner surface material and equipment.

TABLE I. LIGHTING REQUIREMENTS FOR INTERIOR AREAS, TASKS AND ACTIVITIES [4]

Type of area, task or activity	**E_m (lm/m^2)**	**UGR**	**U_0 (E_{min}/E_m)**	**R_a**
Classrooms	300	<19	0,6	80
Black, green and white boards *(Vertical illumination)*	500	<19	0,7	80
Art rooms	500	<19	0,6	80
Circulation areas, corridors	100	<25	0,40	80

EDUCATIONAL BUILDING DESIGN GUIDES

The features of educational buildings such as playing a role in the development of the new generations, influencing its environment and energy-saving potential increase the importance of the studies about them. In this regard, as a designed environment, school buildings directly affect the educational activities in a positive or negative manner. The related ministries, local governments, universities and non-governmental organisations in many countries of the world carry out studies to increase the comfort of the education spaces. In this context, the design guides for schools, action plans, training programs for students and teachers, and evaluation systems have been created. Such systems and frameworks are important for guiding the relevant people such as managements, administrations, and designers.

Design guides, which have been published by the pertinent institutions and organizations of the countries to enable building the educational spaces to a specific standard, aim to guide the designers by laying down the design standards according to the national conditions. The guides include both type and sizes of the space and suggestions on the impact of the building on its environment. They provide reference information to the designers on various topics such as

- Constructing annexe to the existing schools,
- The renewal and development of the existing schools,
- Retrofit applications to be applied in various areas in schools (lighting, acoustics, thermal, carrier system, etc.),
- Energy-efficient use and increasing efficiency,
- The design and improvement of the conditions of the physical environment (visual, auditory, thermal comfort).

In this paper, a total of 70 design guides, which have been published after 2000 for designing the education buildings by various institutions and organizations in 14 countries were analysed [5]-[22]. The guides have been categorized into four groups such as "Design, Retrofit, Energy use and Lighting" according to their weights given therein. In this context;

- Between 2002 and 2016, 47 "General Design Guides for Schools" published by fourteen countries,
- Between 2004 and 2015, 8 "Lighting Retrofit Guides for Schools" published by three countries,

- Between 2007 and 2015, 9 "Energy Use Guides" published by three countries,
- Between 1999 and 2010, 6 "Lighting Design Guides for Schools" published by three countries.

were analysed in terms of artificial lighting information (Table 2).

TABLE II. TYPES OF GUIDES & PUBLICATION DATES DISTRIBUTION BY COUNTRIES

Country	Types of Guides & Publication dates								
	Design Guides		*Retrofitting Guides*		*Energy Usage Guides*		*Lighting Design Guides*		*Total*
	number	*Publication date*	*number*	*Publication date*	*number*	*Publication date*	*number*	*Publication date*	
USA	16	(2002-2016)	4	(2004-2014)	7	(2007-2011)	2	(2004-2010)	**29**
United Kingdom	6	(2002-2014)	-	-	-	-	3	(1999-2014)	**9**
Ireland	7	(2008-2014)	2	(2009)	-	-	-	-	**9**
Canada	4	(2007-2012)	-	-	1	(2010)	-	-	**5**
New Zealand	2	(2004-2015)	-	-	-	-	1	(2007)	**3**
Turkey	3	(2010-2015)	-	-	-	-	-	-	**3**
Australia	1	(2011)	-	-	1	(2015)	-	-	**2**
UAE	2	(2010-2012)	-	-	-	-	-	-	**2**
Scotland	1	(2007)	-	-	-	-	-	-	**1**
North Ireland	1	(2011)	-		-	-	-	-	**1**
Kosovo	1	(2015)	-	-	-	-	-	-	**1**
Indonesia	1	(2009)	-	-	-	-	-	-	**1**
Qatar	1	(2010)	-	-	-	-	-	-	**1**
South Africa	1	(2012)	-	-	-	-	-	-	**1**
Europe Union Project	-	-	1	(2015)	-	-	-	-	**1**
International Energy Agency Project	-	-	1	2014	-	-	-	-	**1**
Total	**47**	**(2002-2016)**	**8**	**(2004-2015)**	**9**	**(2007-2015)**	**6**	**(1999-2014)**	**70**

The lighting parameters stipulated in the standard and regulations and information/measurements in the lighting part of the guides *(illuminance-E; glare-UGR; illuminance uniformity-U_0; light colour/colour rendering index-R_a)* have been based and tabulated under quality, quantity and surface features of the lighting topics. The tables also indicate the standard and regulations taken as a reference by the guides and other information on lighting design. An example of the aforementioned tables is presented in Table 3.

TABLE III. LIGHTING REQUIREMENTS IN DESIGN GUIDES FOR SCHOOLS IN COUNTRIES

			Quantitative aspects	**Qualitative aspects**		
Country/Publisher/Year	***Guide name***	***Type of areas***	***Illuminance (E_m; lux)***	***Illuminance uniformity (U_0)***	***Colour rendering index (Ra)***	***Glare (UGR)***
USA/Collaborative for High Performance Schools (CHPS)/2006	Best Practise Manual-Design	Classroom	450 (min.300)	-	>80	-
		Blackboard	450 (min.300)	-	>80	-
		Circulation areas	100	-	>80	-
		Recommendations	Detailed information on design recommendations about natural and artificial lighting are given. ***Correlated colour temperature (T_{cp}):*** 3000-5000K ***Energy consumption:*** The energy consumption for artificial lighting should be max.12,9 W/m^2. ***Lamp selection:*** T5 and T8 fluorescent lamps with electronic ballast should selected. ***Reference standard / regulation / code:*** IESNA			
United Kingdom/The Department of Education and Skills/2002	Building Bulletin 95-Schools for the Future Designs For Learning Communities	Classroom	350	-	-	-
		Art rooms	500	-	-	-
		Recommendations	Some recommendations about natural and artificial lighting are given. ***Illuminance (E_m):*** 350 lux for general works, 500 lux for detailed works. ***Reference standard / regulation / code:*** Building Bulletin 87 (BB 87), Building Bulletin 90 (BB 90).			

EVALUATION AND CONCLUSION

The information/criteria in the lighting parts of the design guides are summarized under the titles of quantitative and qualitative aspects of lighting based on the lighting conditions recommended in the standards and regulations.

When the guidelines are analysed according to the lighting information they contain;

- There is no information about lighting conditions in 30 of the design guides.
- 10 of the guides have not provided information on artificial lighting conditions but indicate the standards and regulations on lighting.
- 30 of the guides have information on lighting design. Among these,
  - 13 guides provide lighting information only for classrooms.
  - 17 guides provide lighting information toward the possible space types in a school.
- In 17 out of 30 guides, which have provided lighting information, have provided information on the illuminance, in 6, illuminance and colour rendering index have been provided, and in 7, illuminance and illuminance uniformity, glare, and colour rendering index features have been provided.

When the numerical values in Table 4 regarding the lighting parameters in design guides are analysed,

- *Illuminance (Em):* Shows significant deviations between countries and years. For example, the minimum value that must be in the US classrooms is 300 to 600 lux. It is 300 lux in European countries, 240 lux in New Zealand and Australia, 500 lux in UAE and 200 lux in South Africa.
- *Glare (UGR):* The guides indicate that the glare from the direct sunlight, especially in the classrooms has to be prevented. It is highlighted that the lighting devices in the classrooms must be positioned in a way not to be in the field of view of students and teachers. It is indicated that 19 value must not be exceeded for glare as a numerical value.
- *Illuminance uniformity (U_0):* Most of the guides, providing information on lighting, have mentioned that the illuminance has to have a uniform distribution in the classrooms but have not stated a numerical value. 0.6-0.8 values have been provided for a horizontal plane at 70 cm height for a uniform distribution of light in classrooms.
- *Colour rendering index (R_a):* Colour rendering index, which is important for colors "realistically" or "naturally", is defined as 80 and above for the classrooms.

TABLE IV. LIGHTING RECOMMENDATIONS FOR CLASSROOMS IN DESIGN GUIDES FOR SCHOOLS IN COUNTRIES

Country	Publication dates	*Illuminance (E_m; lux)*	*Illuminance uniformity (U_0)*	*Colour rendering index (Ra)*	*Glare (UGR)*
Turkey	2010-2015	300	-	-	-
USA	2002-2016	300-400-450-500-550-600	8:1	>80, ≥85	≤19, <19
United Kingdom	1999-2014	300-350	≥0,8, 8:1	>80	
Scotland	2007	300	≥0,8	>80	≤19, 20:1
Ireland	2008-2014	300	-	-	-
North Ireland	2011	300	-	-	-
New Zealand	2004-2015	240	-	>80	≤19
Canada	2007-2012	-	-	-	-
Australia	2011-2015	240	-	-	-
UAE	2010-2012	400-500	-	-	-
Indonesia	2009	500	-	-	-
Qatar	2010	-	-	-	-
South Africa	2012	200	-	-	-
Kosovo	2015	300-500	-	-	-
Europe Union Project	2015	300	0,6	>80	-
International Energy Agency Project	2014	300	0,6	>80	-

Taking the evaluations above into account, almost half of the guides analysed have mentioned that lighting is important for schools but the other half has not sufficiently mentioned the lighting. The guides on lighting generally provide suggestions for the classrooms and have not mentioned the other spaces in the school. Furthermore, while most of the guides provide information on the illumination level, the other issues such as illumination uniformity, glare, modelling or energy use have not been sufficiently mentioned. As a result, it can be said that importance given to the school lighting has been improved, and countries have improved their studies on this topic, but there are some differences between the accepted standards. The research findings have presented useful and basic information that will guide the new guides on school lighting.

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The Relationship Between Energy Saving and Visual Comfort in Different Lighting Sources

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***Abstract*— Fluorescent lamps and the new light source LED as the most commonly used light sources both in homes and offices are especially preferred due to low energy consumption. Dimming is often used in both lighting to more energy saving. The dimming used in lighting control has destructive effects such as harmonics, THD and power factor. There are also negative effects on visual comfort which is more difficult to measure at the same time. In this study, the relationship between visual comfort and energy saving dimming was investigated. A survey was conducted for this purpose and the results were evaluated and suggested solutions.**

***Index Terms*— energy saving, lighting control, visual comfort**

I. INTRODUCTION

Global energy problem has increasing importance every day. Energy efficient products (e.g. LEDs) and transition methods are used to solve this problem. There are several ways to obtain energy saving in conventional lighting systems such as changing ballasts and/or luminaries, adapting these systems to control interfaces, using lighting scenarios or reactive power compensation.

There is a lot of research and study done on this subject all over the world. In-depth analysis of International Building Research Establishment (BRE) publication of Energy Consumption Guide [1] and Chartered Institution of Building Service Engineers' (CIBSE) previous reports [2], it is seen that 20 – 40% of worldwide building energy consumption is directly related to artificial lighting systems. Governmental buildings in USA are responsible more than one thirds of national electrical energy consumption and 25 – 40% of this value is due to artificial lighting energy consumption [3]. Statistics about Canada show that 10% of institutional electrical energy consumption is directly related to lighting installations [4]. Nonresidential annual lighting energy consumption in European Union is about 160 TWh and 40% of this consumption is originating from buildings' artificial lighting systems [5]. As global energy consumption increases dramatically and lighting energy saving steps forward as the most possible way to save electrical energy, both scientific and commercial studies focus on lighting more than ever. Unfortunately lighting energy efficiency and saving issue is a two edged sword. Obtaining savings in lighting energy both new LED technologies and transition methods cause disruptive effects on energy quality parameters. Even if dimming strategies used Total Harmonic Distortion (THD) and Harmonic current (THDI) ratios, power factor (PF) values are distorted significantly. Mentioned energy quality parameters are regulated by IEC and EN with various standards [6-7]. In this study under different scenarios and dimming THDI and PF values are measured, analyzed for different systems and a method to solve the recent problems is suggested.

A. Sivaji stated in their study that light colour and colour temperature have significant effects on office workers and that office workers who work especially under warm white coloured artificial lighting devices have greater alertness and perception levels [8]. In a survey based study carried out by Wei et al. on the satisfaction level of office workers, it was observed that visual comfort in offices illuminated with high colour temperature artificial lighting de- vices was lower than offices illuminated with low colour temperatures even when the brightness level was high. As a result, luminaires with colour temperatures of 3500 K were preferred when selecting the light colour [9]. M. Islam et al. investigated, which of the two luminaire types -those with fluorescent or LED lamps- having the same luminance level, made office workers feel more comfortable and in- creased their visual perception. It was revealed that luminaires with LED lamps, which have lower colour temperatures, were preferred by the workers [10]. In their studies, Charness and Dijkstra determined experimentally that young adults had increased perception levels at lower illuminance levels compared older adults [11]. As a result of a wide scale experimental field study, Chung and Burnett determined that office users preferred working at high illuminance levels [12]. In a field study by Philips Company, investigating the productivity performance as well as worker psycho- logy and biology, illuminance levels required by workers at different sectors were determined and it was observed that under working conditions with higher illuminance levels, the working performance increased considerably. In addition, the increase in the production of sleep hormones at low illuminance levels was also addressed [13].

Beside all this study, visual comfort important issue that is not focused on. Some operations to save energy are negatively affecting visual comfort. When the issues of energy efficiency and savings in lighting are being investigated, all of the effects that take place during these should be addressed as a whole. Considering these, this study concentrates on the measurement of the perceptions of users who work in similar or the same working environments, under different light levels, different light colours, and different energy consumption levels, and the relationship of these with electrical distortions.

II. EXPERIMANTAL

The Sakarya University, Department of Electrical and Electronics Engineering allocated 3 testing and experimenting rooms for this study and experiment. The rooms were located on the M-6, 3rd floor of the 4-storey Engineering Department building. The exact coordinates of the rooms were 40º 74´ north latitude and 30 º 33´ east longitude. The surface area of the rooms was 24 m^2 and each room had 1 window on their northwest wall. A thin film layer was applied to the windows in order to eliminate daylight glows. As a result, the inflow of 100% direct daylight from the windows was prevented. The light transmittance of the windows was measured as 67%. The dimensions of the window on the northwest direction were 1.5 m × 1.2 m and its total area was 1.8 m^2. According to section 21 of the IEA report, the effective window surface area was 1.2 m^2 and similarly the effective window height was 1.5 m. The Lighting Laboratory was located on the 40º 74´ North latitude and 30 º 33´East longitude, on the ground floor of the M-4 Engineering Department. The room faced the west and northwest direction and although it had an actual ceiling height of 3.80 m, the apparent ceiling height was 2.85 m because of an installed suspended ceiling. The window dimensions in the room were 2.45 m × 1.75 m and the total window area was 4.29 m^2.

The old artificial lighting system (6 units of 4 × 18 fluorescent lamps, with double parabolic mirror louvre) of test and experiment room 3 (TR3), which was the most important test and experiment room of the thesis study, was replaced with a LED system equipped with 1 × 41W middle class LED panels (6 units of 60 cm × 60 cm LED panels). The ballasts of the old system in test room 1 (TR1) were replaced with dimmable electronic DALI ballasts. Both rooms had systems with a dimming feature. Philips LED drivers with DALI feature (92% efficiency, pf=0.95) were used in TR3 and OSRAM DALI RC BASIC lighting automation system was used in TR1. TR2 was designed as a hybrid room; the conventional ballasts of an armature that had 3 fluorescent lamps were replaced with DALI ballasts, while 3 armatures were replaced with LED armatures that had DALI ballast and were used in TR3. The fluorescent armatures that were used in TR2 and TR1 were 4 × 18 W armatures. With a switch level of 100%, the following illuminance levels were obtained in the rooms, respectively: 510 lux with the artificial lighting system in TR3, 275 lux with the system in TR1, and 400 lux with the hybrid system in TR2.

Figure 1. Test and Experiment room 1 (Fluorescent)

Figure 2. Test and Experiment room 2 (Hybrid)

Figure 3. Test and Experiment room 3 (LED)

Electrical parameters such as the voltage, lamp currents, active/reactive powers, total harmonic distortion (THD, THD_I) were measured individually several times in periods of 1 second, 10 seconds, 15 seconds, 30 seconds, 1 minute, and 5 minutes with an electrical energy analyzer (Janitza UMG 503) that was connected at the input point of the systems. While dimming in TR2 and TR3 was carried out manually using a system remote control, manual switch, and software provided by the armature provider Arlight Company; in TR1 and TR4, this was carried out via DALI RC BASIC.

The total energy consumption for an operation at a switch level of 100% was measured as 250.2 Wh for TR3, 444 Wh for TR1, 346 Wh for TR2, and 1030 Wh for TR4, respectively. 5 different dimming levels were applied for each of the four lighting systems.

Main purpose of our study was determining how disturbing effects affected the more difficult-to-measure parameters such as visual comfort and working performance. Before commenting on weather a specific lighting design is economic and energy efficient, first, user satisfaction and visual comfort should be investigated [14]. For this purpose, a study based on a survey evaluation was carried out with a group of 40 participants in the test rooms where we had carried out our measurements. In this study, after reviewing previous studies and evaluating different attitude scales, the Likert Scale was chosen as the survey attitude scale to determine user satisfaction and visual comfort at the lighting conditions applied in the constructed experiment rooms. The Likert Scale is a 5-point scale. In the Likert scale, answers include statements such as “strongly agree, agree, don’ know, disagree, and strongly disagree” or an attitude scale ranging between parameters equivalent to these. Every answer is assigned with a numerical value. The Likert scale is highly recognized worldwide and is a scale with high reliability.

The constructed survey consists of 2 parts. Part 1. questions “Personal Information”, which consists of demographic questions, and the Part 2. measures user reactions on “visual comfort and visual perception in the Experiment Room”. The survey was carried out with 40 volunteering participants and the survey results were analyzed using the SPSS 16.0 statistical data analysis software package [15].

The survey was applied to the participants in the 3 different experiment rooms. The first room was an experiment room that had a total of 6 conventional type fluorescent armatures with 4 ×18 Watt power and a luminous color temperature of 4000 K. In the second experiment room there were 3 double parabolic fluorescent armatures with 4 ×18 Watt power and a luminous color temperature of 3000 K and 3 LED armatures each of 41 W power and a luminous color temperature of 3000 K. In the third room there were 6 LED armatures, each of 41 W power and a luminous color temperature of 3000 K.

The survey participants spent 20 minutes in Room 1 and approximately 30 minutes in the other rooms. The participants were asked to evaluate the visual conditions and the different lighting conditions in rooms 2. and 3. when the switch levels of lighting systems were at 100% and 50%.

Before performing the survey, the participants were allowed 15 minutes in order to adapt to the conditions of the room and they were asked to answer the survey questionnaire after this period. The participants were told that during these 15 minutes they could use the computers allocated for their use as they like, while they were only asked to select and read any 2 pages from the books that were placed before them.

At the end of the 15 minute period, the users were asked to look at previously specified points in the experiment rooms and then open specific documents on the desktop of the computes allocated for their use and read the text in these documents. Then after carrying out these procedures, the participants were asked to adjust the switch level of the lighting systems to 50% using the remote controls that they were handed and repeat the same procedures 2 minutes later.

The survey was comparative and contained determining questions regarding the personal satisfaction and visual comfort at the applied lighting conditions.

The survey questions that were asked to the participants were based on the following:

- The visual comfort experienced in the room
- The distribution of light in the room
- The light color in the room

- Evaluation of the effect of the lighting conditions in the room on the working performances of the participants
- Evaluation of the ability of participants to discriminate the colors and patterns of the door cases
- Participant evaluations regarding the ability to read the document in the computer
- Evaluations by participants who experienced reading difficulties

III. ASSESSMENT AND COMPARISON OF THE SURVEY RESULTS

When the answers obtained from the survey were assessed, it was revealed that the experiment room with the cold white light color was the room that the users were least satisfied with and evaluated its visual comfort as the lowest. Experiment Room 2, which can be defined as a hybrid room, was ranked second in terms of satisfaction and visual comfort, while the highest visual comfort and user satisfaction was reported for Experiment Room 3. These results were obtained for a lighting switch level of 100%. In the second case, when the switch level was reduced to 50%, it was observed that the visual comfort level was higher in Experiment Room 3. Generally, the lighting type preferred by the participants was the system that combined artificial and daylight.

The survey participants reported that generally when the lighting systems performed at their full capacity, their visual comfort was high and their perception levels were higher. In the second case, when the illumination capacity was decreased by 50%, the survey results obtained from both Experiment Room 2 and 3 indicated that some colors were difficult to distinguish and the perception level and visual comfort were reduced. The survey participants reported that they had difficulty in reading and discriminating the colors when dimming was applied and emphasized that they especially had difficulty in perceiving the purple, blue, and green colors. The participants observed that the best working conditions were those in experiment room 3 (LED).

IV. CONCLUSION AND RECOMMENDATIONS

When the overall findings, test and experiment results, user feedbacks, and electrical parameters that were obtained in this study were assessed, the following conclusions were reached:

- Although energy consumption can be reduced by using dimmed lighting systems, distortions arise in other electrical parameters.
- The maximum total harmonic distortion increases as a result of dimming.
- Harmonic distortions that arise as a result of dimming lead to energy loss in the light spectrum.
- The Color Rendering Index decreases to a certain degree as a result of dimming.
- The visual performance declines as a result of dimming.
- The decline in the visual performance reduces the perception level.
- Dimming can result in performance and alertness reduction in older workers.

- In order to eliminate harmonic distortions, the active filtering method can be applied. However, this method is expensive in today’s technological conditions.

- With increase in the number of electronic components used with the purpose of providing dimming, harmonic distortions and thus energy losses in the spectrum increase as well.
- Utilization of LED lamps -which are more energy efficient, have higher saving rate, and provide higher brightness level compared to conventional lamps- without dimming is an option that can prevent electrical distortions.
- While designing the lighting system of a volume, the use of unnecessary quantities of light as well as the application of unnecessary light controlling and thus the formation of electrical distortions can be prevented by paying attention to the visual perception level required for a certain job, instead of applying dimming.

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Optimization of Lighting Power Consumption in Buildings

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***Abstract*—The paper deals with possibilities for architectural application of Stokes mathematical model of light propagation in pile of plates within architectural space. Absorption of light in basic elements of architectural space – wall, ceiling and floor – decrease lighting efficiency in buildings. The following hypothesis has been developed: By using transparent glass surfaces the absorption of light can be minimized. The light intensities of all light sources and reflections in a building are summed. More natural light is allowed to enter deeper into a building. Computation of Stokes model and measurements on scale model have been made with an aim to test the hypothesis. The results show that lighting power consumption in buildings is significantly reduced. Although some disadvantages i.e. discomfort glare, unusual perception of space, privacy issues have to be considered. Proposed model of illumination moves the barrier of physical space toward virtual space**.

***Index Terms*— Absorption, architecture, glass, lighting, transparency.**

INTRODUCTION

Light is what enables us to visually perceive the space in which we exist, its living and non-living part. Apart from other senses, especially hearing, smell and touch, light allows us to build in the brain the most comprehensive information about everything that surrounds us. These are data, based on which, consciously or subconsciously, we make decisions for our actions, as well as we can anticipate actions of others. A special spatial network of impulses is established which we are constantly attached with. In human perception of space, light is of the utmost importance because we rely on visual perception mostly. In architectural sense light can be understood as a part of a spatial mechanism, like a kind of "raw building material" that is immaterial but still creates and reveals the space around us through the act of lighting. The above-mentioned spatial mechanism (a relationship between light lighting, luminary, luminance) as a sort of algorithm, serves to achieve a certain useful result, which is called illuminance and its visible effect which is called brightness. The brightness is the final result of lighting, it is perceptible on surfaces by naked eye and thus it becomes an architectural spatial element. To achieve a well-balanced perception of space it is important that the brightness of the elements that form this space vary. It is therefore necessary to compose a space by rhythmic exchange of more bright and less bright surfaces, as well as larger and smaller surfaces. Due to various compositions of illuminated surfaces, different expressions were developed in time such as, dark space, bright space, mysterious space, well-balanced space, dynamic space etc. These expressions also designate different emotions that are evoked when observing and using these spaces. The above-mentioned terms also describe special type of ambiences that are called luminous ambiences. Luminous ambience is a special architectural spatial level, defined by various light sources and surfaces, with material and visual properties, that the light is reflected from. Luminous ambience is an important »building block« of the entire architectural space. It can provide a variety of impressions of the same physical space: fuzzy, contrasting, balanced, dynamic etc. Professions, which deal with illumination, have invested a huge effort in the last decades to achieve the optimum ratio between the necessary illumination and the required energy, so the efficiency of state-of-the-art light sources is getting better and better. However, nowadays, for lighting the interior of buildings, even using LED technology, we still consume approx. 15% - 40% of the total electricity needed for the functioning of the building as a whole. With the introduction of smart lighting systems, 30% - 40% of electricity can be saved, depending on the purpose of the building and the distribution of the interior spaces, etc. Further improvements can be achieved by replacing conventional materials used for walls, floors and ceilings (plaster, wood, textiles, various plastics, etc.) with glass surfaces enabling so called “Light sharing”, which literally means that the rooms share the amount of light that, at a certain point, enters the building. This additionally reduces the need for electric lighting of the rooms at night time as well as the need for additional electric lighting in the daylight time.

With the development of information technology over the last few decades, another kind of space has been established. It was called Virtual Space. This new space became parallel or simultaneous to the physical space. The particularity of the virtual space lies in the fact that it does not apply to all physical laws of the real space. For example the law of gravity, which we can ignore if desired. In virtual space, the audio and visual component of perception prevail, therefore, light and sound are the sole building blocks of the virtual space. Various user interfaces allow us to literally "sink" into this artificial environment, to move inside it as avatars, to shape it, even to destroy parts of it… In a virtual environment where gravity loses its meaning, even light does not come mostly from above, which is accustomed to real space. Light in virtual space can come from anywhere and thus support a feeling that is similar to the feeling of floating in weightlessness. The usual methods of orientation over space change. The absolute ratio up : down changes in the virtual space to the relative ratio above me: below me. Light, as the most important building block of the virtual space, gets a new role that does not only mean upgrading or simulating real space but also creating new spatial experience. With light and light only, it is possible to create an ambience in a virtual world. Terms from the field of real world-optics, such as radiation, reflection and absorption are gaining a new meaning in the virtual world. An ever-evolving information technology, also including other technologies, with ever-new interfaces that allow contact or transition between the real world and the virtual world will in the future gradually blur or even delete the border between the two.

On a base of above stated a hypothesis / research question can be brought out:
Is it possible to create a hybrid virtual / real space, made of glass, that will have properties of one and the other kind of space with the aim to reduce the consumption of electricity needed for its illumination?

THE EXPERIMENT

The impact of the use of glass surfaces on reducing electricity consumption in buildings is further tested in two different ways. First way is by optical treatment of the idealized model of the pile of glass plates, an estimate of the reduction of the electricity, that is necessary for a uniform horizontal illumination of the glass structure of a compact cube shape is made. It is based on assumption that almost every building is structured from walls, floors and ceilings that represent an envelope of every room. The second way is by measurements of the illumination on the physical model of the 6-storey light-shaft dimension 5.8 x 3.6 x 22 m in scale 1:20, it has been demonstrated that the consumption of electricity, after replacing the usual walls with glass plates, is significantly reduced.

iii. 1. Optical treatment of idealized model of pile of glass plates model

Buildings are composed of elements – walls, ceilings and floors. Analogous physical model is space, confined with three mutually perpendicular piles of plates $\mathbf{N_x}$ **,** $\mathbf{N_y}$ **,** $\mathbf{N_z}$, as shown in "Fig. 1".

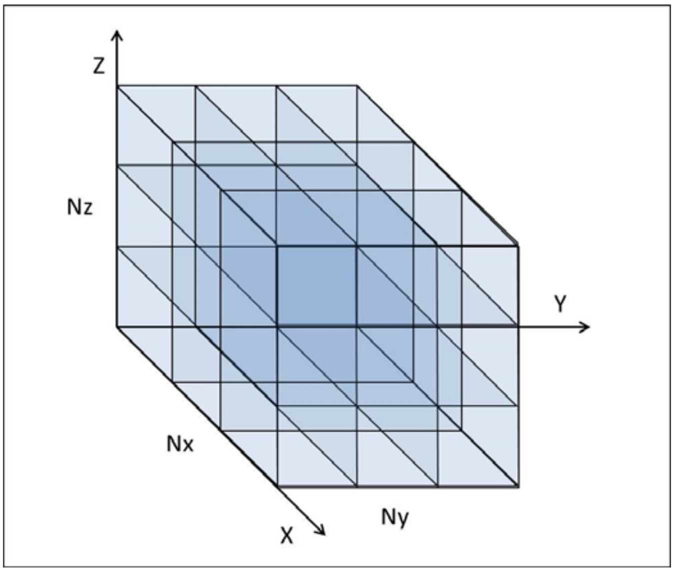

Figure 1. Model of the building (T. Novljan, 2017).

Buildings are illuminated with light sources to achieve desired illumination level. When a light beam incidents on the surface of the plate (such as a wall, ceiling or floor) we must treat this surface as a boundary between two media of different optical properties.
A part of the light is reflected back, a part is absorbed in the media while the rest is transmitted through the plate "Fig 2". Reflectance – the ratio of reflected power to the incident one – is denoted by **R,** Transmittance – the ratio of transmitted to the incident power – is denoted by **T** and Absorption A is defined as the fraction of light power absorbed in the media. Light flux - light power per square meter – is denoted by **I**.

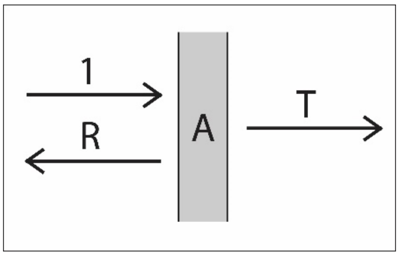

Figure 2. Light incidents on the plate (T. Novljan, 2017).

Due to the *conservation of energy, we have* $\mathbf{A + R + T = 1}$

Typically the transmission of wall, ceiling and floor is zero. Part of the light flux that is not reflected from the plate is absorbed, therefore $\mathbf{1 = R + A}$, if $\mathbf{T = 0}$.

The main reason for low lighting efficiency in buildings is absorption. Absorption is loss of light. The floor has highest absorption and lowest reflectance.

Losses are reduced by minimizing the absorption. Reflectance remains equal, we just replace absorption with transmission, therefore $\mathbf{1 = R + T}$, if $\mathbf{A = 0}$.

We want to find out the ratio of average illumination, if in the same building we replace absorptive plates (T = 0) with transparent plates (A = 0).

"Pile of plates" is an idealized physical model we use for calculations of spatial distribution of light flux and estimation of efficiency.

1D model. On $\mathbf{N_z}$ paralel transparent plates of the same thickness **d**, spacing **D** and material, the light is partially reflected and partially transmitted. The problem was mathematically treated by J. Rihtar [1] and more precisely by G. G. Stokes [2].

"Pile of plates" model is composed of infinite plates, but for estimation of light efficiency we must restrict the dimensions to finite object.

3D model. So this pile of infinite plates in **z** direction is intersected by a pile of plates in both perpendicular directions x and y with $\mathbf{N_x}$ and $\mathbf{N_y}$. So we get a space which is similar to a building construction, constituted of small cells with transparent walls and illuminated with isotropic light source ("Fig. 1").

Isotropic light source is substituted by three light beams of equal magnitude in mutually perpendicular directions denoted by $\mathbf{I_x}$, $\mathbf{I_y}$ and $\mathbf{I_z}$. By this assumption the problem is analytically solvable.

Each component of the light source $\mathbf{I_x}$, $\mathbf{I_y}$, $\mathbf{I_z}$ is separately applied to the model. We begin by calculating the direction **z**. Let's place the light source $\mathbf{I_z}$ in each chamber with index ***l***. We calculate contribution of the light source $\mathbf{I_z}$ placed in ***l***-th chamber to the light flux in **k**-th chamber $\mathbf{I_k}$ and then sum up contribution of all the light sources ***l***. We get the partial light flux in **k**-th chamber $\mathbf{I_k^C}$.

Then we calculate partial light flux $\mathbf{I_i^C}$ and $\mathbf{I_j^C}$ in the same way for **x** and **y** direction, where index **i** runs in **x** direction from **1** to $\mathbf{N_x-1}$ and index **j** in **y** direction from **1** to $\mathbf{N_y-1}$. Total light flux is the sum of all partial light fluxes $\mathbf{I_i^C}$, $\mathbf{I_j^C}$ and $\mathbf{I_k^C}$. In each cell **i,j,k** of the building the total light flux is defined by the matrix $\mathbf{B_{ijl}}$:

$$\mathbf{B_{ijl} = I_i^C + I_j^C + I_k^C}$$

One half of the total light flux is identical to the horizontal illuminance and can be measured.

This is an approximation for illumination of cells in building. We try to improve this approximation with some corrections. These corrections are involved in calculation with multiplication of $\mathbf{B_{ijl}}$ by correction factor **Q.** The absorption in low iron glass is small and can be neglected. In case of isotropic light distribution we have to evaluate the reduction of flux because of angular dependence and transverse transmission.

Estimations: The ratio between the average illumination in case of transparent plates (A = 0) and average illumination in case of absorptive plates (T = 0) is:

Building with 5 x 5 x 5 plates	1.67
Building with 10 x 10 x 10 plates	4.85
Building with 15 x 15 x 15 plates	10.57

Illuminating the building by natural light is most energy efficient. Lowering the reflectivity and therefore increasing transparency of the building will improve illumination of the inner space with natural light. The natural light will penetrate deep inside the building. Instead of reflection we must increase the light emittance **E** of plates to maintain luminosity of the plates. Plates become transparent lighting panels with minimal reflection, maximal transmission and are a planar light source.

iv. Measurements of illuminance

In the experiment illuminance inside of corridor was measured. Of interest to us was difference between absorptive and transparent inner walls.

For the purpose of the experiment a corridor was assembled "Fig. 3". Inner dimensions of the corridor were 18 cm x 29 cm x 109 cm and the reflectance of the walls was 0.85. One side of the corridor was closed and the other was open. Planar luminaries, glass light guides with reflectance of 0.12, were used as a light sources when switched on and as glass plates when switched off.

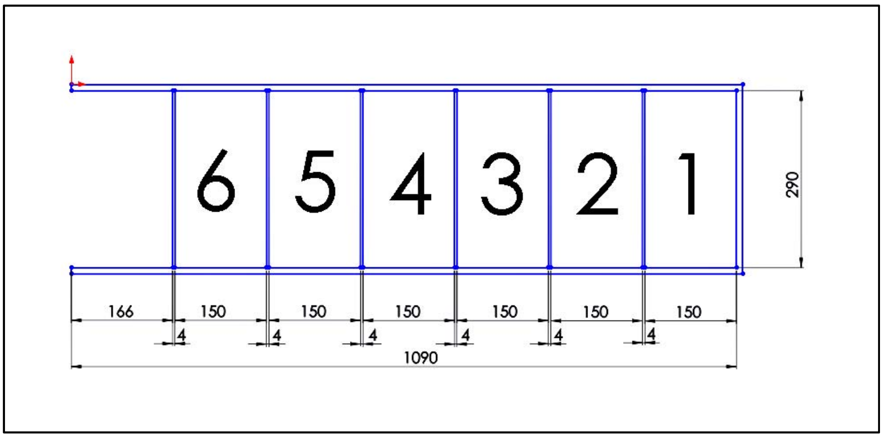

Figure 3. Flor plan of the corridor (I. Bilbija, 2017).

For the first phase of the experiment corridor was partitioned in to six cells by absorptive walls with reflectance of 0.85.

Illuminance was measured in each of six cells. This phase represents six empty rooms with light source and white walls.

For the second phase corridor was partitioned to create six cells using planar luminaries. Illuminance was measured in six cells for each luminary separately.

While one luminary between two cells was turned on other were turned off and were therefore only glass plates separating cells. Illuminance in each cell was measured. Combining all the measurements of phase two gave us average illuminance for the corridor.

This phase represents six rooms separated by glass plates "Fig. 4".

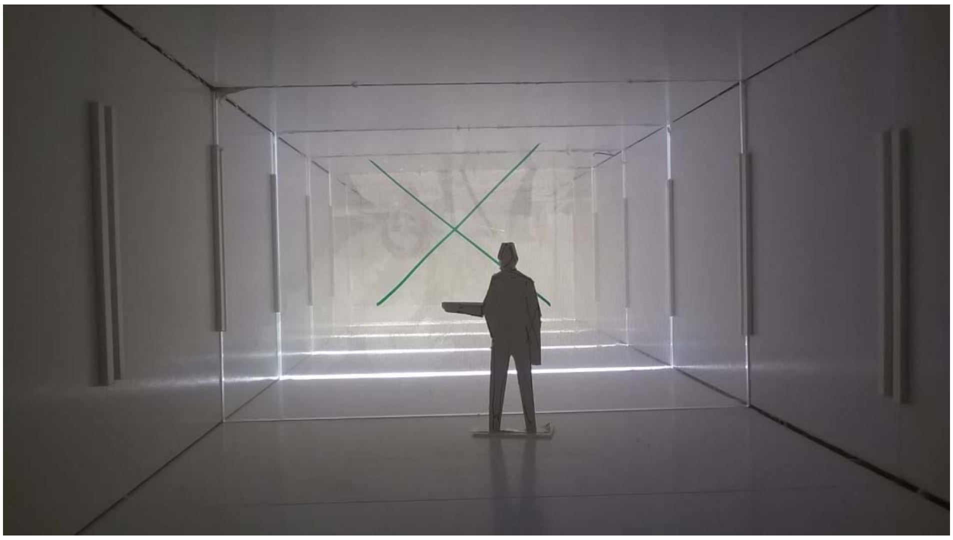

Figure 4. Scale model of corridor with transparent walls (photo I. Bilbija).

Average illuminance inside the corridor of phase two was 19.6% ± 2% higher.
Illuminance for both phases was measured with Gossen Mavolux 5032 over 5 runs.

CONCLUSIONS

From both above described experiments it is possible to draw the following conclusions:

- transparent reflective plates can be used as walls, floors and ceilings;
- with the use of transparent plates the light intensities of all light sources in a building are summed;
- transparent reflective plates contribute to the overall distribution of light through space in buildings;
- transparent reflective plates reduce the consumption of electricity;

Massive implementation of glass plates as partition walls, floors and ceilings in buildings is still limited to common spaces i.e. corridors, halls etc. Various limitations and even disadvantages such as discomfort glare, lack of privacy and disorientation have to be considered. Human brain today still needs some opaque surfaces and other clearly perceivable architectural elements that show where is" up" and where is "down" in order to maintain balance. Of course, in time all above stated disadvantages can be overcome fine-tuned architectural interior design that combines the use of opaque and transparent materials/surfaces. Functions of the rooms have to be considered too. In restrooms or in meeting rooms, for example, special attention has to be put on maintaining of privacy. Large surfaces of glass floor will have to be designed in such way that they will not cause vertigo or become slippery. Further research has to be made in order to find how to implement an optimal combination of transparent and non-transparent surfaces in buildings. A combination, or a "collaboration" of floor, ceiling and wall surfaces, transparent and opaque, has to be established that will satisfy both, nowadays way of perception of space as well as reduction of electric energy needed for the illumination of buildings.

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Illumination Levels for Office Work in Thailand: Standards vs Occupants' Perspective

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***Abstract*— This study investigated the illuminance levels actually used for office work in Thailand and surveyed office workers' opinion regarding the lighting at their desks. This is to establish whether the illuminance levels recommended in Thai standards (300, 400 and 600 lux) are too high which leads to unnecessary energy consumption. The survey was carried out with 372 samples. While the illuminance levels on office desks were up to 17 times difference, illuminance levels at most desks ranged between 300 and 400 lux. From office workers' responses, it was possible to establish a model to predict users' response from the illuminance level measured at the centre of a desk. Based on the model, the current recommended illuminance level of 400 lux should be reasonable for office work with computers rather than 600 lux as the probability of feeling deep shadows is low (0.314) and it is more energy-saving.**

***Index Terms*—illuminance, standards, office, survey, energy conservation**

INTRODUCTION

Illuminance levels on working plan were used in various office lighting standards as a quantitative measure to ensure safety and visual performance of users. Insufficient illuminance could result in visual discomfort, reduction of visual performance or personal safety. On the other hand, excessive illuminance leads to unnecessary energy consumption in buildings. Recommended illuminance levels in lighting standards and recommendations throughout the world are diverse. Mills and Borg [1] reviewed recommended levels for office lighting in 19 countries between 1930 and1990 and the recommended levels were up to 20 times difference. This suggests that office lighting recommendation is dynamic and influenced by various factors such as economic, social conditions, politics as well as available technology. The current study attempts to survey the actual illuminance levels used for office work in Thailand and users opinion about the lighting to determine whether the recommended illuminance levels in Thai standards are too high.

LIGHTING STANDARDS IN THAILAND

In Thailand, lighting in office building is standardized by two regulations. The first one is Ministerial Regulation No.39, B.E. 2537 (1994) Issued pursuant to the Building Control Act, B.E. 2522 (1979) [2]. This building regulation requires 300 lux for general office lighting. The second one is Ministerial Regulation on The Prescribing of Standard for Administration and Management of Occupational Safety, Health and Environment in Relation to Heat, Light and Noise B.E. 2549 (2006) [3]. This occupational safety regulation requires 400 lux for general office work, 400 lux for general work with computer and 600 lux in the area for data entry and information display. The trend of recommended levels in this regulation is different from some international standards, where recommended illuminance for computer work (typing, data processing) are usually similar to recommended illuminance for clerical work (reading, writing). Considering the prevalence of computer which is self-illuminated, more illumination on display screens will reduce screen contrast and cause distracting reflection. The appropriateness of recommended illuminance levels for office work, particularly for area with computer work in Thai standards is questionable. The survey of actual illuminance used in Thai office and the perspective of Thai office workers regarding the lighting at their desks is one way to determine whether the current recommended levels are sensible.

METHODOLOGY

This study measured lighting levels at various positions on office desks and surveyed the opinion of office workers regarding the lighting conditions at the desks. In total, there were 372 desks and users surveyed from 9 offices in Thailand. Participants in the survey had similar visual tasks which were clerical works on computer and paper. Participants had been told to set the lighting at the level they normally used for working so they could turn on, off or dim the light from the levels installed in their offices in accordance with building regulations. The lighting survey included the measurement of illuminance and luminance levels. This paper discusses only the illuminance measurement. Illuminance levels at each desk were measured at 11 positions. There were five measurement positions on the top of the desk including four positions to obtain average illuminance on the desk as recommended in Canada [4] and Hong Kong standards of assessment [5] and one position at the centre of the desk. And there were six measurement positions at computer area including two positions on the keyboard to obtain average illuminance on the keyboard, two horizontal positions on the top of computer screens to obtain average horizontal illuminance on computer screens and two vertical positions on the computer screens to obtain average vertical illuminance.

The survey of office worker opinions regarding the lighting conditions was carried out using Office Lighting Survey (OLS) questionnaire developed by Eklund and Boyce [6]. The questionnaire used in this survey consisted of nine statements and one question as shown in Table I.

TABLE I. STATEMENTS IN THE OLS QUESTIONNAIRE USED IN THIS STUDY. (AFTER EKLUND AND BOYCE [6])

Item	Topic	User's opinion
1	Overall the lighting is comfortable.	□ Agree □ Disagree
2	The lighting is uncomfortable bright for the tasks that perform.	□ Agree □ Disagree
3	The lighting is uncomfortable dim for the tasks that I perform.	□ Agree □ Disagree
4	The lighting is poorly distributed here.	□ Agree □ Disagree
5	The lighting can causes deep shadows.	□ Agree □ Disagree
6	The light fixtures are too bright	□ Agree □ Disagree
7	Reflections from the lighting hinder my work.	□ Agree □ Disagree
8	My skin is an unnatural tone under the lighting.	□ Agree □ Disagree
9	The lights flicker throughout the day.	□ Agree □ Disagree
10	How does the lighting compare to similar workplaces in other buildings?	□ Worse □ About the same □ Better

The participants in the survey responded to the statement in the questionnaire by choosing whether they agree or disagree with the first nine statements and choose appropriate answer in the question in item number 10. The responses to nine statements will be analyzed to determine their relationships with the illuminance levels measured at their desks. Since the responses to the statements, the dependent variables in this study, are dichotomy (Agree or Disagree), the technique of logistic regression was used in the analysis to fit a regression surface to the data [7]. Logistic regression model uses one or more dependent variables to predict the probability of the presence of the characteristic of interest which, in this case, agreement or disagreement with the statements about lighting (1). The logistic regression model makes it possible determine how users respond to lighting at a certain illuminance level, particularly at the recommended levels in current standards.

$$p_y = \frac{e^{b_0+b_1X}}{1+e^{-(b_0+b_1X)}} \tag{1}$$

p = Probability of the agreement with the statement about lighting

b_n= parameter of the model

e = 2.71828

Since the probability of agreement could not be used to develop a linear function model with the predictors (illuminance levels). To obtain the logistic regression model, probability was converted to odds or the ratio between the probability of agreement with the statement about lighting to the probability of disagreement with the statement (2). Odds were then transformed into the natural logarithm of the odds or loge odds or ln odds or logit to achieve a linear function. Logistic regression equation is written in the form of (3).

$$\text{Odds} = p / 1 - p \tag{2}$$

$$\text{Log}_e\,(\text{odds}) = \ln\,(\text{odds}) = \ln\,(p/1-p) = b_0+b_1X \tag{3}$$

RESULTS

Table II summarizes the results of the lighting survey at workplaces. The illumination levels measured at the centre of the desks (MEAN = 357.22 lux) were very similar to the average illuminance obtained from 4-point measurement on the same desks (365.99 lux). The illuminance level on keyboards and on display screens (measured horizontally) were slightly higher than the illuminance on desks. The survey was carried out at the offices with similar administration tasks involving both computer and paper tasks however it was found that the illuminance values at workstations are considerably varied. For example, the average illuminance on the desk ranged from 59 to 1021 lux, that is the maximum level was 17 times the minimum level in the survey. The average illuminance was very close to the recommended levels in the standards (300 lux and 400 lux) for general office works and general office work with computers but much lower than 600 lux recommended for data entry and information display. Fig. 1and 2 show the histogram of the illuminance level measured at the centre of the desk and the average illuminance at the desks. It can be seen that illuminance levels of most desks fell between 300 and 400 lux. Only 4% of the office workers had illuminance levels over 600 lux at their desks.

TABLE II. SUMMARY OF THE OFFICE LIGHTING MEASUREMENT

Lighting measurements	MEAN (lux)	SD (lux)	MIN (lux)	MAX (lux)
Illuminance at the centre of desk	357.22	159.42	59.25	1021.30
Mean illuminance on the desk	365.99	170.43	58.00	1001.00
Illuminance on keyboard	341.93	148.58	55.00	949.90
Horizontal Illuminance on display screen	428.87	204.31	55.79	1410.50
Vertical illuminance on display screen	214.02	102.73	28.00	956.20

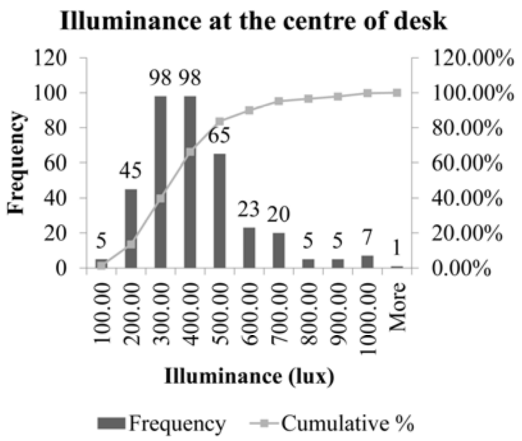

Figure 4. Illuminance levels measured at the centre of the desks

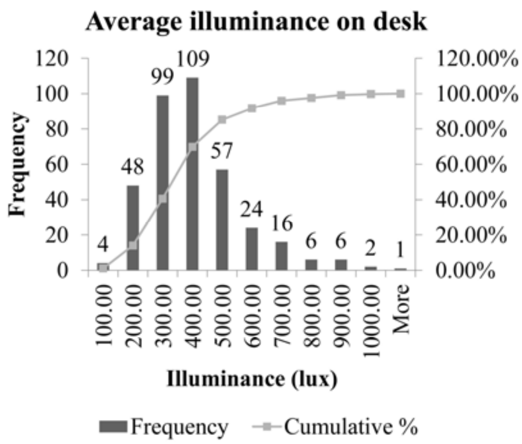

Figure 2. Average illuminance levels from at 4 positions on the desks

Fig. 3 shows the results of the survey of users' opinion regarding the lighting conditions at their desks. In general, most users gave positive responses regarding their lighting conditions. But the results reveal three major problematic issues with the lighting of workplace: reflections from lighting, poor distribution of lighting and deep shadows caused by lighting.

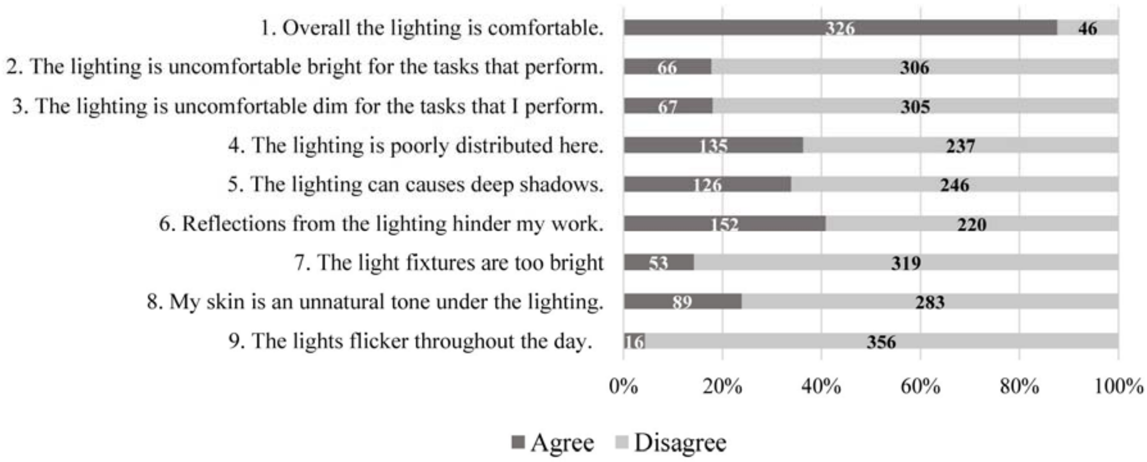

Figure 3. Summary of the responses to the OLS questionnaire.

The responses from users were also explored with logistic regression analysis to fit a model to predict users' response to lighting based on the lighting condition. Table III shows some logistic regression results that were statistically significant and Table IV shows the variables and coefficients in the models. It was found that when the illuminance at the centre of the desk increases, the odds of reporting that the lighting is uncomfortable dim are significantly reduced ($\chi^2(1)$ =4.211, p=0.040). When the average illuminance on the desk increases, the odds of agreeing that the lighting causes deep shadows are significantly decreased ($\chi^2(1)$ =17.256, p=0.000). Likewise, the odds of agreeing that the lighting causes deep shadow are significantly decreased as the illuminance at the centre of the desk increases ($\chi^2(1)$ =18.306, p=0.000). The illuminance on the desk also relates to the odds of agreeing that the light fixtures are too bright. The odds of agreeing that the light fixtures are too bright increase significantly when the average illuminance on the desk increases ($\chi^2(1)$ =4.761, p=0.029) or when the illuminance at the centre of the desk increases ($\chi^2(1)$ =5.667, p=0.017) . It is not surprising that the illuminance at the centre of the desk and the average illuminance at the desk relate to the user perspective about the lighting in the same pattern because their measurements in this survey were very similar.

TABLE III. LOGISTIC REGRESSION RESULTS BETWEEN ILLUMINANCE AND THE ODDS OF AGREEMENT WITH THE STATEMENT ABOUT LIGHTING

No.	Independent variable	Dependent variable (Odds of agreement with statement)	χ^2	df	sig
1	Illuminance at the centre of the desk	"The lighting is uncomfortable dim for the tasks that I perform."	4.211	1	p=0.040
2	Average illuminance on the desk	"The lighting causes deep shadows."	17.256	1	p=0.000
3	Illuminance at the centre of the desk	"The lighting causes deep shadows."	18.306	1	p=0.000
4	Average illuminance on the desk	"The light fixtures are too bright."	4.761	1	p=0.029
5	Illuminance at the centre of the desk	"The light fixtures are too bright."	5.667	1	p=0.017

TABLE IV. VARIABLES IN LOGISTIC REGRESSION EQUATIONS TO PREDICT THE ODDS OF AGREEMENT WITH THE STATEMENT ABOUT LIGHTING

No.	Independent variable	Dependent variable (Odds of agreement with statement)	Variables			Constant		
			b_1	χ^2(df)	sig	b_0	χ^2	sig
1	Illuminance at the centre of the desk	"The lighting is uncomfortable dim for the tasks that I perform."	-0.002	3.811(1)	p=0.051	-0.894	7.164	p=0.007
2	Average illuminance on the desk	"The lighting causes deep shadows."	-0.003	14.814(1)	p=0.000	0.428	2.101	p=0.147
3	Illuminance at the centre of the desk	"The lighting causes deep shadows."	-0.003	15.513(1)	p=0.000	0.419	2.134	p=0.014
4	Average illuminance on the desk	"The light fixtures are too bright."	-0.002	4.223(1)	p=	-1.028	7.154	p=0.007
5	Illuminance at the centre of the desk	"The light fixtures are too bright."	-0.002	4.932(1)	p=	-0.986	6.958	p=0.008

The model between the illuminance at the centre of the desk and the odds of agreeing that "the lighting causes deep shadows" (Model 3) was used to explore further due to the highest χ^2 and the fact that experiencing deep shadows was found to be one of three main issues with office lighting in this survey.

From the model 3 in Table IV, we can get the regression equation as follows.

$$\ln(\text{odds}) = \ln(p/1-p) = 0.419-0.003E \tag{4}$$

p = Probability of the agreement with the statement about lighting

E = Illuminance measured at the centre of the desk

This equation can be used to determine the odds and chance of agreeing that "the lighting causes deep shadows" for any illuminance level measured at a desk. For example, at 300 lux (standard for office works in Ministerial Regulation No. 39), a person will have a log odds of 0.419-0.003(300) = -0.481. So this person's odds are $e^{-0.481}$ = 0.618 which means that the person is 0.618 times more likely to agree than disagree with the statement. And the person's probability of agreeing that "the lighting causes deep shadows" is 0.381, and probability of not agreeing is 0.619.

At 400 lux (standard for general office works in Ministerial Regulation for occupational safety, health and environment), a person will have a log odds of 0.419-0.003(400) = -0.781. So this person's odds are $e^{-0.781}$ = 0.458. And the person's probability of agreeing that "the lighting causes deep shadows" is 0.314, and probability of not agreeing is 0.686.

At 600 lux (standard for office works with computers in Ministerial Regulation for occupational safety, health and environment), a person will have a log odds of 0.419-0.003(600) = -1.381. So this person's odds are $e^{-1.372}$ = 0.251. And the person's probability of agreeing that "the lighting causes deep shadows" is 0.201, and probability of not agreeing is 0.799.

Also, the equation can be used to obtain the illuminance level to achieve the predetermined odds or probability of agreeing that "the lighting causes deep shadows". For example, to achieve the odds where a person have the same chance of agree and disagree with the statement or the odds of 1, the illuminance level should be (0.419-ln (odds))/0.003 =139.67 lux.

DISCUSSION AND CONCLUSION

The outcome from the lighting survey in the first part of this study shows that the illuminance level commonly used at workplace with computers in Thailand was around 300-400 lux which is similar to the recommended levels for general office works in Thai ministerial regulations. On the contrary, there were only 4% of the office workers surveyed had the illuminance level at their desks at 600 lux (the recommended level for data entry and information display) or above. It is interesting that, for similar office work, the illuminance levels at workstation were largely varied. For example, for the illuminance level at the centre of the desk, the maximum value surveyed was 17 times the minimum value surveyed which could be attributed to personal difference and preference. These personal factors should be considered in creating desirable visual environment. The second part of the study shows the views of the users regarding their lighting. Based on the results, a logistic regression model was developed to predict the odds and the probability of agreeing that the lighting causes deep shadows from the illuminance level measured at the centre of a desk. At 300 lux, the probability is 0.381; at 400 lux, the probability is 0.314; at 600 lux, the probability is 0.201. This information could be used to weigh between user preference and lighting load which contributes to energy consumption of buildings. Overall, the current recommended illuminance level of 400 lux may be reasonable for office work with computer as the probability of feeling deep shadows is low and consume less energy than using the illumination level of 600 lux as currently recommended for data entry and information display.

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BIM and Lighting Design

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***Abstract*— The building design and thus the lighting design will change fundamentally with Building Information Modelling. BIM will be the next building design standard. There are a lot of changes in the design process and in the project communication.. The density of information in planning increases in many ways, what is helping to reduce errors, to design buildings more efficient, cheaper to build and to maintain. On the other hand, these data have to be produced, structured and managed. This abstract introduces BIM and its influence on the lighting world. What will change for lighting designers, architects and the entire lighting industry?**

***Index Terms*-- Building Information Modelling, BIM, IFC, Lighting Design, Autodesk® Revit®**

BIM Definition

BIM is no software and no data format; it is a building data structure that is systematically applied in three-dimensional space. All building objects, such as light fixtures, got a lot of properties and a relation to other objects (e.g. a light fixture has electrical and photometric characteristics and is mounted on a ceiling).

Figure 1. Rendering out of Autodesk® Revit® with a overlay of the product attributes (screen copy)

BIM has the chance to replace CAD as today's standard planning tool. Like once CAD itself replaced the drawings created on drafting board with pencil and ink. But the step from CAD to BIM is deeper and also changes processes. Paper and CAD are quite common in many ways. In both we just found a bunch of vectors and a human is needed to identify the building parts and elements. In BIM even a machine can understand what is inside cause the objects are attributed and described in a hierarchic data base structure.

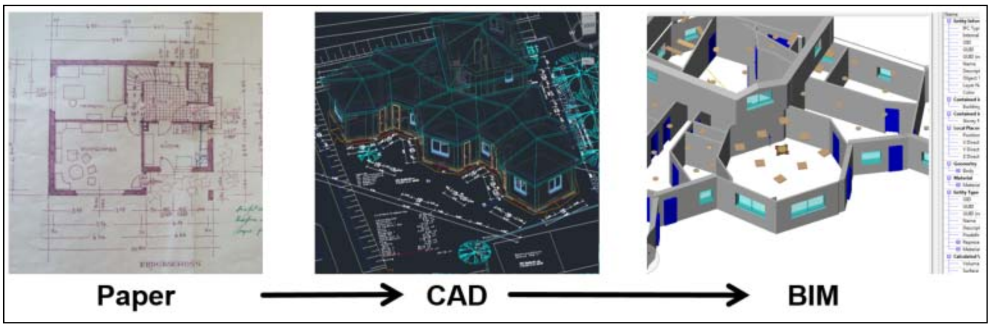

Figure 2. Building design development of the last decades in samples (photo and screen copies)

BIM is more than just a data model: There is also a different work process for all involved building disciplines and for all chronological phases of the building; from planning to demolition.

In the past and today the architect is the central information node and keeper of the planning state by allocate drawings for all disciplines for each planning period. Here CAD has only improved the handling and the plan processing compared to paper era; but not the principle of the plan comparison of different sources and the maintenance of a current state.

With BIM the digital building model is the location of the current design state, even after the completion of the building. All specialist designers could work simultaneously on the same 3D building model and that across from the structural engineer via HVAC to interior designers. In that way problems will be detected quickly and directly without anyone overlaying and comparing two 2D drawings.

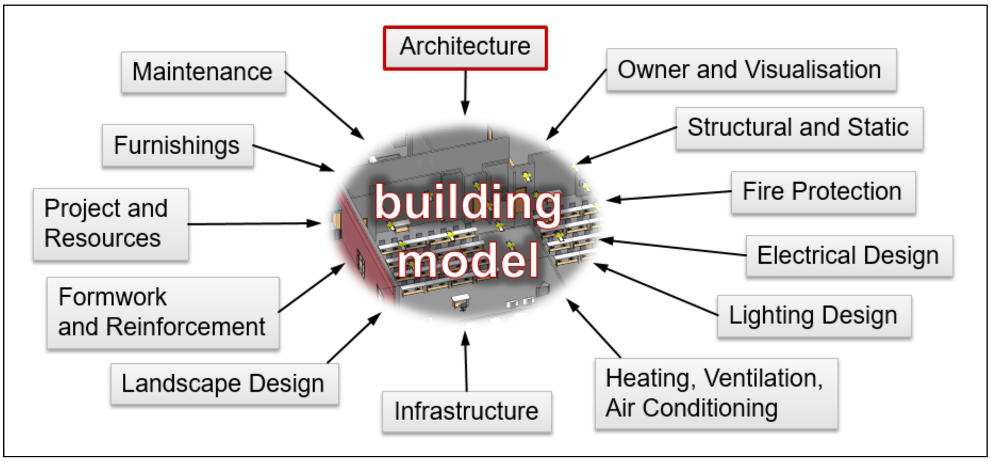

Figure 3. Focus at a BIM model from all designer fields. The virtual building model delivers always the current state of the design.

The virtual Building of BIM is for the complete lifecycle: from scratch, to design, to analysis, to documentation, to construction, to operation and to demolition or renovation. In all of this phases BIM could support with a rich data model and act as source or sink. For example a user interface for a lighting control software could benefit from a BIM model for visualization and positioning. Quite interesting is also the option to store IOT data form a building, including luminaires, in or nearby a BIM database. To store information about the building material (hazard elements or recycling material) is very useful for the demolition.

In real BIM projects everyone realizes soon that the problems are in the details, still a lot conventional communication is needed and that BIM has not yet arrived in the everyday planning. There are a lot of changes in the design process and in the project communication. We are in an early state of BIM. So things could be altered and defined, especially for lighting.

SPREADING OF BIM

Time and financial savings are possible with BIM cause a more detailed design state is available earlier, which reduces change costs. Also checks and analysis gets cheaper. So BIM get a mandatory for public tenders in several countries.

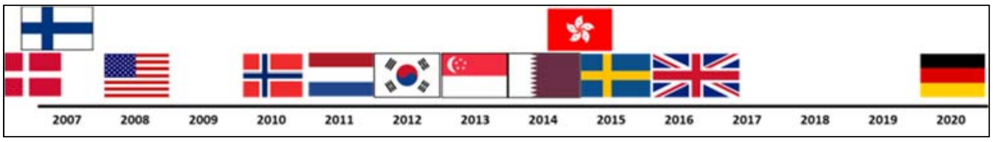

Figure 4. Countries in a sorting, when they gets a BIM law or a mandatory for the building industry.

Especially in Australia, USA, Northern Europe and the Arab world BIM has become one of the most important building design routines and displace step by step classical CAD. The University of Qatar just employed 100 BIM experts in one rush. In areas with more new building constructions (like in Asia or Arabic countries) BIM is more in usage as in areas with a lot of existing buildings for renovations (like in Europe).

In Europe the distribution and knowledge of BIM is divided. While the Netherlands, UK, Finland, Denmark and Norway are working very extensively in the direction of BIM, the rest of Europe majority has just stared the praxis with pilot projects. The EU founded a EU BIM Task Group to reflect the interests of the European Union on BIM.

In Germany a phased plan was published by the Ministry of Transport. The Federal Government supports BIM to 100% and promotes with tens of millions first infrastructure projects (BMVI). BIM is mandatory for public tenders from

2020 in Germany. Also the Ministry of Buildings starts with a directive to consult BIM methods at building projects up from 5 Mio. Euros.

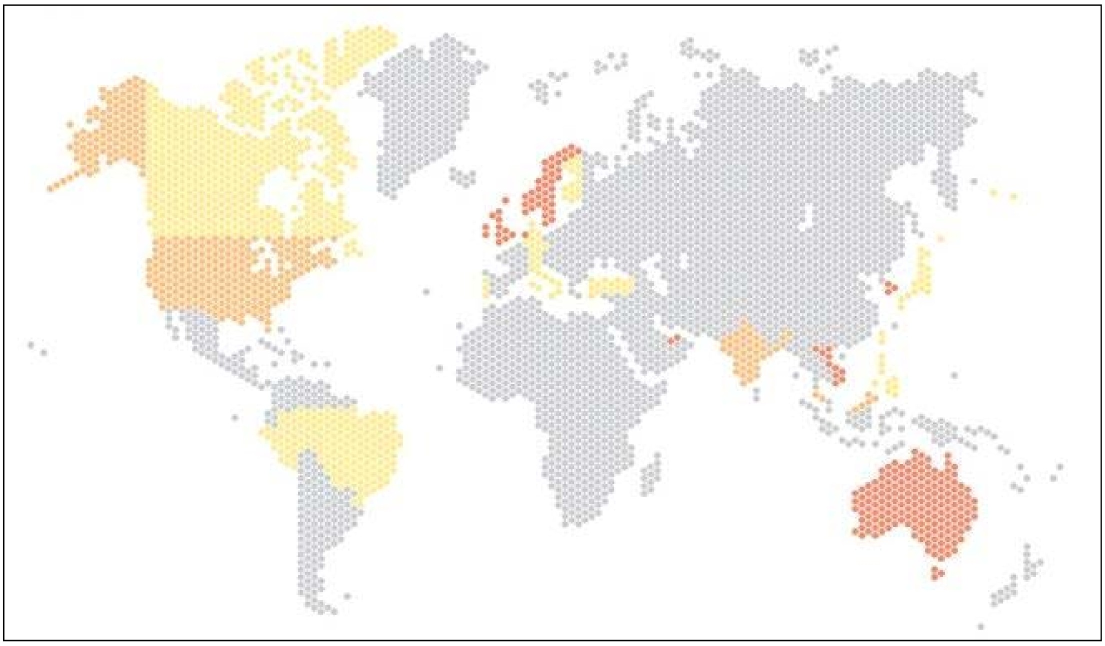

Figure 5. Where BIM is a hot topic (Google trends)

STANDARDIZATION

Since 1987 BIM standardization is existing at ISO (ISO/TC 59/SC 13) with around 8 active standards. The secretary is located in Norway. Since 2015 also DIN Germany and CEN establish BIM committees with 4 working groups each. The secretary of CEN/TC 442 is also located in Norway.

BuildingSMART is an important global society for BIM standardization worldwide. Here a lot of companies and associations works practically at BIM methods, formats, processes and gain experience for standardization. BuildingSMART has liaisons to the important standardization bodies and committees.

At the moment standardizations projects with the following topics are processed: BIM terminology, LOD – level of development, IFC format, product data attribute definition, product data templates, object libraries, BIM processes, data structures for dynamic and relativistic product data, data containers, information exchange manuals.

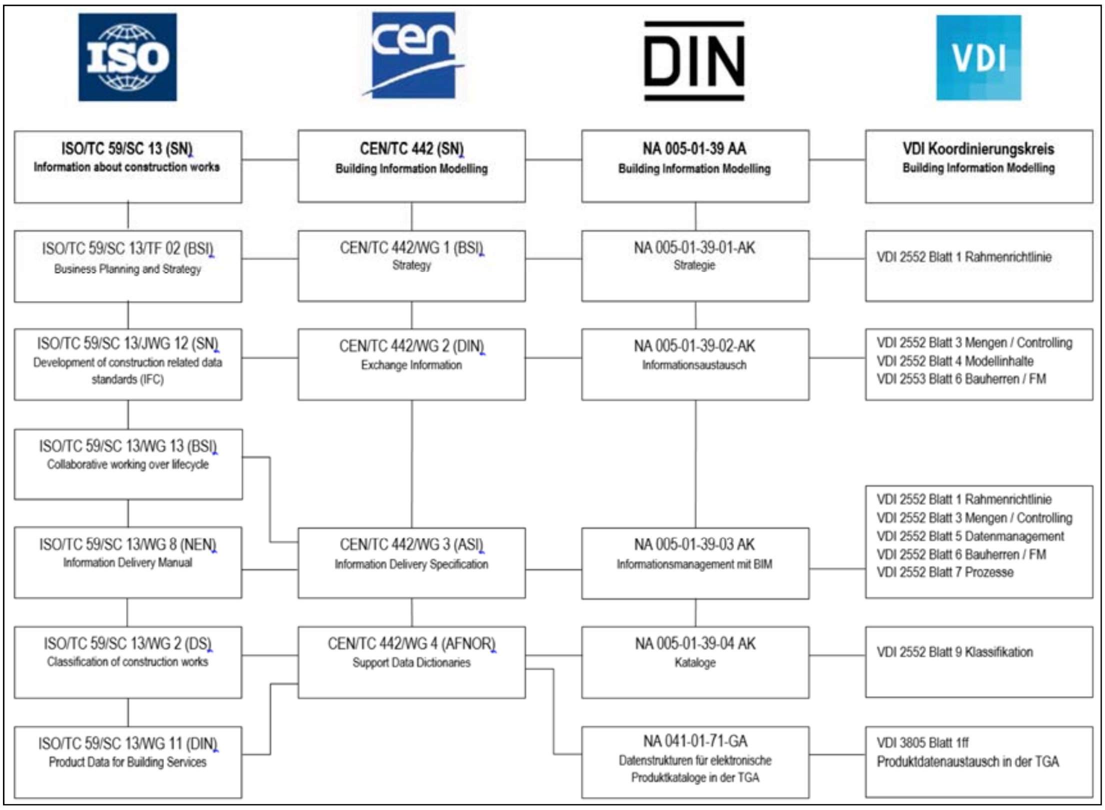

Figure 6. BIM standardization bodies from a German perspective (from a CEN/TC 442 presentation of DIN)

BIM Software

The CAD world market leader Autodesk provides currently that most common BIM Building Design program: Autodesk® Revit®. More BIM programs are ArchiCAD from Graphisoft, which are popular among architects and used virtual building in quasi BIM style since 1983, Vectorworks and Allplan, from Nemetschek both, and Tekla Structures from Tekla, a Finnish software company. All use their own closed file and exchange formats.

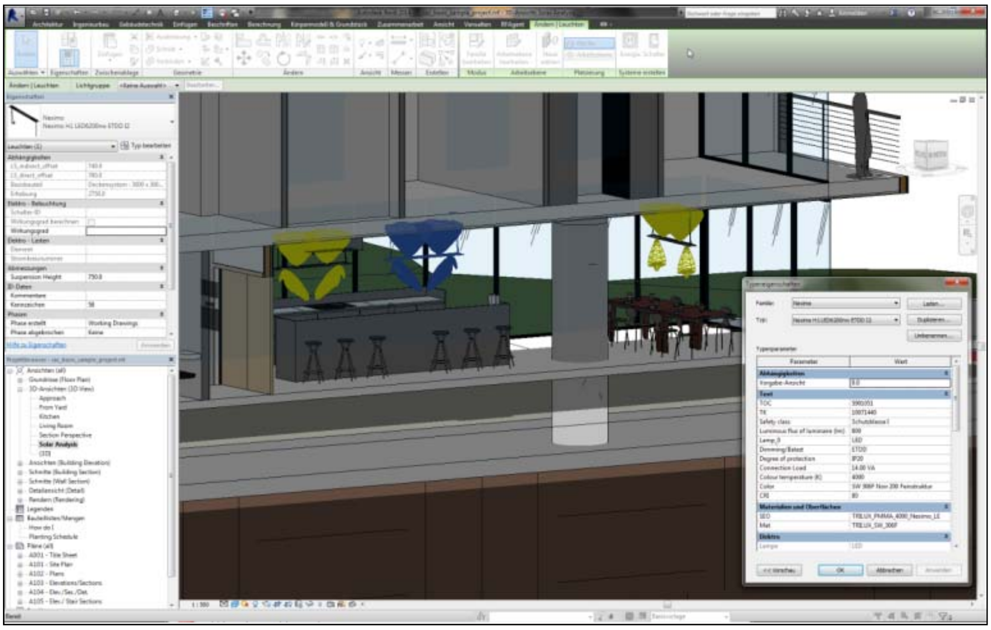

Figure 7. Autodesk® Revit® (screen copy)

Open BIM Data formats

In order to provide a building models format across the applications, the international industry consortium buildingSMART defined in the year 2000 the file data format IFC (Industry Foundation Classes). Since the release IFC4 it is an official global ISO standard (ISO 16739:2013). IFC is more a schema as a file format. So most of the IFC files are written in EXPRESS form. But also XML, OWL or even SQL can contain a IFC schema. IFCMXL is in ISO standardization right now.

IFC4 could contain goniometric light sources (light distribution curve) and luminaire geometry and information. The IFC definition is free available at the buildingSMART website. There are several viewers and editors for IFC files published. All BIM applications should have at least a IFC interface to allow an open BIM file exchange.

At the moment it is not possible to provide just single building elements, like light fixtures, in a IFC file. Cause by definition a IFC has to contain a site, location and a building. But buildingSMART is working on a building product IFC format to enable am exchange of single building elements.

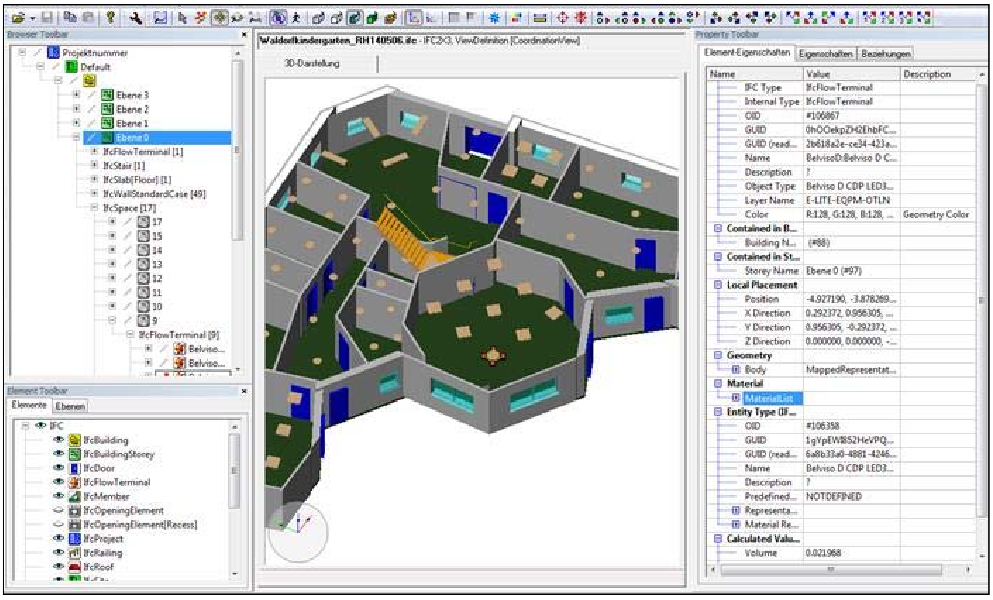

Figure 8. FZK Viewer from KIT, Germany with a IFC2x3 file (screen copy)

LIGHTING CALCULATION WITH BIM

With the light fixtures, renderings are also possible in BIM. Thanks to the LDCs, mealy in IES format, even photometric lighting calculations are possible. This is currently only possible with the Autodesk® Revit® plug-ins ElumTools™ by Lighting Analysts, the US software company that also distribute AGI32.

The usage of BIM files for lighting calculation application brings the benefit that no rooms needs to be rebuild like from a CAD import. The room size, structure and location is instantly accessible for lighting calculation. And the result in luminaire type and position could be exported back to the architect or customer in a BIM / IFC format.

Today just gbXML and 2D/3D CAD formats are supported as interfaces in DIALux and Relux. A IFC import interface is published with DIALux evo 7. Relux plan to publish an Revit® plugin in 2017.

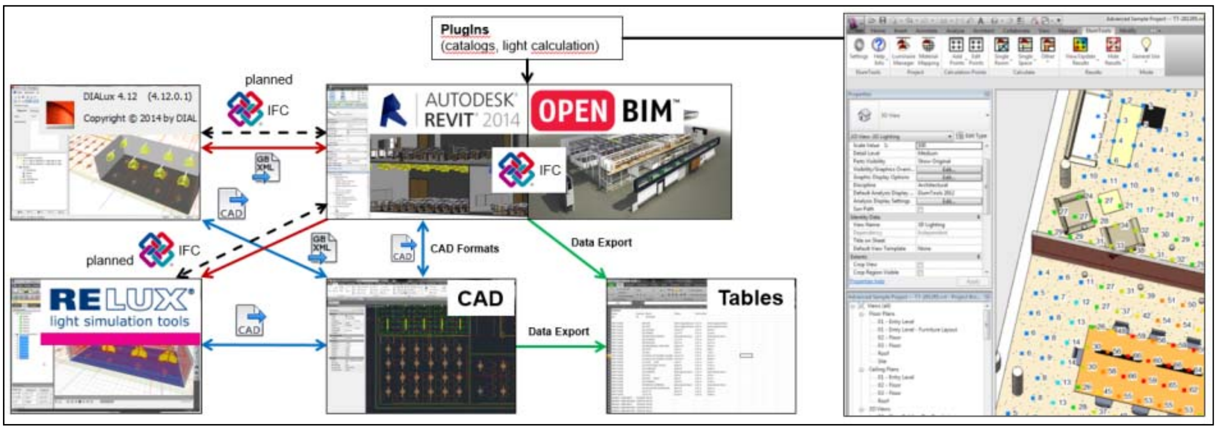

Figure 9. Interfaces and exchange formats between BIM and lighting design applications (screen copies)

LIGHT FIXTURES IN BIM

Architects working with BIM, expect the availability of 3D luminaire models with BIM information available at no cost and at any time. Some lighting manufacturers offer for some years BIM models, usually in the Revit® format of their products. These light fixtures are partially geometrically variable controlled by parameters (e.g. pivot able auxiliary modules) and have light distributions.

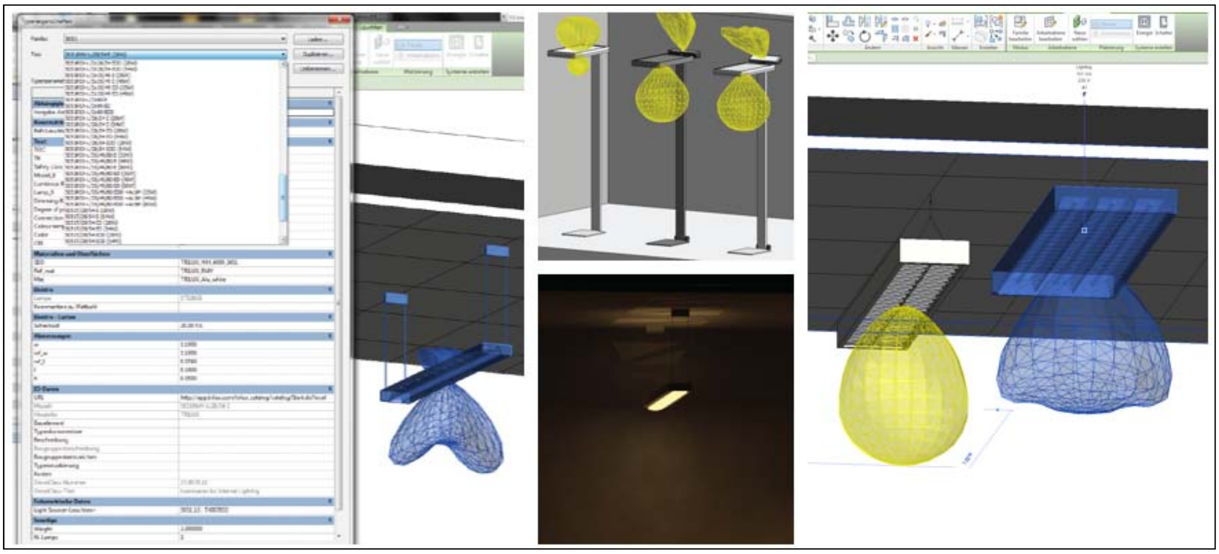

Figure 10. BIM model samples of light fixtures in Revit® (screen copies)

The effort to create BIM luminaires is much higher as at DIALux or Relux models. There is more content, more functions, more variants and more material options. Relux offers via there platform relux.net a Revit® luminaire files download out from the Relux luminaire database for free.

Light fixtures could also described in BIM without geometry, but with a lot of information attributes. For example in UK and in the USA attribute excel sheets with hundreds of attributes are valid BIM product description files.

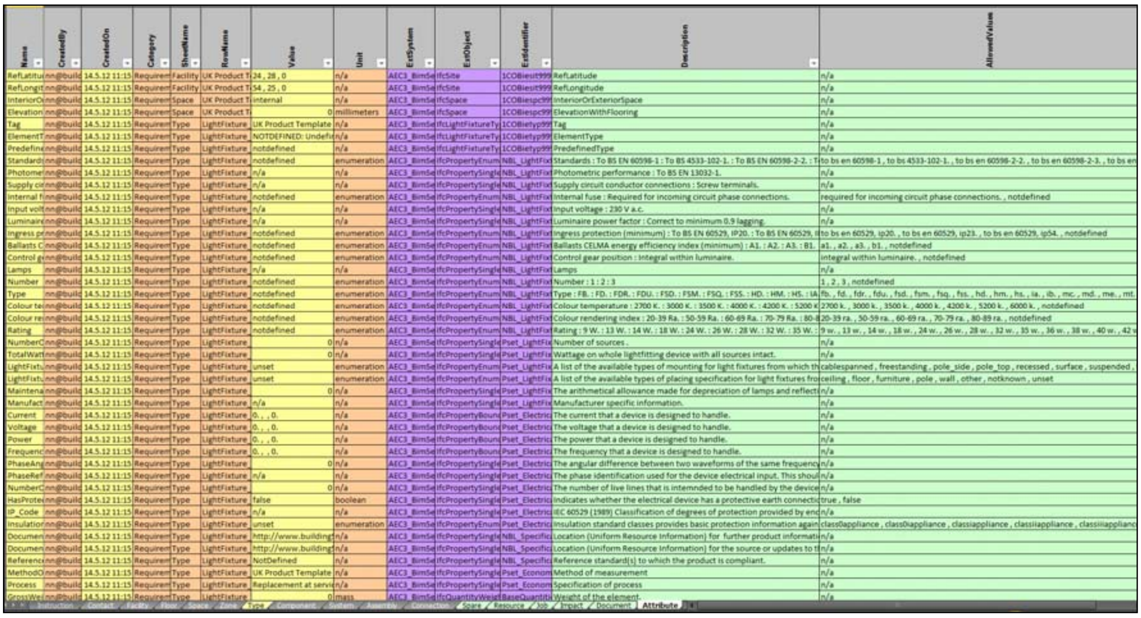

Figure 11. COBie (Construction Operations Building Information Exchange) sheet (screen copy)

ATTRIBUTES AND PRODUCT DATA

In this days the attributes and values of luminaires in BIM are not harmonised. For example: BIM users who ask a BIM model with luminaires from several manufactures for a lamp list gets a heterogenic result. For every vendor the user will get one column and he has to match them manually. This is reality with the BIM praxis today in a lot of situations and far away from the vision of an easy and structures building information exchange across all discipline borders.

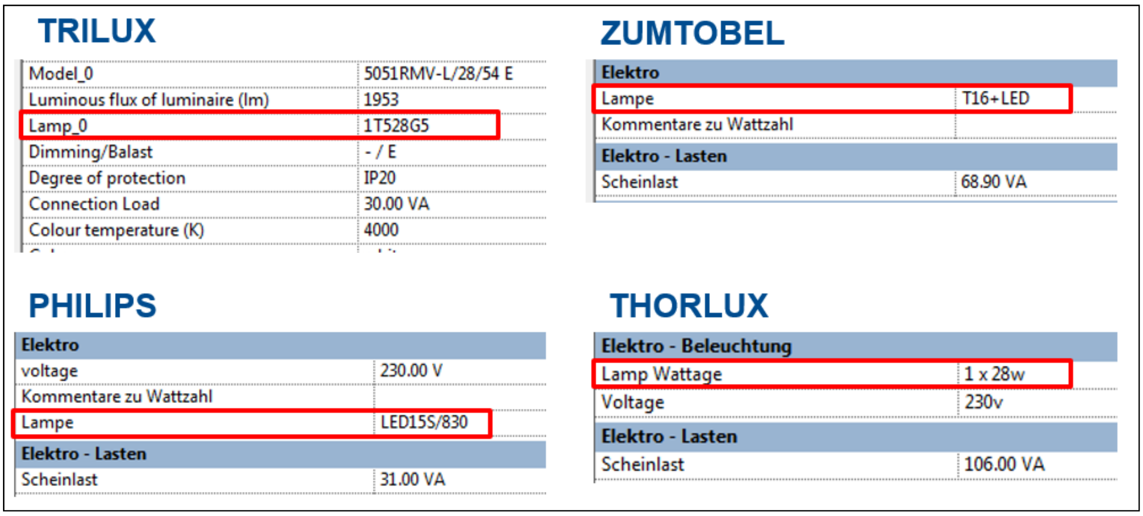

Figure 12. Samples of the “same” Revit® luminaire attribute from different vendors (screen copies)

For a sufficient usage of luminaires in BIM the attributes and value definitions has to be harmonised across the whole industry. This attributes has to be standardized at ISO and CEN level and should be access able in BIM applications and in IFC in order to work effective with light. The attribute naming and description has to be universal and common. And an ID is needed for a machine readable purpose and for a mapping of different product databases. The European standardization is working intensively on attributing the attributes.

The buildingSMART Data Directory is an attribute server from buildingSMART with a free read access to everyone. This is an blueprint for a central building product attribute catalogue. There are issues with the government of this attribute data. The entries has to be reflected and checked by experts (e.g. luminaire attributes by lighting professionals) and in periodically updates, cause attributes changes over the time (e.g. on luminaires: lamp sockets gets irrelevant and melanopic action factor has to be added as attribute).

A rich base for an initial filling of an European attribute database (a CEN Data Dictionary) could be the attributes out of the existing European CEN standards. With an periodic scan of all standards also updates and the maintenance could be realised.

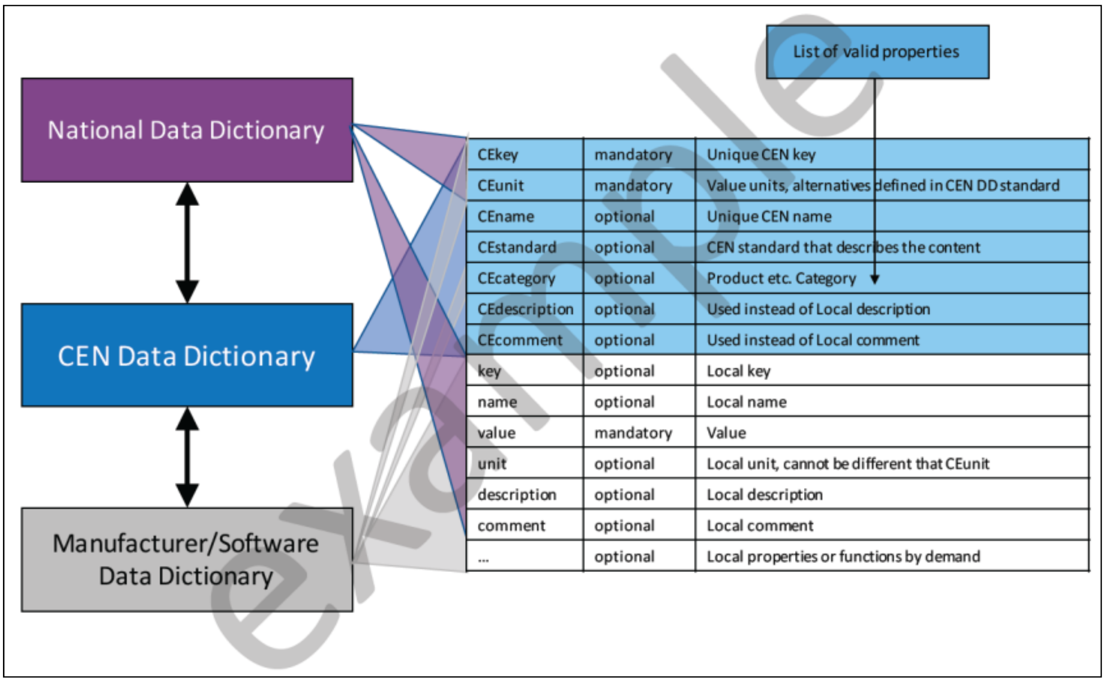

Figure 13. presentation made by Tomi Henttinen during the second meeting of CEN/TC 442/WG 4 on September 13th

All manufactures of building products should prepare to gets there product attributes map able to other products databases with IDs and a common attribute description. The requirements on product data from the users will rise in width, depth and dynamic.

At ZVEI, the German lighting industry association, we established a group of European lighting manufactures and software vendors to discuss and publish all lighting relevant attributes with an equal name, description and an ID. This attribute list will make a luminaire data exchange from manufacturer to software application and to the user / designer more easy and with less misinterpretations.

At ETIM, an international association for product classification data for wholesaler, a lot of BIM activities are started. Even a common three dimensional geometry of products should be developed. In general could ETIM, beside other today existing product classification systems, could be a good base for the lager BIM demand on structured data.

In Europe the market needs beside specific data form manufactures also generic / neutral product data, in order to create neutral tenders. At the start on a building design process the level on detailed specific data is high. But after the design short before on site construction the tender has to be neutral with less specific data. After the tender process in the construction phase the product has to be specific and rich again. For neutral BIM product models are also some ideas and standards in development.

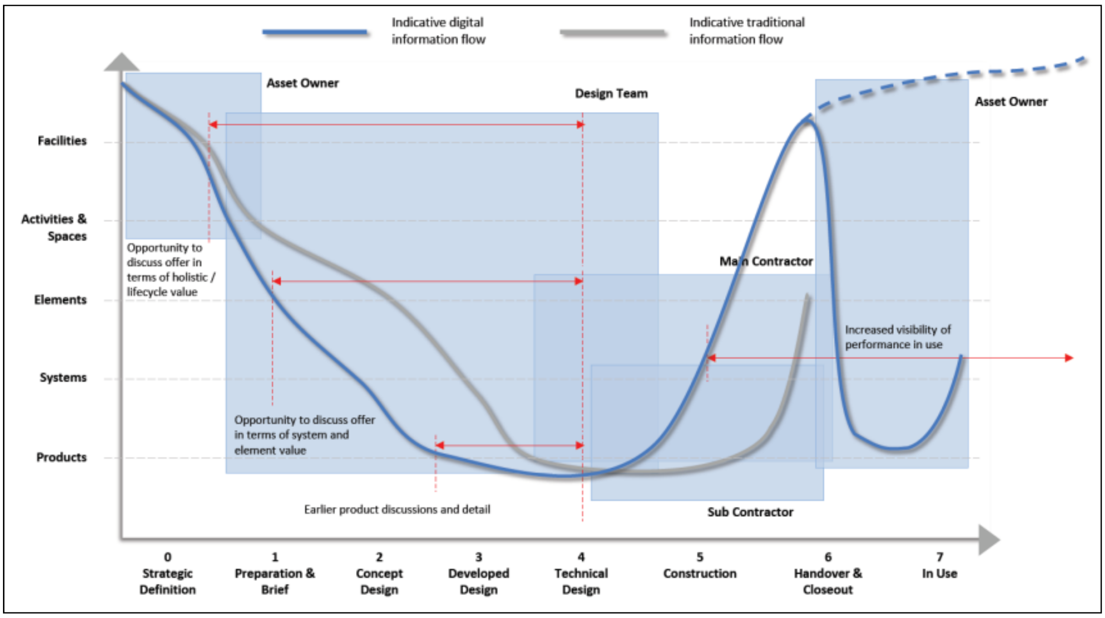

Figure 14. Information flow, granularity and changing points of interaction using digital processes (Steve Thompson, Product Data Definition)

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An Expo Box for Flicker

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***Abstract*— This paper presents the measurements of light intensity of different light sources and the production of an expo box for the purpose of observing light phenomena. With the help of measurements, an insight on how light intensity usually fluctuates in the various types of lamps was obtained. For easy observation and study of temporal light artefacts, such as flicker and stroboscopic effect, an expo box with an option to adjust the supply voltage signal was constructed.**

***Index Terms*—flicker, LED, light intensity, Stroboscopic effect, temporal artefact**

INTRODUCTION *(HEADING 1)*

Nowadays, the number of LED lights on the market is increasing, as they are becoming more and more popular due to their high efficiency and extended lifetime expectancy compared to other lights [1]. Additionally, LEDs are distinguished by their properties, such as easy control, the size of the light source according to the produced light, and the fast response of the emitted light to the current flowing through the diode [2].

When talking about response to the current, unlike LEDs, conventional lamps are relatively slow. Non-LED light sources such as gas-discharge or incandescent lamps typically do not exhibit a zero-light output, even during the off-cycle. Phosphor in the gas-discharge or the filament in incandescent lamps continues to glow even when the AC supply voltage passes a zero point [1]. Because of this, it is expected that light from LEDs will be perceived differently than light from conventional lamps that operates at the same low frequency voltage (50 Hz or 60 Hz depending on country). This difference can cause visible temporal artefacts, such as flicker or stroboscopic effect [2].

Flicker is the most well-known temporal artefact and it is described as visible fluctuation of light intensity. At a certain frequency, called critical flicker frequency (CFF), there is no more visible fluctuation of light intensity – no visible flicker. The CFF is different for different observers but usually lower than 100 Hz [2].

Another temporal light artefact is stroboscopic effect, which is at first invisible to a static observer in static environment. But as soon as there is a moving object, it will appear to move discretely rather than continuously. Because visibility of this effect depends on the speed of the observed object, it can be seen at any modulation frequency [2].

MEASURING LIGHT INTENSITY CHANGES

In the first experiment, different types of light sources that are currently available on the market have been measured. With this, it was desired to secure an approximate display of the light intensity fluctuations in different types of light technologies on the market.

A. Setup

To measure changes in the light intensity of light sources, it is necessary to have a measuring procedure. Given that there is no standard test procedure for measuring light fluctuations [3], measuring setup was designed by Laboratory for lighting and photometry from the Faculty of Electrical Engineering in Ljubljana. The setup is primarily composed of light-impermeable box (106 x 46,5 x 48,5 cm), an analogue photosensor (chip TSL252) and digital oscilloscope (Agilent, DSO-X 2024A, 200 MHz, 2 GSa/s). The composite system is shown in Fig. Figure **71**.

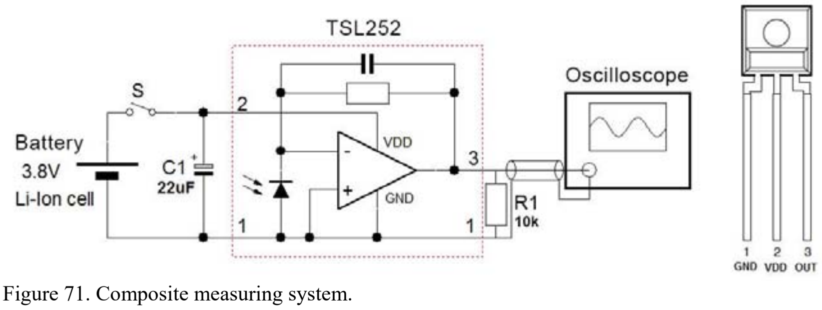

Figure 71. Composite measuring system.

All measured lamps were connected to the main voltage of 230 V and frequency of 50 Hz. Measurements were carried out in a light-impermeable box to prevent disturbances that would otherwise take effect due to the light from the surroundings. Additionally, the lamps were measured 5 minutes after switching them on, due to any possible transient occurrences. Open measuring box is shown in Fig. Figure **72**.

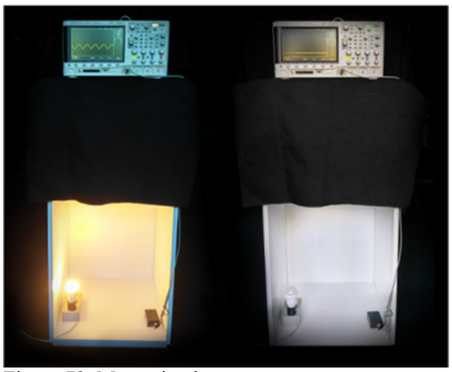

Figure 72. Measuring box.

B. Results

Data was captured using an oscilloscope with a resolution of 20k value / 100 ms, saved in a csv file and then processed with Matlab. Measured data is presented in TAB. TABLE **XI**.

Flicker index and Percent flicker were calculated for each measured light source. Percent Flicker is calculated by (1), where A is maximum and B is the minimum light output during a single cycle.

$$PF = \text{Percent Flicker} = (A - B) / (A + B) * 100 \quad (1)$$

Flicker Index is calculated by (2), where A1 is area above the line of average light output and the A2 is area under the average light output curve for a single cycle.

$$FI = \text{Flicker Index} = A1 / (A1 + A2) \quad (2)$$

TABLE XI. MEASURED LAMPS AND THEIR PROPERTIES

Measurement #	Technology	Power [W]	Base	PF [%]	FI [-]	Figure
1	Incandescent	60	E27	11,15	0,03	Figure 73 – L
2	Halogen	70	E27	9,96	0,03	Figure 73 – D
3	Fluorescent	20	E27	8,65	0,02	Figure 74 – L
4	Fluorescent	9	E27	18,7	0,04	Figure 74 – D
5	Fluorescent	20	E27	8,11	0,01	-
6	Fluorescent	20	E27	9,79	0,02	-
7	Fluorescent	23	E27	6,89	0,01	-
8	Fluorescent	20	E27	12,37	0,02	-
9	Fluorescent	20	E27	16,87	0,03	-
10	Fluorescent (UV)	25	E27	35,97	0,07	-
11	LED	9	E27	18,34	0,05	Figure 75 – L
12	LED	9	E27	21,29	0,03	Figure 75 – D
13	LED	2	E27	100	0,29	Figure 76 – L
14	LED	4	E27	1,95	0	Figure 76 – D
15	LED	5	E27	7,39	0,02	Figure 77 – L
16	LED	2,5	E27	14,19	0,04	Figure 77 – D
17	LED	1	E14	64	0,17	Figure 78 – L
18	LED	5,5	GU10	6,49	0,01	Figure 78 - D
19	LED	12	E27	43,58	0,13	Figure 79 – L
20	LED	12	E27	3,12	0	Figure 79 – D

In most of the measurements of the light flux, a strong 100 Hz component can be noticed. In fluorescent lamps, as shown in Fig. Figure **74**, high-frequency components can be further observed. These high-frequency components are most likely the result of an electronic ballast operating at high frequencies.

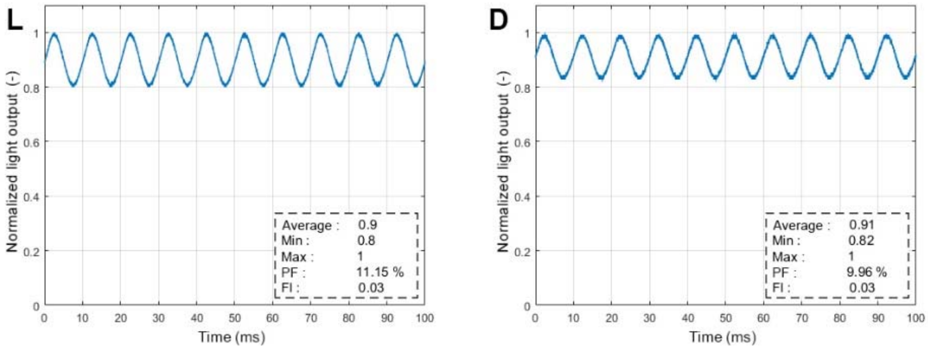

Figure 73. Examples of Incandescent lamp #1 – L, Halogen lamp #2 – R.

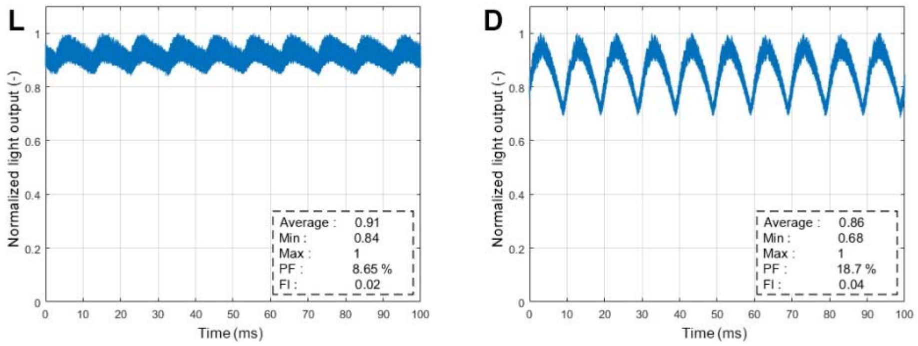

Figure 74. Examples of Fluorescent lamp #3 – L, #4 – R.

LED measurements are shown in Fig. Figure **75** to Fig. Figure **79**, where a lot of different light signal patterns can be noticed. The appearance of the stroboscopic effect is highly probable for the lamps in Fig. 5 - L, Fig. 8 - L and Fig. 9 – L. The visibility of this phenomenon is less likely for other LEDs because the oscillations of light flux is very low or invisible to the human eye due to the high oscillation frequency.

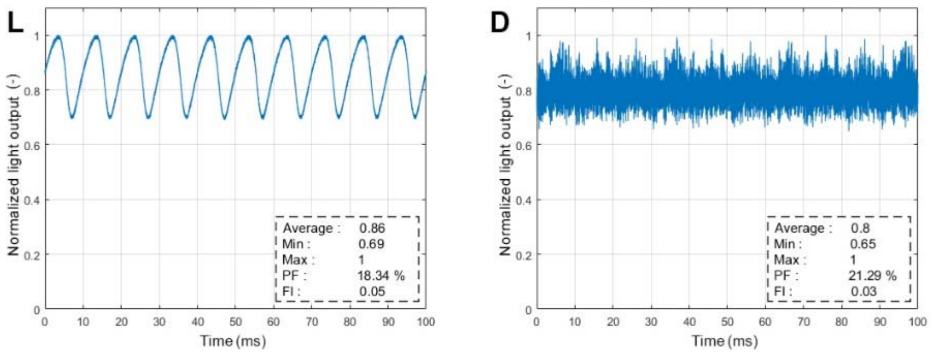

Figure 75. Examples of LED lamp #11 – L, #12 – R.

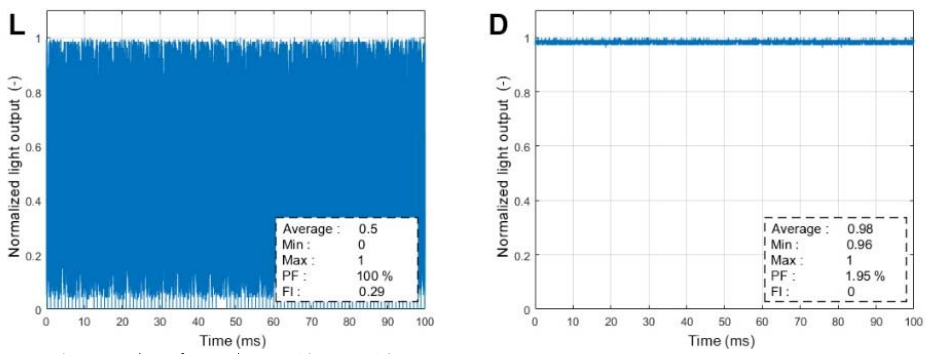

Figure 76. Examples of LED lamp #13 – L, #14 – R.

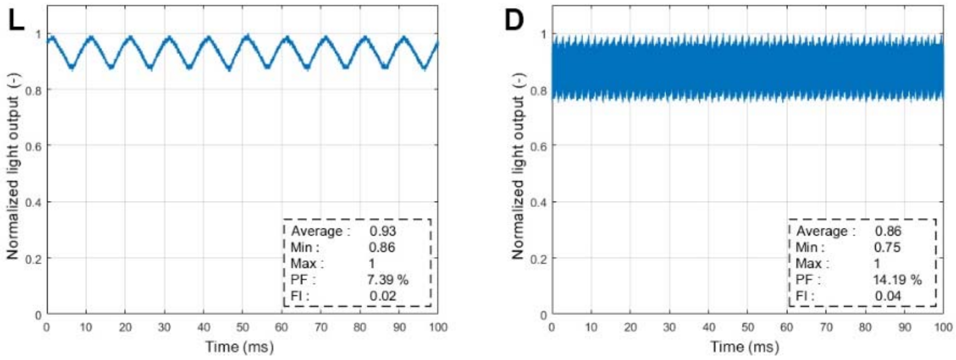

Figure 77. Examples of LED lamp #15 – L, #16 – R.

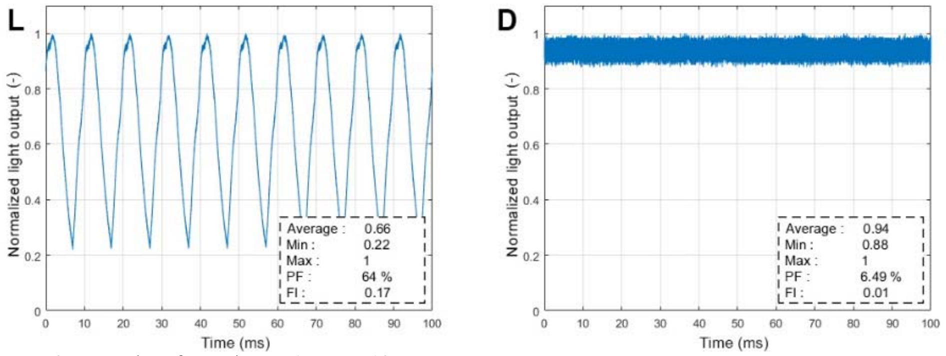

Figure 78. Examples of LED lamp #17 – L, #18 – R.

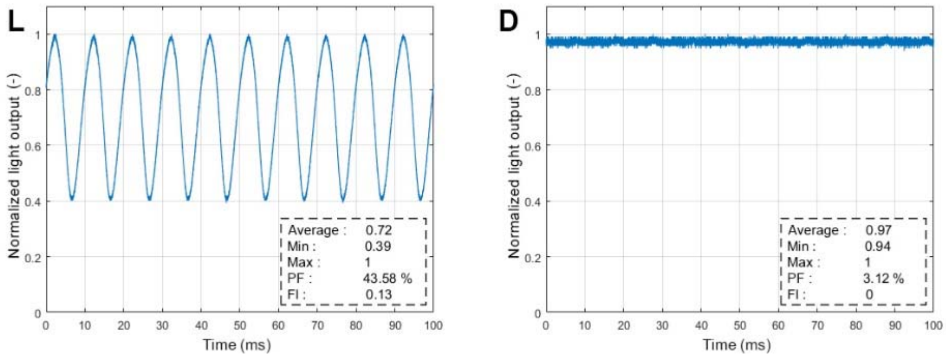

Figure 79. Examples of LED lamp #19 – L, #20 – R.

EXPO BOX

To observe the problem caused by temporal light artefacts, two exhibition boxes were made. For each exhibition box, an identical electrical circuit (Fig. Figure **80**) and front panel (Fig. Figure **82**) were designed and manufactured. One of the completed boxes is shown in Fig. Figure **81**.

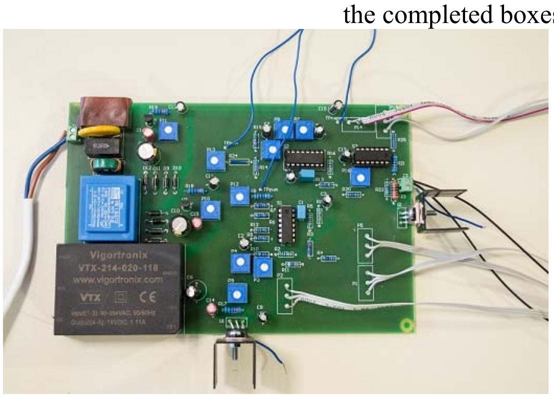
Figure 80. Electrical circuit.


Figure 81. Complete expo box with front panel at the top.

Observation of temporal light artefacts is done with two identical boxes that are side by side. Each box has a front panel (Fig. Figure **82**) with potentiometers for adjusting the signal properties, a switch for selecting the desired signal (sine / square) and an oscilloscope showing the shape of the light flux captured with a photosensor. The potentiometers can change the different characteristics of the signal by which the light emitting diodes are powered (frequency from

50 Hz – 500 Hz, duty cycle from 0 % – 100 %, amplitude from 0 - 1 and offset from 0 - 1). This way, the observer can set different light settings in each box and compare the light of one and the other.

Figure 82. Front panel of expo box.

Using these expo boxes, it is easy to observe various lighting phenomena with different power supply settings. In the future, it will help to observe and study the visibility of the flicker and the stroboscopic effect.

CONCLUSIONS

Temporal light artefacts, such as a flicker and a stroboscopic effect, are common in light-emitting diodes that are improperly designed for alternating voltage. Nowadays, there are many LEDs for alternating voltage on the market, among which there are also those that are unsuitable for use in rooms where people spend most of their time. Such lamps have a bad influence on human well-being and can be extremely dangerous to a certain population. Given that the presence of LEDs on the market is increasing, a standard should be established to determine which lamps are suitable for use and which ones are not.

It was necessary to create some kind of a system for demonstrating and observing temporal light artefacts. Therefore, this exhibition box was designed and manufactured. There were quite a few problems with the frequency interference and instability of the signal during the production of the power supply for the expo box. All problems were successfully solved. The final product has the option of selecting a sinusoidal or square signal with a switch, adjusting the frequency from 50Hz to 500Hz, adjusting the duty cycle at a square signal from 0% to 100%, setting the amplitude from 0V to 11V and setting the voltage offset from 0V to 11V. With the help of an expo box, the observer can successfully observe flicker or stroboscopic effect in LEDs.

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The Engineering Assessment of Floodlighting Design

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***Abstract*— The main aim of this paper is to highlight the engineering problems associated with the assessment of floodlighting design from a technical standpoint. It presents a new tool for the preliminary assessment of a floodlighting design at the design stage. This assessment is performed using some new and practically-definable parameters. Additionally, the results are shown for the calculation of these particular parameters in some specific floodlighting designs. The possibility of the preliminary assessment of floodlighting in this manner has been based on the results of these calculations. It can be confirmed, by the use of both computer simulations and these calculations, that the lighting designer can have an impact on energy efficiency and light pollution issues by the appropriate selection of, and small changes to, the positioning and directionality of the equipment being used.**

***Index Terms*— energy efficiency, floodlighting, floodlighting utilisation factor, light pollution**

INTRODUCTION

Floodlighting is a very broad and popular area in modern lighting technology [1]. This is no doubt connected with the sudden and recent increase in the development of LED light-sources. Nowadays, more and more buildings and objects worldwide are being illuminated at night. In most cases, this floodlighting is done in such a way that light is emitted from luminaires located at the bottom of the object [2]. In such cases, a large part of the luminous flux emitted from the light sources used in the lighting equipment can miss the object entirely. This situation is very disadvantageous [3]. First of all, it causes electrical energy to be wasted [4]. One floodlighting design alone does not give rise to a large waste of energy because the total power output of the lighting equipment installed is fairly low. However, over several hundred designs the waste of power can be quite substantial. When an object is illuminated in an ineffective way, it can cause a relatively large and unnecessary waste of electrical energy. Secondly, the luminous flux which does not reach the selected surface has an impact on skyglow [5]. Moreover, it has an impact on the phenomenon of light pollution. This issue has been very widely commented on in the literature recently with regard to cause and effect [5], [6], recommendations for designs [7], [8], [9], standards [10] and measurements [11], [12]. A floodlighting design should be assessed, not only in terms of its visual beauty, but also from a technical viewpoint [4], [12]. The glare issue from light sources [13] should also be precisely considered, to make the design safe for its recipients. This issue has not yet been defined in any technical or legal regulations connected with illuminations such as floodlighting. Hence, a large number of designs are created in an improper manner from an engineering point of view. However, there is the possibility of creating some useful parameters to assess floodlighting in relation to the energy efficiency of lighting and to the phenomenon of light pollution. These parameters are discussed and defined in the next section of this work.

DEFINITION OF NEW PARAMETERS

FLOODLIGHTING UTILISATION FACTOR

The Floodlighting Utilisation Factor (FUF) is defined as (1) of useful luminous flux ϕ_u which is aimed at the surface of a floodlit object and which causes a specific visual effect (such as luminance), and the total luminous flux ϕ_t coming from all the light sources used in that lighting solution [4].

$$FUF = \frac{\phi_u}{\phi_t} \cdot 100\ [\%] \tag{1}$$

MAXIMUM FLOODLIGHTING UTILISATION FACTOR

The maximum value of floodlighting utilisation factor defines the maximum theoretical value of FUF for particular design. It is the defined as (2) of total luminous flux emitted from all used luminaires, and the and the total luminous flux ϕ_{0t} coming from all the light sources used in that lighting solution. The value of it is related with the quality of manufacturing of the lighting equipment by LOR (Luminaire Output Ratio).

$$FUF_{\max} = \frac{\phi_{top}}{\phi_{0t}} \cdot 100\ [\%] \tag{2}$$

LOSS OF LUMINOUS FLUX

The loss of luminous flux parameter is basically defined by formula (3). It is a difference between the between the sum of luminous fluxes from all luminaires and useful luminous flux. It can be also presented in relative form (4) as relative loss of luminous flux parameter. It describes this part of luminous flux from all luminaires that don't aim the object and it is scattered up near the illuminated object. In general, it is a direct cause of the light pollution phenomenon due to the issue of floodlighting.

$$\phi_{loss} = \phi_{top} - \phi_u \; [lm] \tag{3}$$

$$\phi_{loss}^{'} = \frac{\phi_{loss}}{\phi_{top}} \cdot 100 \; [\%] \tag{4}$$

COEFFICIENT OF FLOODLIGHTING UTILISATION FACTOR

The coefficient of floodlighting utilisation factor is defined as the proportion between the value of floodlighting utilisation factor for such lighting solution to the maximum value of floodlighting utilisation factor for this solution. It present in the simplest way a quality of lighting equipment used in particular concept. What is more it can be very useful to preliminarily assess the design in relation to energy efficiency and light pollution.

$$CFUF = \frac{FUF}{FUF_{\max}} \cdot 100 \; [\%] \tag{5}$$

THE METHOD OF CALULATION OF FLOODLIGHTING UTILISATION FACTOR

The value of FUF can be obtained by using Autodesk 3dS Max [14]. This software was chosen because of its usefulness during the process of floodlighting design by means of the method of computer visualisation [15] and because of the precision of the calculations obtained [16]. The values of illuminance (illuminance distribution) can be obtained by using a calculation plane Light Meter. The user has the opportunity of changing the accuracy of the calculation by modifying the amount of calculation points. The Light Meter can be of any arbitrary size and the user can bend it freely or set it in any position. Then, by placing the calculation surfaces in a specific manner with respect to the illuminated object, the value of loss of luminous flux can be properly obtained. When the illuminated object or building is enclosed by six Light Meters, forming a cuboid (or a cube, depending on the geometry of the inside object) – Fig. 1., this method of calculation can be called the Cuboid Method of calculation of loss of luminous flux. By simply summing the luminous flux (6) from every wall of the cuboid, we can obtain the loss of luminous flux (7) and hence all the other useful parameters based on formulae (1)-(5).

$$\phi = \int_S E ds [lm] \tag{6}$$

$$\phi_{loss} = \sum_{i=1}^{6} (E_i S) = \sum_{i=1}^{6} (E_i a^2) \tag{7}$$

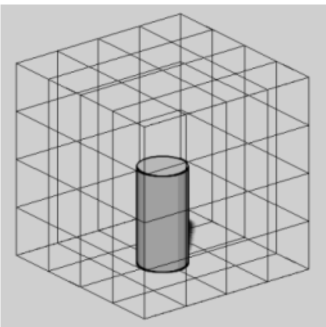

Figure 15. Schematic idea of The Cuboid Method – the illuminated object is enclosed by six Light Meters.

METHODOLOGY OF THE RESEARCH

Two different concepts have been created for the floodlighting of an actual building - the Tenement House, located in Warsaw - as a computer model (simulation) in 3dS MAX. The first of these concepts is based on a method in which the luminaires are installed directly on the surface of the illuminated area (Fig .2). In the second concept, the illumination is arranged from a distance (Fig. 3.). A summary of the lighting equipment is presented in Tables I and II. Both concepts were carefully analysed and the calculation was also performed using 3dS Max, according to the Cuboid Method, as presented above. The calculation was prepared for direct illuminance only. The size of the Light Meters and the accuracy of the calculations was optimized to achieve reliable data. All parameters were calculated for five different positions of the luminaires: 0° - reference position (the initial positioning of the lighting designer). A negative value of the angle means that the luminaires were pivoted in the opposite direction to the surface of the building and the converse is true when the value of the angle is positive.

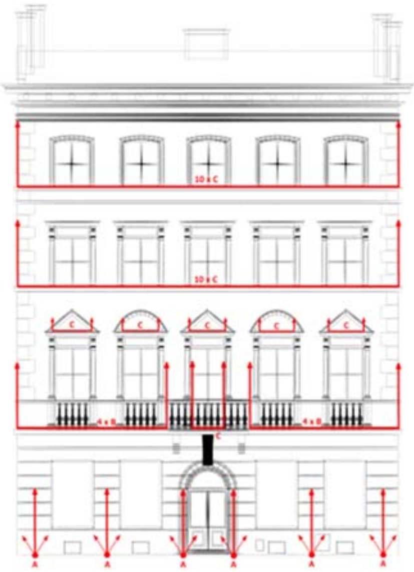

Figure 16. Scheme of location of lighting equipment for the first concept of floodlighting the Tenement House.

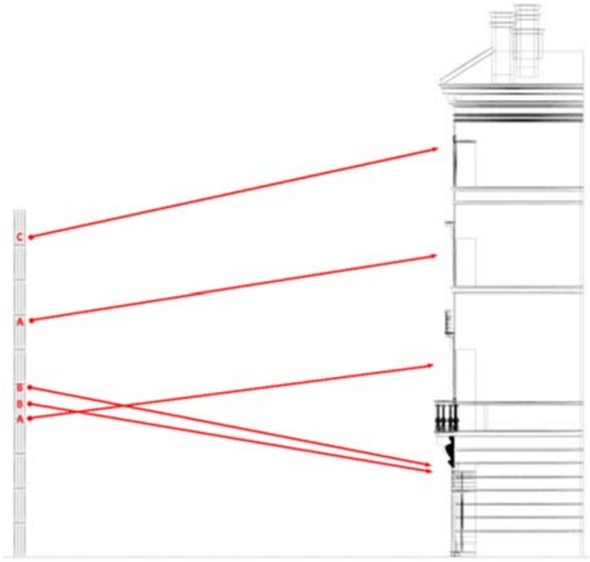

Figure 17. Scheme of location of lighting equipment for the second concept of floodlighting the Tenement House.

Figure 18. Compu ter visualisation of the first concept of floodlighting the Tenement House (angle 0°).

Figure 19. Compu ter visualisation of the second concept of floodlighting the Tenement House (angle 0°).

TABLE V. SUMMARY OF LIGHTING EQUIPMENT FOR THE FIRST CONCEPT OF FLOODLIGHTING.

Symbol	Type of luminaire	Distribution	Amount [pcs]	Type of light source	T_c [K]	P_0 [W]	P_{lum} [W]	ϕ_0 [lm]	ϕ_{lum} [lm]	LOR [%]
A	ground recessed	rotationally symmetrical	6	MH	4000	20	23	1600	896	56
B	linear	axially symmetrical	8	LED	4000	-	16,3	192	113	59
C	linear	axially symmetrical	26	LED	4000	-	16,5	540	319	59

TABLE VI. SUMMARY OF LIGHTING EQUIPMENT FOR THE SECOND CONCEPT OF FLOODLIGHTING

Symbol	Type of luminaire	Distribution	Amount [pcs]	Type of light source	T_c [K]	P_0 [W]	P_{lum} [W]	ϕ_0 [lm]	ϕ_{lum} [lm]	LOR [%]
A	floodlight	axially symmetrical	2	MH	4000	70	88	6600	4224	64
B	floodlight	rotationally symmetrical	2	MH	4000	20	23	1600	1027	67
C	floodlight	axially symmetrical	1	MH	4000	150	167	14000	8960	64

RESULTS OF CALULATION

Firstly, the calculations show that the typical values of FUF and CFUF are rather small. For FUF, the value is in the region of 30-40% and for CFUF it is 60-70%. This means that the floodlighting design can be optimized in accordance with these parameters. The higher the value of FUF, the smaller the waste of energy and the smaller the influence on the phenomenon of light pollution. What is more, the higher the CFUF value, the better the floodlighting design from an engineering point of view. When this parameter is equal to 100%, it means that all the luminous flux from the luminaire reaches the illuminated area. There are no light-spill issues, due to the fact that the radiation is direct. Floodlighting will always have some impact on light pollution in terms of indirect light. This is directly connected with the coefficient factors of illuminated surfaces and the type of reflectance. However, unfortunately, there is no way of influencing these factors. A situation may arise where an illuminated object is white, and therefore it cannot be illuminated because of the high value of the coefficient factor. However, it can be done in a reasonable manner by preparing a simple analysis of the different methods of floodlighting a particular object. In this paper, two different methods of floodlighting: concept 1 – from a distance, and concept 2 – from a facade, are presented. It transpires that the levels of the parameters of FUF and CFUF are almost the same in both concepts. Moreover, the first concept is more sensitive to small changes in the positioning of the lighting equipment. The range of FUF for angles between -10° to +10° is from 24-52% and for CFUF it is from 42-90%. In contrast, much more stable values of these parameters are achieved for floodlighting from a distance. The range is 34-42% for FUF and 54-62% for CFUF in this case. Furthermore, it is found that floodlighting designs cannot be analysed only in relation to visual aspects or only in relation to technical aspects; both aspects should be analysed at the same time. The changing of the position or positioning of the luminaires causes a change in the floodlighting image – by changing the luminance distribution (Fig. 6-11). In this case, it is seen that greater changes occur in the image in the second concept. The more acceptable change in image is achieved in the first concept. There is also a much better usage of luminous flux, resulting from the increase in the values of FUF and CFUF. The issue of the positioning of luminaires should be considered by the lighting designer from both a technical and engineering standpoint, and it must be borne in mind that visual aspects are also very important in such an illumination.

TABLE VII. RESULTS OF CALCULATION FOR THE FIRST CONCEPT OF CALCULATION

ϕ_{0t} $[lm]$	ϕ_{top} $[lm]$	$FUF_{\max}$ $[\%]$	Angle [°]	ϕ_u $[lm]$	ϕ_{loss} $[lm]$	ϕ'_{loss} [%]	$FUF\,[\%]$	$CFUF\,[\%]$
25 176	**14 566**	**58**	-10	6159	8407	58	24	42
			-5	8241	6325	43	33	57
			0	**10 186**	**4380**	**30**	**40**	**70**
			+5	12 337	2229	15	49	85
			+10	13 135	1431	10	52	90

TABLE VIII. RESULTS OF CALCULATION FOR THE SECOND CONCEPT OF CALCULATION

ϕ_{0t} $[lm]$	ϕ_{top} $[lm]$	$FUF_{\max}$ $[\%]$	Angle [°]	ϕ_u $[lm]$	ϕ_{loss} $[lm]$	ϕ'_{loss} [%]	$FUF\,[\%]$	$CFUF\,[\%]$
30 400	**19 552**	**64**	-10	10 483	9069	46	34	54
			-5	12 252	7300	37	40	63
			0	**12 897**	**6655**	**34**	**42**	**66**
			+5	12 973	6579	34	43	66
			+10	12 819	6733	34	42	66

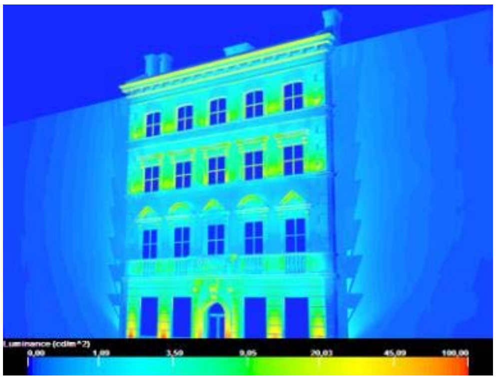

Figure 20. Luminance distribution on the illuminated surface of the Tenement House (first concept, angle -10°).

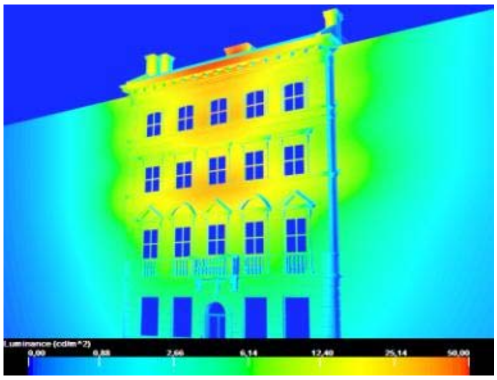

Figure 21. Luminance distribution on the illuminated surface of the Tenement House (second concept, angle -10°).

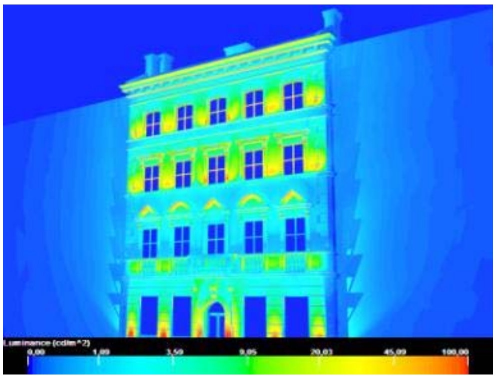

Figure 22. Lumina nce distribution on the illuminated surface of the Tenement House (first concept, angle 0°).

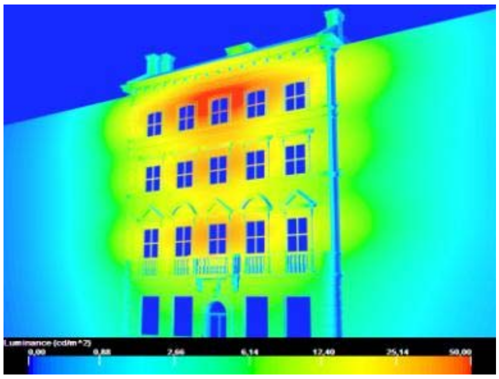

Figure 23. Lumina nce distribution on the illuminated surface of the Tenement House (second concept, angle 0°).

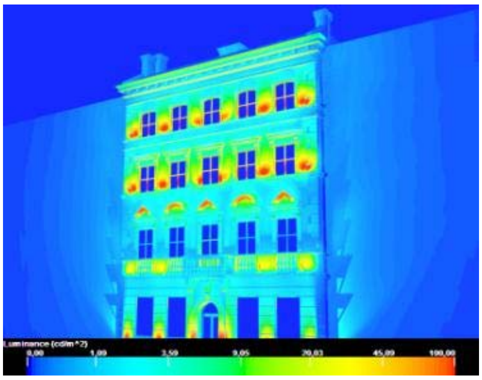

Figure 24. Lumina nce distribution on the illuminated surface of the Tenement House (first concept, angle +10°).

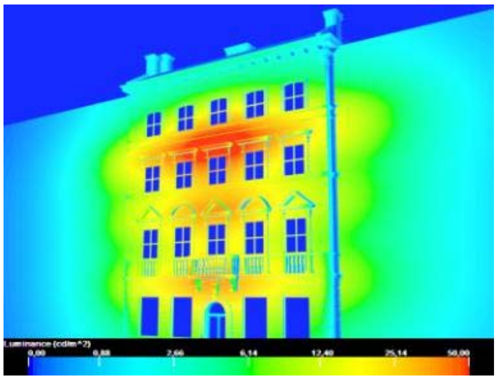

Figure 25. Lumina nce distribution on the illuminated surface of the Tenement House (second concept, angle +10°).

CONCLUSIO

This paper is a serious attempt at considering the floodlighting of objects with reference to energy efficiency and the phenomenon of light pollution. Some useful parameters for preliminary assessment have been defined and implemented in practice. A method of finding the best possible balance between the technical aspects of floodlighting (energy efficiency and light pollution) and visual beauty can definitely be provided. Energy efficiency and the phenomenon of light pollution are very important issues that are commented on widely in the literature nowadays. Some legal regulations or technical standards for floodlighting in relation to these issues should be considered in the near future. This will be the basis for further research by the Author of this paper.

FUNDING

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Smart Design of Thin Direct-Lit Luminaires

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Abstract—**Common LED based direct-lit luminaires for general lighting applications are using LEDs as light sources, which are placed with a certain distance in a regularly arranged array. In order to achieve a homogenous light distribution a diffuser sheet has to be placed on the out-coupling side in a certain height above the LED array. The required height is determined by the distance between the LEDs. For this so-called DHR (distance (of the LEDs) to height (of the diffuser sheet placement) ratio) values of 1 are hardly achievable. To overcome this limitation additional optical elements like freeform lenses are necessary. In this contribution we discuss a smart design concept for very thin freeform lenses with a maximal height of 75 µm that allow to maintain a uniform illumination in a flat direct-lit backlight using an LED-array with a comparably large distance between the individual LEDs. The concept emphasizes the use of a Roll-to-Roll process for the cost-effective fabrication of the thin freeform optics.**

Index Terms—

INTRODUCTION

Light sources based on light emitting diodes (LEDs) have a lot of advantages that outperform their conventional counterparts like incandescent or compact fluorescent lamps. This includes lifetime, reliability, energy saving as well as their compact sizes to mention just some of them [1,2].
Albeit LED based light sources become more and more common in our daily live, there are a lot of challenges ahead to further improve LED based luminaires, including improvements of efficiency, white light quality and luminaire design. In this regard, in the following we extend our previous discussion [3] on a design concept for a direct-lit luminaire for general and architectural lighting. As discussed in [3], a direct-lit luminaire has a close relationship to the more recognized direct-lit backlight for liquid crystal displays (LCD) used in the premium segment of television (TV) sets. The possibilities for a homogeneous luminance and a very flat construction in combination with a large display size are the reasons why LED based light sources have become very attractive for the backlight unit (BLU) of LCD television sets. Still, these potentials are also very appealing for a direct-lit luminaire aiming at general and architectural lighting applications. Usually, for a BLU the individual LED dice are arranged in an array and the higher the packaging density of the LED dice is the higher is also the uniformity of the irradiance on a target plane. However, a higher packaging density goes along with higher costs since a larger number of LED dice is needed. Further disadvantages of a higher packaging density may be restrictions of the available space and thermal issues.
Therefore, the research goals for direct-lit BLUs on the one hand focus on large-scale uniform illumination, and on the other hand on an increased distance between the individual LED dice. Several LED arrangements have been investigated in this regard in combination with the superposed illumination/irradiance of the LEDs on a certain target plane, e.g., for achieving a homogenous illumination for a rotational symmetric illuminance of a single LED [4,5]. However, the optimal arrangement alone is not sufficient for achieving both a uniform illuminance and a thin BLU height. Generally, the ratio of the distance between two LEDs and the height (or the thickness) of the BLU, i.e. distance-height ratio (DHR), should be as high as possible. In order to be able to increase the distance between the LEDs of an LED-array while keeping the target plane at a constant height one needs additional optics. Several studies report on the use of freeform optics in this context [6-8]. The related strategies e.g., rely on a freeform optic for a single LED die which generates a uniform square shaped irradiance distribution with a certain width d. Using an array of such freeform optical elements allows to generate a uniform irradiance distribution on the target plane, which, e.g., can be a diffuser element, which transforms the uniform irradiance distribution into a uniform radiance. With such a concept, backlight with a large size of several square meters and a uniform luminance showing a high DHR value of up to 3 can be realized.
Still, parameters lie large size area, homogeneous luminance, high efficiency, a tuneable brightness, very thin height with a high DHR value are desirable properties, not only for LCD displays but also for luminaires targeting on general lighting. While the freeform optics generates the uniform irradiance at the target plane the diffuser sheet allows for angular mixing of the light so that a uniform luminance can be obtained. High DHR values are desirable because of the lower number of individual LEDs needed, which reduces the costs and lowers the electrical power necessary to operate the luminaire. And a higher DHR value favours the design of very flat luminaires which again facilitates their integration, e.g., into walls for indoor lighting. Still, in order to be able to construct very flat direct-lit luminaires, one should be also able to keep the height of the optics as low as possible.
In the following, we extend the discussion on our recently presented design scheme for cthin freeform optical elements with an effective height of about 70 µm for a direct-lit luminaire with a high DHR value and an effective height of

10 mm, i.e. height of the target plane relatively to the LEDs. In particular, here we discuss non-rotationally symmetric FF elements, which are of relevance in order to avoid the overlapping of the irradiance distributions of the individual elements, which, e.g., is the case for rotationally symmetric FF elements.
Figure 1 summarizes the direct-lit luminaire concept with a thin FF element for achieving a homogeneous irradiance on the target plane where a diffuser sheet is placed, as discussed in our previous publication.

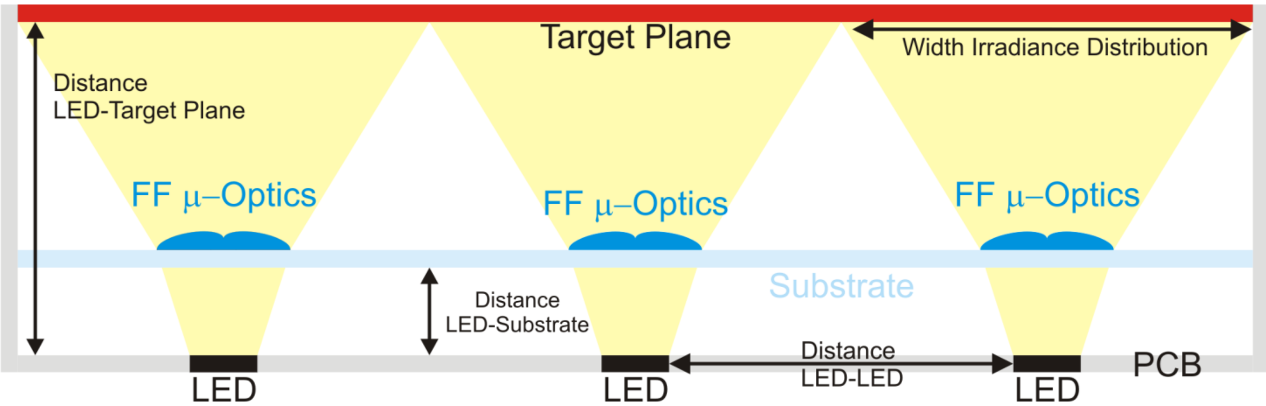


Figure 1: Schematic of a direct-lit luminaire concept with flat freeform optics for achieving a homogeneous irradiance on the target plane, at which a diffuser sheet is placed.

EXPERIMENTAL

The details of the design procedure for the freeform (FF) optical elements have been published elsewhere [3]. Briefly, the procedure bases on a two dimensional approach that applies Snell's law in a ray mapping scheme, see Fig. 2. The FF algorithm allows the determination of a complex optical surface in a sequential process. It allows to transform an arbitrary angle dependent radiant intensity distribution $I_s(\theta)$ of a light source into a calculated angle dependent radiant intensity distribution $I_L(\theta)$ which is generating the desired irradiance distribution when illuminating the target plane [8]. This means, the ray mapping scheme correlates rays emitted by the light source with calculated points R on the target plane (see Fig. 2a). This allows the design of an optical surface which refracts the emitted rays towards the calculated points R (see Fig. 2c).
In order to find an optical element which is capable to fulfil this condition, the radiant intensity distributions $I_L(\theta)$ and $I_S(\theta)$ are discretized into M rays with different propagation angles $\theta_L{}^i$ and $\theta_s{}^i$ respectively, with i = 1, 2,…, M. By this, the points R^i on the target plane can be determined (Fig. 2a). The rays emitted from the source must hit these points to create the desired irradiance distribution on the target plane. The points B^i, which are defining the FF surface, are calculated in a sequential process by determining the surface normal vectors N^i in a way that, according to Snell's law, the rays are refracted towards their corresponding points R^i on the target plane (Fig. 2b). After defining the A^0 B^0 and N^0 as starting parameters the sequential process is composed of three iterative steps (Fig. 2b):

- Determining the position of the point A^i by intersecting the i-th ray with the bottom surface and calculating the change of the propagation direction by Snell's law.
- Determining the position of the Point Bi by intersecting the tangent corresponding to the point B^{i-1} with the actual ray refracted at point A^i
- Calculating the normal vector N^i in B^i in a way that the actual ray refracts towards the point R^i on the target plane.
- In order to create very thin FF lenses, we implemented an additional transformation algorithm directly in the sequential process of calculating the FF curve, which allows us to design flat FF lenses by defining two threshold values which define the minimal and the maximal height of the B^i points. The distance between the bottom surface and the lower threshold value therefore corresponds with the thickness of the thin foil (Fig. 2c) and the distance between the lower and the upper threshold values defines the height of the FF structure. In case that the height of a point Bi drops below the lower threshold value during the sequential process, the height is artificially adjusted and the sequential process is continued with the adjusted point B^i (Fig. 2c). With this measure the calculated FF elements can be restricted to a very flat design, which can be fabricated on a thin foil and enables the use of cost-effective manufacturing methods like grey-scale laser lithography for mastering and roll-to-roll processing for large area manufacturing of the optical elements.
- The determined points A^i and B^i are defining a bottom and a top profile of the FF lens and can be transformed into a three dimensional (3D) object by rotating the profile around the perpendicular z axis for 360°. However in this way only rotationally symmetrical irradiance distributions can be generated on the target plane. In order to extend this concept to irradiance distributions with a rectangular shape the 3D FF object has to be "segmented" into different slices with a constant azimuth step size α.

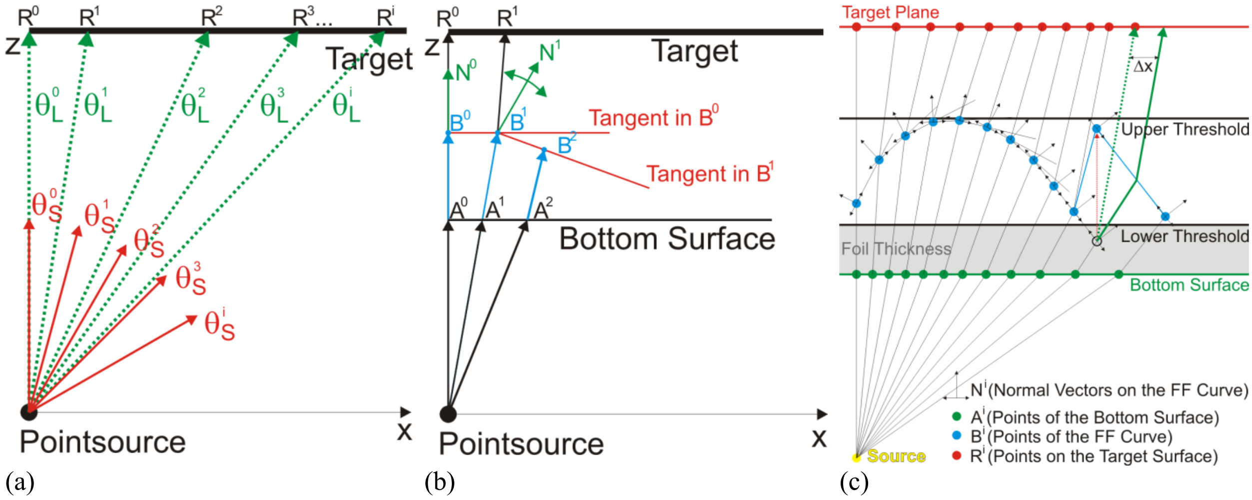


Figure 2: a) Illustration of the discretization of the radiant intensity distribution I_S(□) of the source. b) Scheme of the sequential FF algorithm to calculate the points B^i and A^i, which are determining the top and the bottom curve of the FF element. c) Schematic illustration of the functionality of the implemented transformation algorithm when a point B^i falls below the lower threshold value.

Fig. 3 shows the process for creating such a segmented FF element for a non-rotationally symmetrical irradiance distribution. The shape of the irradiance distribution is divided into different slices. The length of the slices depends on the shape of the irradiance distribution and the number of slices depends on the segmentation angle α. In the next step the FF algorithm is conducted for every slice separately, creating different FF curves for each slice. Rotating these different FF curves around the centre (by the azimuth step size α) allows to generate 3D segments of the FF object. The resulting FF object is composed of these different segments.

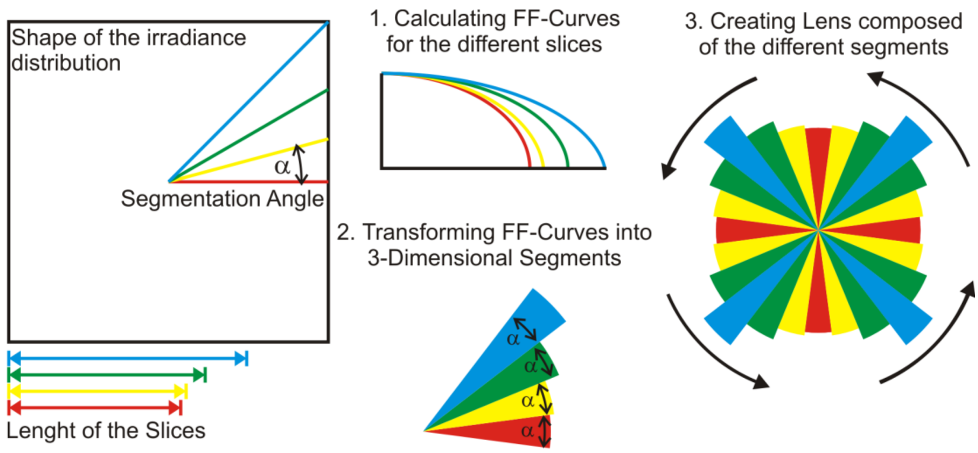


Figure 3: Schematic illustration for creating a 3-dimensional FF element that gives reason for a rectangular irradiance distribution on the target plane.

RESULTS

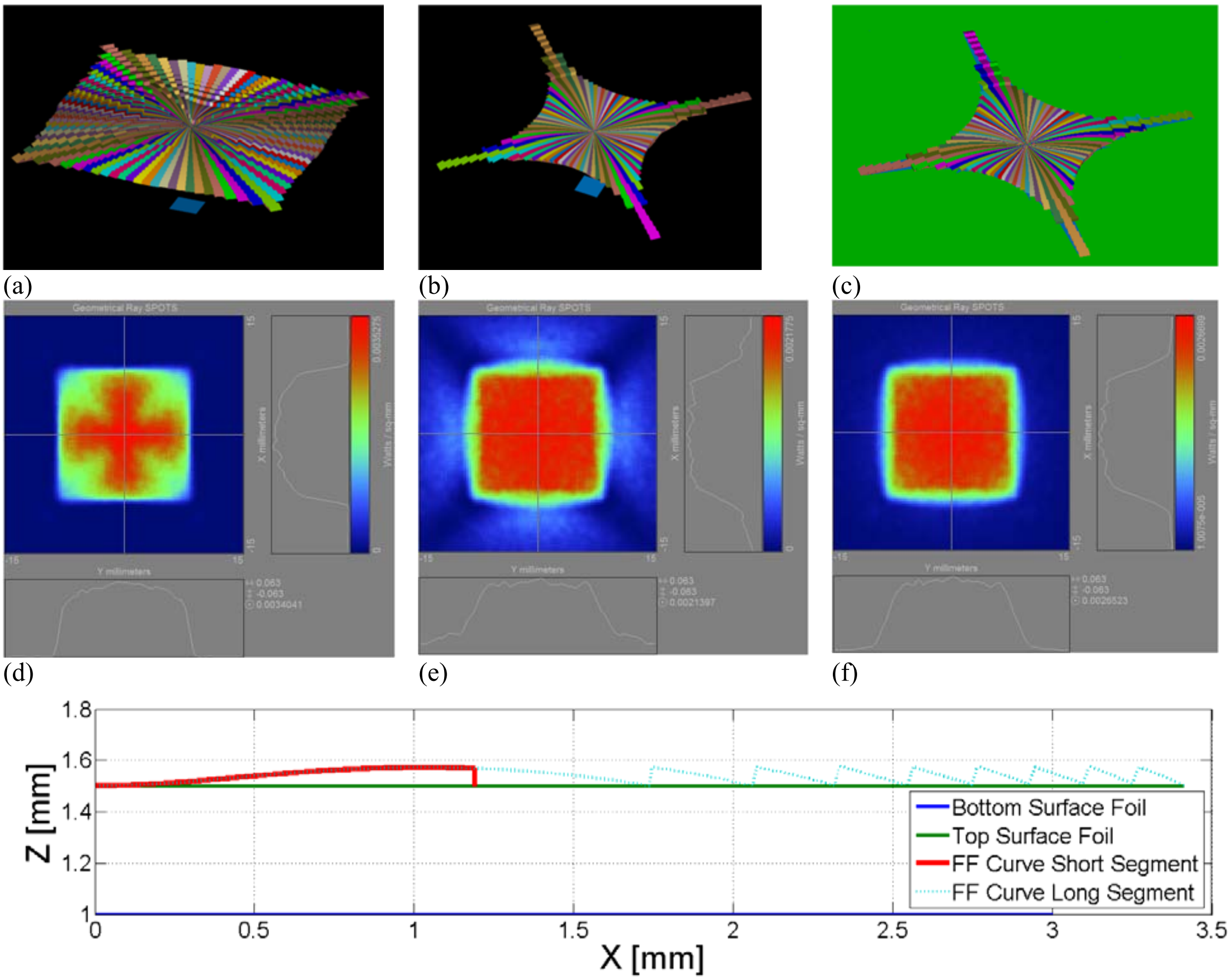
In the following Ray-Tracing (RT) simulation results of different FF elements are presented, which allow to demonstrate the design concepts discussed in section 2.

Fig. 4a, 4b and 4c show top views of flat FF elements that are composed of 98 segments. The design of these FF elements aims on a square shaped irradiance distribution on a target plane that has a distance of 10 mm. As a light source a LED die with a size of 0.5 x 0.5 mm² and a Lambertian radiant intensity distribution is used. The FF elements are assumed to be placed on a 0.5 mm thick foil having a refractive index of 1.517 and a distance of 1 mm between the bottom surface of the foil and the emitting area of the LED die.

Figure 4g shows a cross section of the foil (bottom surface blue line, top surface green line) as well as the calculated FF curves of the shortest (red line) and the longest (dotted blue line) of the segments of the FF element shown in Fig. 4b,c.

Due to the transformation algorithm that limits the height to a predefined value, the segments of the FF elements consist of different numbers of “teeths”. This number again depends on the number of times the curve dropped below the lower threshold value during the sequential calculation process. However, due to the transformation algorithm the maximal thickness of the different segments is not surpassing a height of 75 µm (Fig. 4a,b,c).

The FF algorithm is based on a two dimensional approximation. The individual segments are redistributing the same radiant intensity of the light source on different areas due to the different lengths of the slices, which causes an inhomogeneous irradiance distribution (see Fig. 4d).



(g)

Figure 4: a) 3D Model of a flat segmented FF element (98 segments) designed for generating an irradiance distribution with a square shape on a target plane. d) Corresponding irradiance distribution on the target plane, determined by RT simulations. b) 3D Model of a flat segmented FF element (98 segments) designed for generating a uniform irradiance distribution with a square shape on a target plane. e) Corresponding irradiance distribution on the target plane, determined by RT simulations. c) 3D Model of the flat segmented FF element (98 segments) used in b) with the FF element placed on a diffuser foil. e) Corresponding irradiance distribution on the target plane, determined by RT simulations. g) Cross section of the shortest and the longest segments of the flat segmented FF elements of b) and c).

To encounter for this, the amount of radiant intensity collected by each segment was adjusted in a way that each segment generates the same absolute irradiance value on the target plane (see Fig. 4e). Figure 4e shows the irradiance distributions (determined by RT simulations) on the target plane, generated by the FF element of Fig. 4b. As one can see, due to this correction, the FF element now allows for a uniform irradiance distribution within the target area. However, the amount of radiant intensity which is not collected by the FF elements causes some unwanted intensity distribution outside of the target area (see Fig. 4e), which will affect the neighbouring intensity distributions when using the FF elements in an array.
To overcome also this aspect, the FF element of Fig. 4b is assumed to be placed on a diffuser foil (Fig. 4c) having a Lambertian scattering characteristic in order to redistribute rays which are not refracted at the FF element randomly on the target plane. Directly beneath the FF elements, the foil has no diffusing properties. As one can see from Fig. 4f, which is showing the simulated irradiance distribution on the target plane, the diffuser foil is redistributing the unwanted intensity distribution outside of the target area.

CONCLUSIONS

In this contribution a two dimensional FF approach for calculating thin FF elements for lighting applications, e.g., for the use in direct-lit luminaire boxes, was presented. The proposed FF algorithm allows the calculation of FF elements refracting the radiant intensity of LEDs into uniform irradiance distributions with arbitrary shape. Furthermore a threshold value was included in the calculation algorithm enabling the control of the maximal height of the calculated FF elements.

In this way it was possible to calculate a FF element with a thickness of about 75 µm redistributing the radiant intensity of a 0.5 x 0.5 mm² LED light source into a square shaped irradiance distribution on a target plane in a distance of 10 mm. The low height of these FF optical elements facilitates several low-cost fabrication techniques, e.g., the fabrication by a Roll-to-Roll process.

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Using Adjustment to Evaluate Discomfort Glare

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Abstract— **The study of discomfort glare is widely recognised as starting with Hopkinson. In his experiments, test participants were instructed to observe a scene and adjust the source or background luminance until the scene represented the degree of glare described by four discomfort levels. Results from such experiments based on adjustment tasks were used to develop the glare constant and discomfort glare rating formulae for assessing the occurrence of visual discomfort in buildings. Subsequent studies often reported large inconsistencies between discomfort predicted by these glare formulae and the subjective evaluations given by observers. Although commonly undervalued in glare studies, an understanding of different experimental procedures is fundamental to explain the variability found in many studies and provide useful criticism of the alleged precision of glare models. This paper reviews adjustment tasks, demonstrating potential sources of bias in the settings made by this procedure and suggests recommendations to address the issues raised.**

Index Terms— **Adjustment Task, Discomfort Glare, Glare Index, Methods**

INTRODUCTION

An adjustment task has been used in many studies investigating discomfort glare. In this procedure, observers are required to vary the brightness of either the light source or its background until the observed scene represents a certain predefined threshold of discomfort (e.g. 'Just Uncomfortable' glare). Two bodies of work have used adjustment: they are important because the findings were used to develop the models of discomfort used in lighting design guidance.

First, in Luckiesh and Guth [1], test participants, positioned at the centre of a hemisphere and with a test source located directly in the line of vision, adjusted the source luminance to a point which they judged to be at the borderline between comfort and discomfort (BCD). Using these results, Guth [2] later established a model (Equation 1) for defining the perceived level of discomfort for individual glare sources: the discomfort glare rating (DGR).

$$DGR = 0.5 \cdot (L_s \cdot Q) / (P \cdot F^{0.44}) \tag{1}$$

Where: Ls = source luminance (cd/m^2), Q = source size (sr), P = Guth position index (-), F = field luminance including the glare source (cd/m^2).

Guth's DGR system later became known as the Visual Comfort Probability (VCP) (Equation 2), defined as the number of people who would find an installation acceptable. VCP is calculated by means of an analytical function defined in the lighting handbook of the Illuminating Engineering Society of North America [3].

$$VCP = 297\text{-}110(\log_{10} \cdot DGR) \tag{2}$$

The second body of work using adjustment is that of Hopkinson, with one article [4] widely recognised as the founding study of discomfort glare. Rather than identifying the BCD, Hopkinson instructed test participants to make four glare settings corresponding to four separate degrees of discomfort: 'Just Intolerable', 'Just Uncomfortable', 'Satisfactory', and 'Just not Perceptible'. These four degrees are known as the multiple-criterion scale. Petherbridge and Hopkinson [5] carried out a series of studies to investigate discomfort glare and these results were used to develop the Glare Constant (Equation 3). This formula was later modified to include a logarithmic function that took into account the sensitivity of the visual system and the Guth position index [6]. This equation then became known as the Illuminating Engineering Society Glare Index (IES-GI) [7] (Equation 4).

$$\text{Glare Constant (g)} = (L_s^{1.6} \cdot \omega_s^{0.8}) / (L_b \cdot P^{1.6}) \tag{3}$$

$$\text{IES-GI} = 10\log_{10} \cdot 0.478 \sum (Ls^{1.6} \cdot \omega_s^{0.8}) / (L_b \cdot P^{1.6}) \tag{4}$$

Where: L_{sp} = source luminance (cd/m^2), ω_s = source size (sr), and L_b = background luminance (cd/m^2).

The basic form of the IES-GI was later modified by including the features from the CIE glare system [8] and Hopkinson's glare criteria to become the Unified Glare Rating [9], as recommended in the Society of Light and Lighting Handbook [10].

The adjustment task is clearly of importance because the results gained from experiments based on this procedure have contributed to the development of discomfort glare models. There are, however, reasons to suspect the presence of significant error in findings gained using adjustment tasks. For example, several studies have reported large inconsistencies between subjective evaluations of glare sensation and the values calculated by different glare indices e.g., [11]-[12]-[13]. Indeed, Hopkinson [4] had noted in his original study that there was a very wide spread in adjustment settings made for equal levels of glare sensation, explicitly stating that "*For any one observer, the spread between readings of road brightness for a given degree of glare was of the order of +/- 50 per cent*". Note also that while the DGR (Equation 1) and Glare Constant (Equation 3) contain the same four terms, their exponents have different values.

This article discusses the influence of variations in experiments using an adjustment procedure to show how they may affect the conclusions drawn. These variations include: exposure duration; sequence and anchor effects; stimulus range bias; and, observers' experience (expert and naïve) and their understanding of glare magnitude descriptors.

EXPOSURE DURATION

Traditionally, two different approaches to exposure duration have been used in glare studies. Luckiesh and Guth [1] exposed test participants only momentarily to a small artificial source of glare. In each exposure cycle, the source brightness consisted of three one-second 'on' periods, followed by two one-second 'off' periods. This was then followed by a five-second 'off' period before the next cycle. Luckiesh and Guth stated that, when sources of visual discomfort are present in the observer's field of vision (FOV), test participants would momentarily shift their gaze from the visual task to the glare source. Conversely, Hopkinson [4] used a different approach, presenting a continuous source of glare to his observers. This approach was used because sources of glare in any part of the visual field were considered as continuous, hence having a continuous effect on visual discomfort [14].

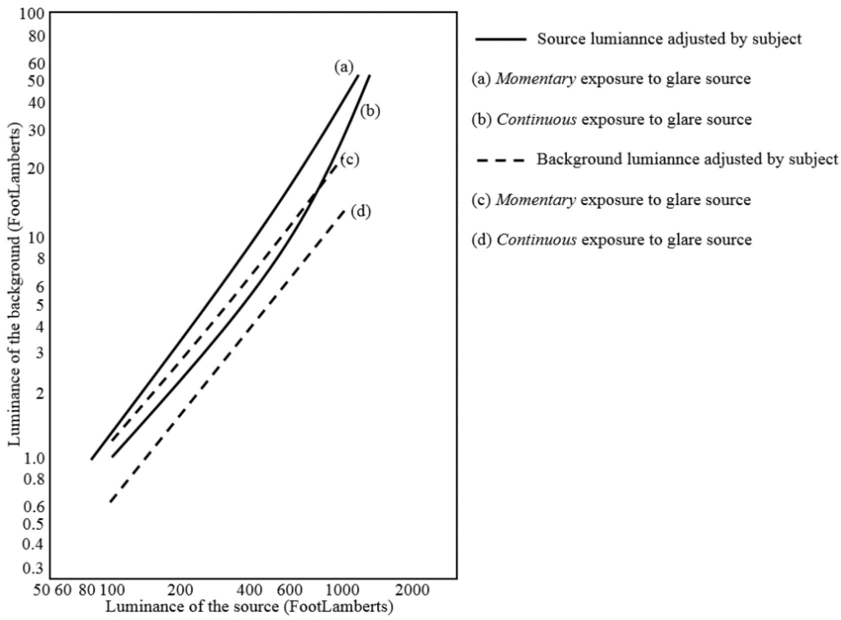

Figure 1. Comparison of glare settings made for momentary and continuous methods of exposure [15].

To investigate whether this matters, Hopkinson [15] set up an experiment that closely matched the design used by Luckiesh and Guth [1]. Three observers were asked to make adjustments to either the background luminance or the source luminance, this being done for both Luckiesh and Guth's (*Momentary*) and Hopkinson's (*Continuous*) methods of glare exposure. Using the BCD criterion, a comparison of the results gained using these two methods suggested that the momentary exposure resulted in higher degrees of variation of background and source luminance than did the continuous exposure (Figure 1). However, it is unclear whether using a larger sample of observers would still produce similar results.

SEQUENCE AND ANCHOR EFFECTS

Hopkinson's adjustments to the four levels of discomfort in the multiple criterion scale were carried out in order of increasing discomfort, from a low (or no) discomfort to a high discomfort level [16]. It is plausible to hypothesise that this procedure could potentially bias the settings. In fact, when a successive setting is made, this will always be to a higher luminance than the previous setting as anything else would be a nonsensical reaction to the increase in magnitude of the glare descriptor. This means that if the first setting was an overestimate, then the second setting is also likely to be. Indeed, Hopkinson noted that "*During the course of an experiment the brightness of the photograph was raised, but was rarely lowered by any large amount*". In addition, the setting provided for one level of discomfort is likely to exert a significant influence (known as an anchor) on the magnitude of the subsequent setting, as it has been demonstrated in the visual preference experiments by Logadóttir *et al.* [17]-[18].

The influence of order bias in an adjustment task can be seen in the results of Pulpitlova & Detkova [19], who used a secondary sequence in addition to Hopkinson's forward-only order of the four glare levels. This secondary sequence was a near-reversal of that used by Hopkinson, other than for the higher two levels of discomfort. In their experiment, the 57 test participants were instructed to make discomfort glare adjustments for both sequences of criteria. The mean luminances are shown in Table I. It can be seen that mean luminances set in the secondary sequence are higher than those obtained in Hopkinson's forward order for all four levels. According to these data, it might be postulated that Hopkinson's results may under-estimate the luminance associated with a certain level of discomfort. Unfortunately, no inferential statistical analysis was provided alongside the data published in the original article by the authors [19].

Given that the sequence in which the glare criteria are evaluated might affect the results, what can be a robust experimental method to avoid biasing the outcomes of a study? One approach might be to use both forward and reverse settings, and then take the means of these settings (for a particular level of discomfort) as the best estimate. An alternative, and likely better option, could be to consider the four levels of discomfort in a randomised order.

Table I. Luminances found by adjustment with settings made to the four degrees of discomfort in different orders [19]

Level of discomfort	**Luminance (cd/m^2)**	
	Hopkinson's forward order (JP, JA, JU, JI)	***Secondary sequence (JU, JI, JA, JP)***
Just perceptible	418	1042
Just acceptable	1330	2189
Just uncomfortable	2836	3110
Just intolerable	4501	5501

STIMULUS RANGE BIAS

The presence of a stimulus range bias implies that the range of the stimulus available to the observer (hence, the range of luminances available with the adjustment controller) has a significant effect on the evaluation that is made. Previous studies of the adjustment procedure have identified a central tendency, specifically suggesting that the reported mean value lies close to the centre of the range of available options [17]-[18]-[20].

Lulla and Bennett [21] evaluated the effect of stimulus range bias using an adjustment task to evaluate discomfort glare using the BCD instead of the multiple criterion scale. Forty observers were assigned to one of two groups, with each group conducting trials with a different stimulus range. Half of the observers adjusted the glare source to a maximum luminance of 300,000 fL (1,027,800 cd/m^2), while for the other half the glare source had a maximum luminance of 30,000 fL (102,780 cd/m^2). The mean BCD in the first case was 26,900 fL (92,159 cd/m^2), in the other it was 3,860 fL (13,224 cd/m^2). These findings demonstrate that settings made using adjustment procedures are influenced by the range of luminances available with the adjustment controller and should not be relied upon for setting an absolute threshold. How to solve this issue? One option could be to use multiple stimulus ranges within an experiment to confirm whether or not range bias is exhibited in the specific context. A second option might be to use adjustment tasks uniquely to establish relative effects but not to identify absolute thresholds.

OBSERVERS' EXPERIENCE

Discomfort glare studies have for long argued whether it would be preferable to use experienced or rather naïve test participants. Luckiesh and Guth [1] recruited fifty observers to take part in their experiment. These participants were chosen without consideration of previous experience, since it was proposed that brightness settings made by an unbiased sample of observers should be more representative of the general population. In one study, Hopkinson [22] compared glare assessments between an experienced and an inexperienced test subject (Figure 2), whereas an experienced subject was defined as "*one who is not only familiar with the technique of making mental assessments under experimental conditions, but who is also familiar with the nature of the problem being investigated*" [22]. For the first few days, the experienced observers set higher luminances than did inexperienced observers, for the same glare threshold. While there is a clear difference, we do not know which is the better data set. Given that the trials took place over 40 days, and assuming that these were repeated settings from the same groups of observers, then by the end even the originally naïve observers should now be considered experienced. Indeed, with time, the difference between the two groups diminishes, with the inexperienced observers tending towards higher luminances and the experienced group tending towards lower luminances. It is he experienced observers who appear to have made the largest change over time, which questions their original definition as being experienced.

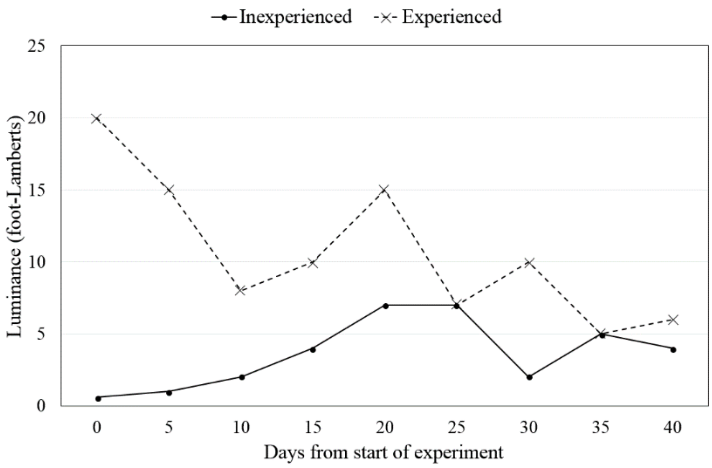

Figure 2. Luminance values for an experienced and an inexperienced observer for criteria of 'just acceptable' criterion under identical conditions over a period of 40 days [22].

Hopkinson [23] proposed that the ability of an observer to make consistent judgements of glare sensation was dependent on their experience with, or technical knowledge of, the experiment, and had previously commented that "*The results naturally showed a very wide spread… The spread of readings was greater for less able or less experienced observers"* [4]. It was for this reason that Hopkinson devised the multiple criterion technique [24], which served as a method to allow participants the opportunity to become familiar with subjective glare evaluations.

Petherbridge and Hopkinson [5] suggested that the multiple-criterion technique "*gives the subject greater confidence in making his judgement*". On occasions when his observers were unable to provide consistent glare settings, Hopkinson would often discard this unfavourable data. This may have given the impression of a stronger association between subjective glare evaluations and calculated glare index. The multiple-criterion technique also "*employs a number of cross checks which assist in achieving a satisfactory approach*" [5]. However, they give no evidence to support the claim of greater confidence and do not reveal the nature nor the results of the cross checks. Due to these reasons, only six observers were selected during experiments carried out for development of the glare constant. The authors explained that "*More observers were originally available, but some had to be rejected as the experiment proceeded because of their inability to make consistent appraisals under constant conditions*" [5]. In essence, Hopkinson's sampling technique seems to suggest that the data collected were not representative of the wider population.

INTERPRETING GLARE SCALE DESCRIPTORS

Since the introduction of the Hopkinson's multiple-criterion scale [4], several modifications have been made to its four levels. Osterhaus and Bailey [25], for example, modified the thresholds into absolute benchmarks: Intolerable, Disturbing, Noticeable, and Imperceptible. One clear difference with Hopkinson is the absence of the word 'just', which implies that the sensation lies at the borderline between absolute thresholds. To help clarify the meaning of their thresholds, Osterhaus and Bailey [25] linked time-span descriptors to glare criteria. These were extended descriptions giving a corresponding amount of time an observer would be able to tolerate a certain degree of glare sensation (e.g., just noticeable glare corresponds to a sensation that can be tolerated for approximately 15-30 minutes [26]).

It is likely that the discomfort magnitude descriptors are not equally well understood. MacGowan [27] stated that "I have found a persistent confusion over the meaning of RG Hopkinson's multiple-criterion scale steps". Akashi et al. [28] reported that "Some observers complained of difficulty in distinguishing between 'just imperceptible' and 'perceptible". Tuaycharoen and Tregenza [13] excluded the criteria of just perceptible, since they found that there was no difference with the criteria of just acceptable. Kent et al. [11] reported that, subjects often expressed their difficulty in understanding the criteria of just perceptible glare and would often asked for further clarification.

This matters because it affects the accuracy and precision of settings made for a given level of discomfort. If naïve observers do not share the same understanding of a descriptor, this will increase the variance amongst the settings (hence affecting precision): if the observers do not share the same understanding as the experimenter this may lead them to target a different objective than expected (hence affecting accuracy). Confusion over language has been demonstrated in studies of brightness and visual clarity [29]. To counter this possibility, it would be desirable for experiments to include some means for confirming understanding of the meaning of the glare descriptors. For example, asking, after completion of an experiment, for participants to describe in their own words the meaning of the criteria.

RECOMMENDATIONS

This brief article has drawn attention to some of the problems that should be expected when using an adjustment procedure to evaluate discomfort due to glare. This is important because adjustment tasks have been widely used in glare experiments, contributing to the development of two fundamental glare formulae: the glare constant and the DGR. There are two symptoms of these problems: first, that many studies have noted a large variance in responses; second, that the experiments on which these glare formulae were derived did not lead to the same empirical function for discomfort glare. Taking evidence from the literature, this article has shown that: a shorter duration of observation led to greater variance of results; anchoring and stimulus range bias affect the estimate of absolute levels of luminance for a given level of discomfort sensation; and, naïve and expert observers may provide different evaluations, with one cause of difference being their interpretation of the meaning of the descriptors of discomfort magnitude.

In future experimental work, the following steps are suggested as best practice:

1. When using an adjustment task with Hopkinson's multiple-criterion scale, the criteria of glare ratings should be randomised to avoid unwanted sequencing effects.
2. Adopt both low and high anchor points before the start of successive trials, using the mean setting from both anchors as a best estimate of the desired setting.
3. Provide a description of the meaning of each glare criterion (this was done in Hopkinson's original study [4]-[5] but does not appear to have been done in many subsequent works) and check that the observer understand this. One approach is to link each criterion to time-span descriptors corresponding to the length of time an observer could potentially tolerate the glare source.
4. Use two or more independent methods to evaluate the same set of conditions. Another widely used procedure is category rating: observers have no interaction with the luminous conditions, but are instructed to evaluate a fixed scene by allocating it to one of several categories that present an alleged rank order of discomfort due to glare [30].

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Color Characteristics of Two-Crystal Leds for Dynamic Lighting

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***Abstract*— Light sources for dynamic lighting require certain level of color rendering for the whole range of correlated color temperatures. There were investigates three combinations of LEDs based of two phosphor LEDs. Color rendering indices (CRI) and color quality scale (CQS) of two-crystal LEDs were calculated. Results showed that it is possible to obtain dynamic white light with high color rendering according to both methods (CRI and CQS). It is advisable to calculate properties of LEDs before implementation because not every random combination of two LEDs will provide high color rendering.**

***Index Terms*-- color rendering, dynamic lighting, LED**

I. INTRODUCTION

Nowadays systems of dynamic lighting become more and more popular. Their distinguishing feature is the function of changing of correlated color temperature (CCT) and luminous flux independently from each other. The most appropriate sources of light for such systems are light-emitting diodes [1]. They let easily adjust a luminous flux in a wide range. However, for implementation of correlated color temperature control it is necessary to use several light-emitting diodes (LEDs) with different color characteristics. One of the most common solution is a combination of two phosphor LEDs where one of them has a warm white light (low CCT) and another one has a cool white light (high CCT). This combination is relatively easy and cheap for realization but has some features. First of them is linked with different spectra for each CCT. Differences in spectral distribution lead to changes in color rendering. Thus, light source for dynamic lighting can’t be fully characterized by the properties of each of the two LEDs. That is why the research of characteristics of such LEDs is an actual task.

CALCULATIONS AND DISCUSSION

There were carried out calculations on the basis of three combinations of LEDs: A+B, C+D, E+F. Each pair consists of one LED with warm white light and one LED with cool light. Spectra of investigated LEDs are shown in Fig. 1.

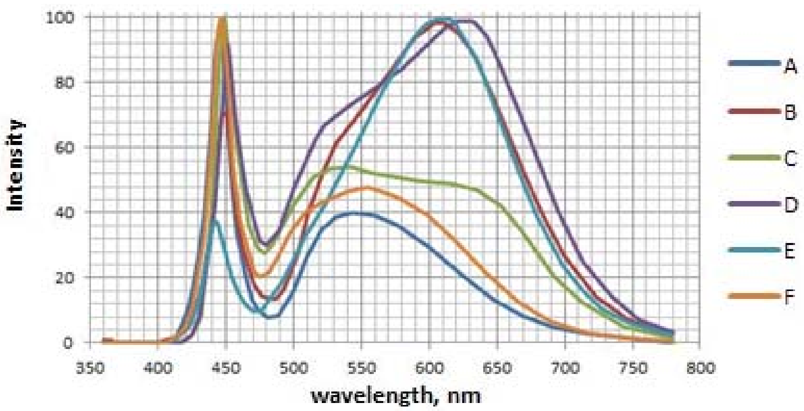

Figure 1. Input spectra of LEDs.

For each combination there were calculated implementable CCTs and color rendering. Color rendering were calculated due to two methods: color rendering index (Ra) and color quality scale (Qa).

Results of calculations are given in Table 1. It contains values of Ra and Q for each combination depending on CCT.

TABLE 1. Value color rendering index (Ra) and color quality scale (Qa) for different CCTs.

Combination LEDs	**Value Ra and Qa**						
A+B	***CCT, K***	3100	3500	4000	5000	5700	6500
	Ra	81	77	74	74	69	71
	Qa	76	74	75	77	75	74
C+D	***CCT, K***	-	3500	4000	5000	5200	-
	Ra	-	92	94	92	93	-
	Qa	-	91	95	92	94	-
E+F	***CCT, K***	3100	3500	4000	5000	5700	6500
	Ra	78	83	83	83	82	80
	Qa	78	77	79	79	77	74

Calculations showed that one of problems regarding such type of LEDs is a limited range of CCT. While in RGB or RGBW LEDs there are no borders of obtained CCT and color itself, two-crystal phosphor LEDs are limited by own temperature of each crystal. Thus, combination C+D doesn't allow obtaining CCT lower than 3500 K or higher than 5200 K.

Another issue is Ra and Qa. Dependence of Ra and Qa on CCT for combination A+B is given in Fig.2, for combination C+D is in Fig. 3 and for combination E+F is in Fig. 4.Generally, it is important to remember that quality of color rendering is not a constant on the whole range of CCT. Due to results, quality of color rendering is varied randomly from Ra/Qa of the crystal with the lowest value of color rendering to Ra/Qa of the crystal with the highest value of color rendering. However, the case of combination A+B differs because Ra for CCT=5700 K is lower than Ra of A or B separately.

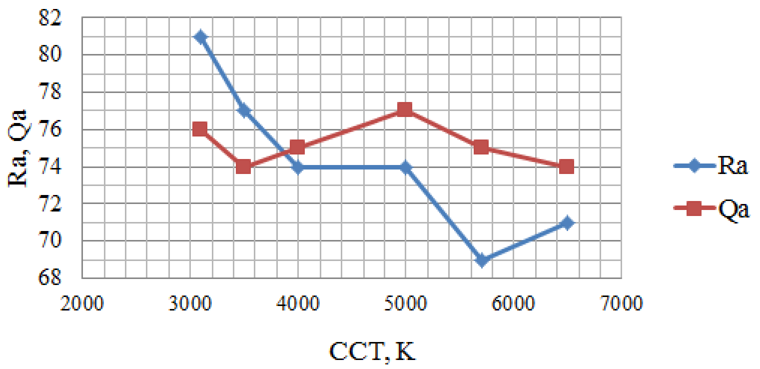

Figure 2. Ra and Qa as a function of CCT for combination A+B.

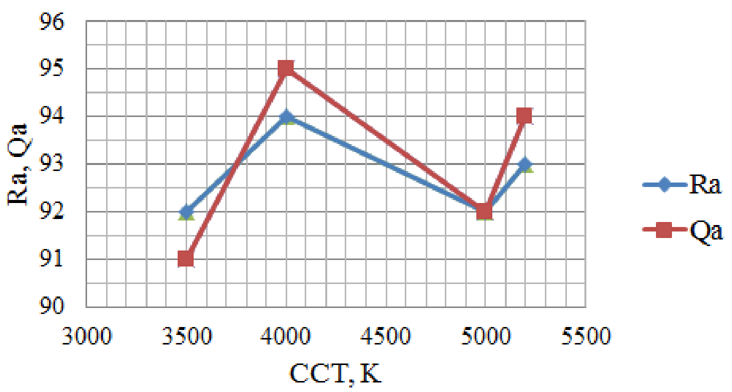

Figure 3. Ra and Qa as a function of CCT for combination C+D.

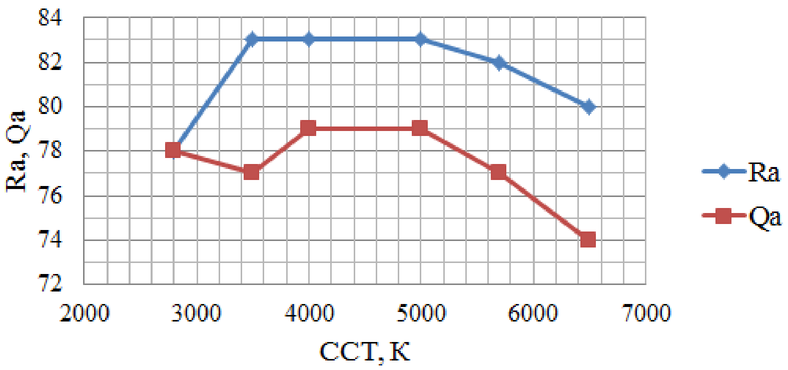

Figure 4. Ra and Qa as a function of CCT for combination E+F.

Conclusion

To sum up, it is important to notice that these features don't make the using of two-crystal LEDs impossible or inexpedient. Such issues should be taken into account while designing the lighting device. Also it is necessary to make calculations or measurements to conclude if a certain combination of LEDs is appropriate for implementation. Correctly selected combination of LEDs allows to achieve high quality color for the whole range of CCTs that is important for dynamic lighting.

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Research Progress on AlGaN-based Ultraviolet Light Emitters

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***Abstract*—We report the AlN film grown by low pressure metal-organic chemical vapor deposition (LP-MOCVD) on nano-patterned sapphire substrates (NPSS) prepared through nanoimprint lithography technique. The X-ray rocking curves (XRCs) of AlN on NPSS show lower dislocation densities than that on flat sapphire substrate (FSS), while the Raman spectra prove the relaxation of strain state in AlN on NPSS. AlGaN-based ultraviolet light-emitting diodes (UV LEDs) of emission wavelength around 264 nm were further fabricated on NPSS-AlN. The electroluminescence (EL) results reveal that the peak emission wavelength has a small blue-shift for UV LED on NPSS compared with that of DUV LED on FSS, while the illumination intensity of the former is much higher than that of the latter. These are attributed to the relaxation of strain, higher internal quantum efficiency and higher light extraction efficiency brought by NPSS.**

***Index Terms*--AlGaN, light-emitting diodes, ultraviolet, nano-pattern, color rendering index**

I.INTRODUCTION

High quality true white light is needed for lots of applications, such as lighting for jewelry, medical lighting, lighting for showcase. One important factor of white lighting is the color rendering index (CRI). For high quality white light, CRI as high as 90 is necessary. Nowadays light emitting diodes (LEDs) serve as the core technology for solid state light. Most of the white LEDs have been fabricated by combining Gallium Nitride (GaN) based blue LEDs chips and yellow phosphors. These LEDs suffers obviously from low CRI of ~70. One solution for this problem is to use ultraviolet LEDs with red-green-blue (RGB) phosphor combinations [1]. There were already reports that white LEDs using deep ultraviolet (UV) LEDs (~280 nm) as the pumping source achieved CRI as high as 90. Therefore high-efficiency UV LEDs could be promising core devices for efficient high quality white lighting [2]. By adjusting the Al composition x in $Al_xGa_{1-x}N$ alloy, the emitting wavelength of AlGaN material could be tuning from 210 nm to 365 nm [3]. This makes AlGaN alloy an ideal material for developing UV LEDs. Here we report our recent research progress on boosting the efficiency of AlGaN-based UV LEDs.

AlGaN-based UV LEDs have been mainly fabricated on sapphire substrates to the present. So UV LEDs always suffer from high threading dislocation density (TDD) and stress for the remarkable lattice mismatch between the sapphire and Al(Ga)N layers[4, 5]. As a consequence, the internal quantum efficiency of the devices and the efficiency of UV emitters are limited. For these issues, Epitaxial lateral overgrowth (ELOG) of AlN on nano-patterned sapphire substrates (NPSS) were used to improve the epitaxial material quality to improve the efficiency of UV LEDs.

II.EXPERIMENT

The nanoimprint lithography technology (NIL) was used to fabricate nano-patterned sapphire substrate, as shown in Fig. 1(a). First, the SiO_2 layer with 200nm thickness was deposited on sapphire substrate by plasma enhanced chemical vapor depositon (PECVD). And then the 300-nm nano-imprint resist was spincoated onto the SiO_2 layer. After that, the hexagonal hole array was transferred to the resist from the printing mold by nano-imprint lithography and followed by inductively coupled plasma (ICP) etching SiO_2. Finally, the sapphire substrate was treated by a mixture of H_2SO_4 and H_3PO_4 solution for 10 min, and SiO_2 film was finally removed by the HF buffer solution (BOE). The size of the cones is about 400 nm, and the period is about 1μm as illustrated in inset of Fig. 1(b).

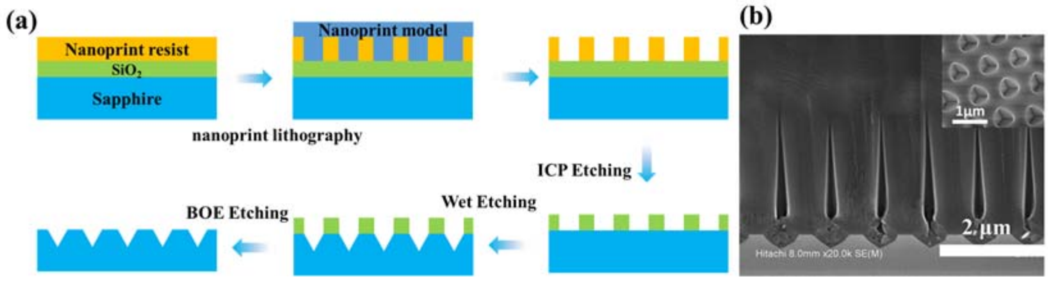

Figure 26. (a)Schemetic of process flow to fabricate NPSS by NIL (b) cross-section SEM of AlN on NPSS (inset is NPSS)

The UV LED`s epitaxial structure was grown by the low-pressure metal organic chemical vapor deposition (LP-MOCVD) technique. Trmiethylaluminum (TMAl), trimethylgallium (TMGa) and amamonia (NH_3) were as aluminum, gallium, and nitrogen sources, respectively [6]. Cp_2Mg and SiH_4 were as the n- and p-type impurities, and hydrogen was used as the gas carrier. First, an AlN buffer layer with thickness of 50 nm was grown on NPSS at 550 °C and followed by around 4 μm AlN at high temperature of 1250°C. The UV LED's structure was further grown on the AlN/NPSS and on common 1um-thick AlN/FSS, including a 20-period AlN/$Al_{0.7}Ga_{0.3}N$ superlattice, a 3 μm n-$Al_{0.7}Ga_{0.3}N$ contact layer, 5-period $Al_{0.65}Ga_{0.35}N/Al_{0.5}Ga_{0.5}N$ quantum-wells, a p-$Al_{0.75}Ga_{0.35}N$ electron-blocking layer, a 50 nm p-AlGaN cladding layer and a 100 nm p-GaN contact layer. The details about epitaxial growth were precisely describe in [7]. UV LED devices were fabricated with the chip size of 500 μm×500 μm by standard LED process, including photolithography, ICP etching, e-beam evaporation, etc. Ti/Al/Ti/Au metal stacks were deposited on the n-AlGaN as the n-type contact and Ni/Au stacks were used as the p-type contact[7]. The schematic diagram for AlGaN-based UV LEDs as shown in Fig. 3(b) .

III.DISCUSSION

Fully coalesced AlN layers were achieved by overgrowth on the NPSS, as presented in Fig. 2 (a). The X-ray rocking curves (XRCs) of AlN film on NPSS and FSS are illustrated in Fig. 3 (a). The full width at half-maximum (FWHM) values of (0002) reflections for AlN films on two different substrates are 84.715 arcsec and 237.5 arcsec, respectively; while the FWHM of the (10-12) reflections are 390.11 arcsec and 694.65 arcsec, respectively. The results mean the AlN film grown on NPSS has much better crystalline quality than the 1um AlN grown on FSS. This is mainly because of the decrease of the threading dislocations (TDD) in the AlN on NPSS. The TDDs in the vicnity of the nano-pattern void bend and depart the vertical growth direction and then terminate at the viods` sidewalls with the lateral overgrowth of AlN as presented in reference [8]-[11], and thus the total TDD were decreased in AlN/NPSS. The higher crytal quality of AlN will benefit the AlGaN layers thereon and futher enhance the internal quantum efficiency (IQE) of LED [12].

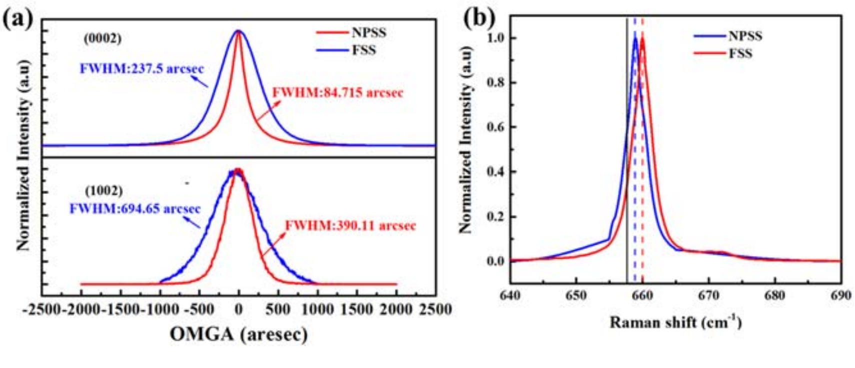

Figure 27. (a) X-ray rocking curves (XRCs) of (0002) and (10-12) diffractions and (b) Raman spectrum for the AlN films grown on the NPSS and FSS.

Fig. 2 (b) shows the Raman spectrum of the E2H phnon mode located at 658.9 cm^{-1} and 660.2 cm^{-1} for AlN layer grown on NPSS and FSS, respectively. Compared to stree-free frequency of 657.4 cm^{-1} [13] illustrated as the black vertical line in Fig. 2 (b), the Raman peak of E_2^H phnon mode of AlN/NPSS shifts 1.5 cm^{-1} which is smaller than that of AlN grown on FSS. The result shows that the AlN epitaxial stress could be partially relieved by the air voids near the nano-patterns as described in reference [13, 14]. The strain relaxation of AlN template will release the stresses of MQWs and then reduce quantum-confined stark effect to improve the IQE of LEDs. This could help promote the performance of UV LEDs[2].

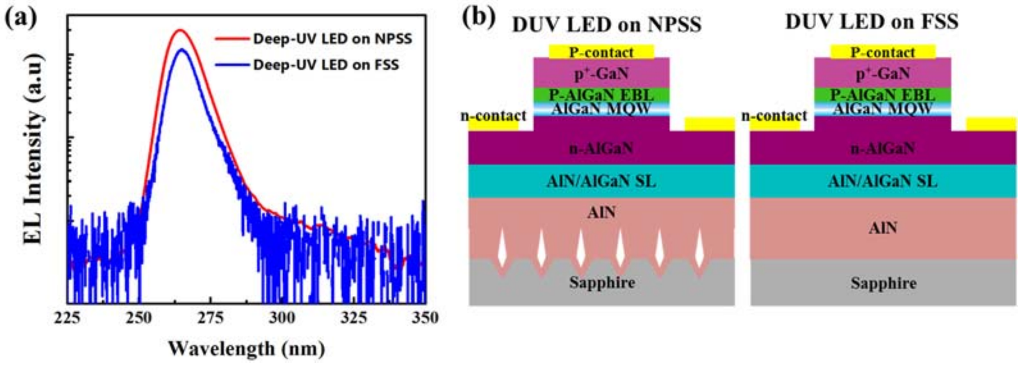

Figure 28. (a) EL spectrum of the UV LEDs grown on NPSS and FSS (b) schematic of the UV LEDs grown on NPSS and FSS

In Fig. 3(a) , the electroluminescence (EL) test showed that the peak emissions wavelength are 264 nm and 264.2nm at typical driving current of 20 mA for UV LEDs grown on NPSS and FSS, respectively. A small blue-shift of wavelength appears for UV LED on NPSS compared with UV LED on FSS, which could benefit from the relaxtion of AlN epitaxial stress. Furthermore, the EL intensity of LED on NPSS is higher than that on FSS that may be caused by the higher IQE and higher light extraction efficiency (LEE). We believe the higer LEE results from the enhancement of the light scattering at AlN/NPSS interface compared with that at AlN/FSS interface and decreasing the total internal reflection and the absorption in the p-GaN layer[10]. FDTD simulation results proves that the light extraction efficiency of UV LED was effectively enhanced by more than 50% with the nano-scale pattern of the sapphire substrates.

IV.CONCLUSION

In conclusion, we have demonstrated the epitaxial growth of high crystal quality AlN film and high performance AlGaN-based UV LEDs on NPSS by LP-MOCVD. The NPSS was fabricated by NIL and wet ething. The AlN film grown on NPSS has shown strain relaxation and high material quality compared to that on FSS as revealed by the results of XRD and Raman spectrum, respectively. The AlGaN-based UV LEDs on NPSS have a 264 nm peak emission wavelength, smaller than that of LEDs on FSS, which is due to the relaxtion of strain in epitaxial layer. The emission intensity of NPSS based UV LEDs is higher than that of FSS based UV LEDs for their high IQE caused by better material quality and relaxition of strain. Therefore, NPSS based UV LEDs proves a viable way for developing efficent solid state UV emitters.

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LED and HPS Luminaires in Russian Greenhouses

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***Abstract*—The report provides a brief analysis of the situation on the market of greenhouse lighting in Russia. The possibility of LEDs allow solve the problem of optimizing the range of PAR light distribution and irradiance levels for specific types of plants for greenhouses. The paper considers the photo-biological studies carried out jointly by lighting engineers and biologists.**

***Index Terms*— greenhouse cultivation, LED irradiators, PAR, photo-biological research, PPFD.**

LIGHING OF GREENHOUSES NOW.

Currently, the greenhouse plant production in Russia is at the stage of dynamic development and implementation of new technologies. The area of heated greenhouses is about 2300 hectares and we expect that by 2020 there will be about 1000 hectares more of modern greenhouses. On approximately 20% of the area all the year round vegetable production is organized (cucumber, tomato) and for this purpose artificial HPS lighting is used during cold and “dark” season. Cucumbers occupy ca. 40% of the area in the greenhouses with supplementary artificial lighting, tomato – 10%, lettuce – 14%, flowers – 36%. Specific electric power in the greenhouse is 150÷250 W/m^2 (for cucumbers) depending on the climatic zone, the illuminance level varies within the range 18÷30 klx and the duration of artificial lighting is up to 5000 hours per year. The total number of lamps installed in greenhouses (mostly 400, 600 and 1000 W) exceeds 1 million units and by 2020 it is expected to double. In Figure 1 shows the amount of greenhouses with artificial lighting for the past 6 years. As you can see 2017 is expected to be a record.

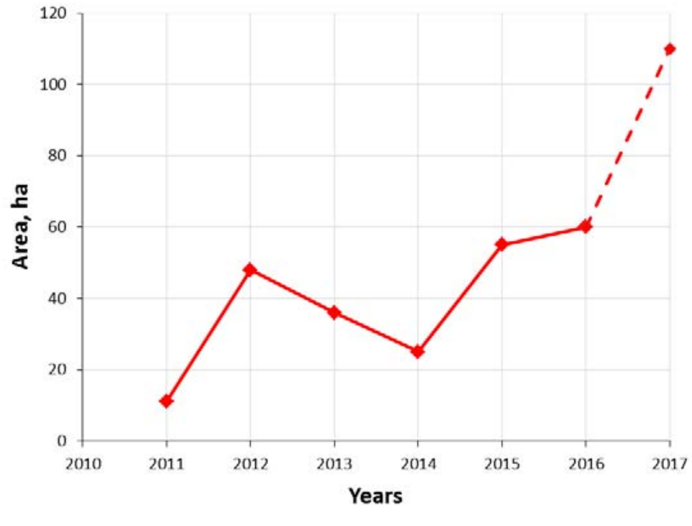


Figure 1. Construction of new greenhouses with artificial lighting

Nowadays, a traditional greenhouse luminaire layout – toplighting – is widely used, but also an additional inter-row lighting (interlighting) comes into use in some of them.

In recent years, LED luminaires come unto use in three areas: toplighting systems for lettuce growing, interlighting systems for cucumber and tomato production, and multitier City Farm installations. Only according to 2017 projects, over 100 thousand of LED lamps will be installed in greenhouses.

LED AND OPTIMIZATION OF LIGHTING PARAMETERS

The arrival of LEDs has stimulated photo-biological studies to optimize the spectrum and radiant for plants. Previously, VNISI was involved in detailed studies in phytotron using selective Metal Halide Lamp (MHL) [1], [2], as a result were formulated requirements for the favorable range for lighting cultivation of cucumber $E_B : E_G : E_R = (15÷20)\% : (35÷45)\% : (40÷45)\%$ and tomatoes $E_B : E_G : E_R = (10÷20)\% : (15÷20)\% : (60÷75)\%$, where E_B, E_G, E_R – correlation on irradiance of plants in "blue" (400÷500 nm), «green» (500÷600 nm) and «red» (600÷700 nm) in PAR ranges by total level E=100 W/m^2.

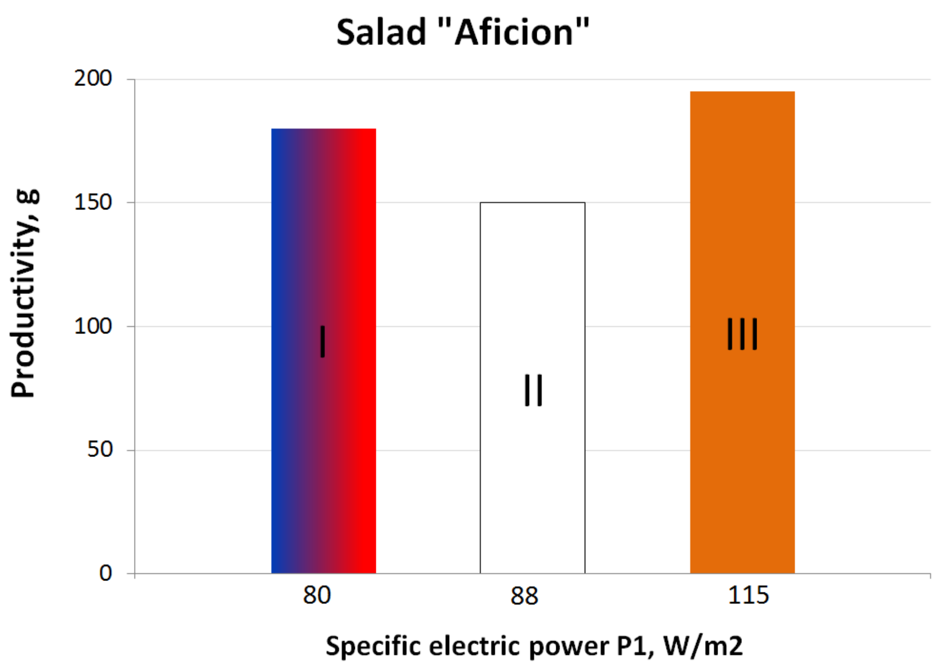
It is well known that various plant species need different spectral and irradiation regimes. We strive to use the unique capabilities of LEDs to optimize these basic LED irradiators parameters and propose new technologies for greenhouse lighting.

Now we are carrying out photo-biological experiments in the phytotron of the leading Russian agrarian institution – Moscow Timiryazev Agricultural Academy – that will allow us to determine the impact of main PAR ranges not only on the productivity, but also on the synthesis of the most important biochemical compounds that are critical for the nutritional value of plants. The distinctive feature of these studies is a variation of photon photosynthetic irradiance (PPFD) levels for each spectral regime.

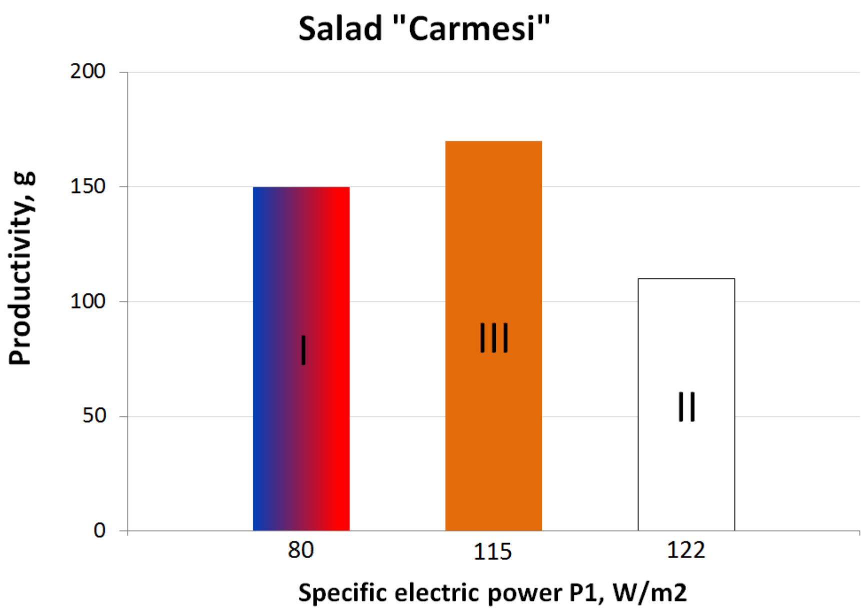
In the first phase, the effect of 4 PAR ranges is studied: "blue" ($\Delta\ \lambda$ = 440 ÷ 475 nm), "green" ($\Delta\ \lambda$ = 500 ÷ 560 nm), "amber" ($\Delta\ \lambda$ = 560 ÷ 600 nm), and "red" ($\Delta\ \lambda$ = 630 ÷ 670 nm). As the control, white LED lamps with CCT = 2500 and 5000 K, as well as the standard HPS greenhouse luminaire are used. Thus, for two plant species, lettuce and basil, "rough" action spectra in response to different irradiance levels are obtained.

On the next phase, the effects of different ratios of radiation in the most effective ranges of headlights on plant growth and development will be studied. The first obtained data will be listed at the poster booth.

Previously, on the basis of studies carried out with two lettuce cultivars in 2014-2015, we observed the possibility of the electricity consumption reduction with LED lighting technology by 30 ÷ 35% as compared to HPS lamps that are currently used for growing lettuce in greenhouses [3] (Figure 2).



a)



b)

Figure 2. Productivity of lettuce to different variants of the spectrum
I – «red-blue» LED irradiator, *II* – «white» LED irradiator, *III* – HPS irradiator

Now, we are looking forward for the possibility of obtaining a broader set of data supporting the usefulness of experimental determination of the spectral and irradiance level requirements for the specific plants and cultivars.

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Simplified Model of Spectral Distribution of Daylight in Interior of the Building

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***Abstract*— The environment inside of buildings is lighted by daylight and it changes through the day. Introducing the distribution of luminance on the sky in ISO 15469:2004 is possible work with parameters of daylight. Finding the spectral composition in interior at any point in space will contribute just on the impact of indoor environment on human physiology. The proposal will also contribute to artificial light, because it is found the desired spectral composition, which erases the differences between the internal and external environment. This paper presents the basis of current knowledge, a simple method for determination of the spectral composition of the internal environment of buildings based on the current model Sky types. Contribution compares the current computing software with a model of the spectral composition of the qualitative parameters.**

***Index Terms*-- Daylight, Spectral power distribution, Lighting calculation tools**

INTRODUCTION

Each building structure which is designed undergoes through various processes in which different stages of construction objects that is dealt with engineers. In the design shall be calculated in areas with daylight openings for direct access. In the early proposal solves these issues of building physics what provides the basis for building, position of the building, shielding objects i.e. what space will be illuminated. In partnership with lighting designers is reached consensus between natural source - daylight and adequate artificial lighting. The essence of daylight is to create the conditions for staying healthy people and good vision conditions for observers to recognise objects in order to avoid premature and excessive exertion and to avoid possible injury. In the interior of the buildings users are advised ensure a clear view of daylight openings in the environment. In some standards define the requirements for sufficient visibility e.g. new European standard. At the same time care must be taken to optimise the performance and energy consumption of all types. Obligation of designers is to use daylight as much as possible in the design of lighting systems so that the time of minimum the required intensity on the working plane complementary in combination with artificial lighting. Energy saving is recommended to use the maximum extent of possible using of daylight in the interior of the building. An essential factor that is gaining prominence in the lighting design is the quality of the light environment. The future will show not only the quantitative parameters such as illuminance, luminance and their proportional quantities but also what type of spectral composition of light is distributed in the enviroment or what spectrum of the light is present when combination of the artificial and daylight is assumed in the considered environment. This spectral composition of the light can be described as qualitative parameter of the interior.

The environment inside of the buildings is illuminated by daylight. It changes continuosly during the day. Introducing the distribution of luminance on the sky in the standard ISO 15469:2004 is possible work with parameters of daylight. Finding the spectral composition in interior at any point in space will contribute just on the impact of indoor environment on human physiology. The proposal will also contribute to artificial light, because it is found the desired spectral composition, which erases the differences between the internal and external environment. Nowadays the calculations of lighting parameters are carried out by using various simulations software. Choosing calculation algorithm is not possible but only allowed method of calculation e.g. point method based on illuminance, flow method based on luminous flux, etc. Computer software work in radiometric variables, i.e. radiated energy is transferred into the space and it is evaluated. Additional factors would be the calculation of the spectral plane, which allows absolute extract all parameters needed for lighting design.

CALCULATION ALGORITHMS OF DAYLIGHT

Lighting calculations are nowadays carried out using computational software. Choosing calculation algorithm is not possible, but only allowed method of calculation, for example. point method based on illuminance, flow method based on , etc.. Programs work in radiometric variables, i.e. radiated energy is transferred into the space and it is evaluated. Additional factors would be the calculation of the spectral plane, which allows absolute extract all parameters needed for lighting project.

Light emitted from the light source or luminaire, creates direct illuminations on surface. If the impact area is the part of the field surfaces, as walls, ceiling, floor, then the light is reflected and absorbed part. This issue is linked to interreflection light in indoors. Algorithms for the calculation of the light distribution are based on the physic equations. In the calculation appear two factors: direct light falling on a surface which is required calculate for different types of LIDC. Interior light is calculated by the square law of light, and is so well known point method. The second factor is the calculation of the internal interreflection in inside of luminaire and area of lighting. It is only the chosen calculation algorithm, how many times iteration will be used. Depending on this calculation will be result more or less accurate. We identify in basic the three computational methods, (Figure. 1) , raytraicing, radiosity and photon maps.

Raytraicing is called algorithm which depends on the direction of light perception. Light rays belong to the direction from which they come. Rays are traced from the light source - forward tracing, or from the eye of the observer - backward tracing, eventually, from both directions. The method is mainly used in the visualization, the calculated light effect from direct light, reflections and mirror surfaces. In this algorithm are limitations as multiple diffuse reflection or indirect effects luminaire.

Radiosity algorithm is dependent on the scene. This is a similar technique as heat transfer. The model is separated on the surface of the surface area. Every surface radiometric is evaluated separately, independently of view. Radiosity algorithm has a problem with the calculation of specular reflection and refraction, but it to constantly improve. The algorithm is mainly used for lighting calculations.

Algorithm of photon maps has got integrating nature, which is used for the global lighting system. The model is dependent on the scene, which uses a number of advantages from previous algorithms. The algorithm is based on any energy - photons that are emitted to the surface, wherein the surface share them with environment and form them, and create i.e. caustic. Result is in created of light rays reflected or crank on irregular area or object. Physical effect has permittivity materials that interact with the light. It is used for simulation scenarios of phenomena light, while light is also behind the objects, outside the view of the observer. [1] [2]

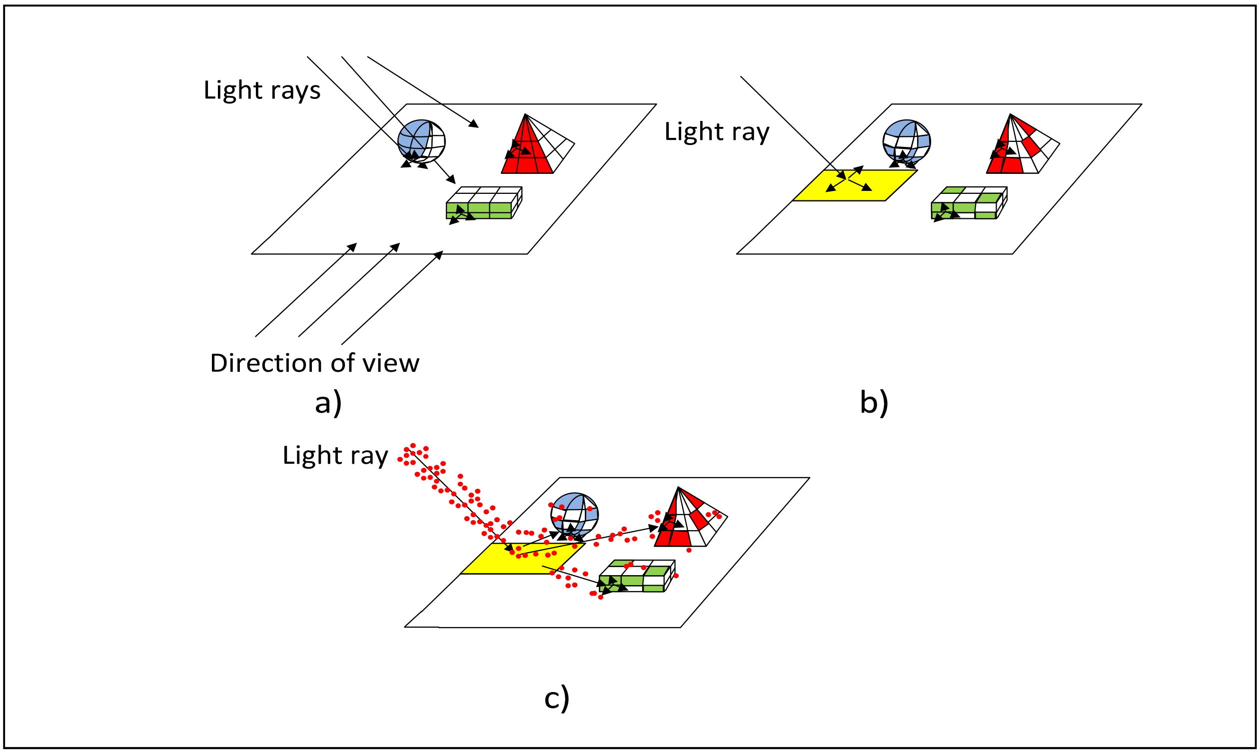

Figure 1. Algorithms for lighting calculation a) raytracing b) radiosity c) photon maps [1]

SIMPLE SPECTRAL MODEL OF SPECTRAL DISTRIBUTION IN INTERIOR

Daylight in the interior is generally composed of three components: the sky component E_z, the reflected component E_j, interior and exterior reflected component E_o, fig. 2. The sum of these components can be model spatial spectral composition of light in the interior too, [2]. Exterior component is particularly important in built-up areas, where the energy depends on surrounding objects, but together may be become a reduction in the sky on hemisphere. Simplified mathematical model provides a solution for calculation of the daylight from various sky types, equation (1), [3][4]. Model includes two components for the sky and for the interior. The calculation is used only for illuminance on a selected area in the interior below overcast sky. Sky ingredient in this relationship is selectively represented as a direct component and interior component is determined by the reflectance of light incidence through the transfer market area in the interior, without the direct beam.

Calculation is extended to spectral transmission power over the wavelength range 380 nm to 780 nm. Model of spreading the spectral composition of the interior has shape.

$$E_i(\lambda)A_i = \sum_{f=1}^{m} \tau(\lambda)L(\lambda)\,(\alpha,\varphi)A_o^{\,2}\cos(\theta_i)\,.\cos(\theta_f) + \sum_{j=1}^{m+n} E_i\,(\lambda)\rho_j(\lambda)A_j^{\,2}\cos(\theta_i)\,.\cos(\theta_f) \qquad (1)$$

where Ei(λ) represents the weighted spectral irradiance on the surface of Ai, τ(λ) is the spectral factor of transmission light through the glazed window system, L(λ) is the spectral radiance of the element depending on the elevation and azimuthal angle, AO is window area, ρj(λ) is the spectral reflectance of internal surfaces of the interior, Ai is the contents of internal opaque surfaces, m is the total number of window and n is the number of reflecting surfaces. Ej(λ) is the spectral irradiance transmitted by window system. The first part of the equation models component of daylight entering the interior, the second part calculates contribution of the light reflected from areas, surfaces and window glazing. For transmission of light through window system is chosen the diffuse transfer of light. Sky component is formed by luminance of sky elements, the sky element is considered as a homogeneous point source of radiation that corresponds in the solid angle incidents on the evaluated area. Sky light passes through the window system with known transmission factor of spectral light, which is part of the area Af that is defined precisely by solid angle of element. Sum of elementary values create total radiation of sky. Elements that contribute to the sky component are bounded by perimeter of the window area. Elements locate outside the solid angle of the window are neglected. The model can be used to calculate the horizontal, vertical and tilt planes of illuminance in the interior, and other parameters.

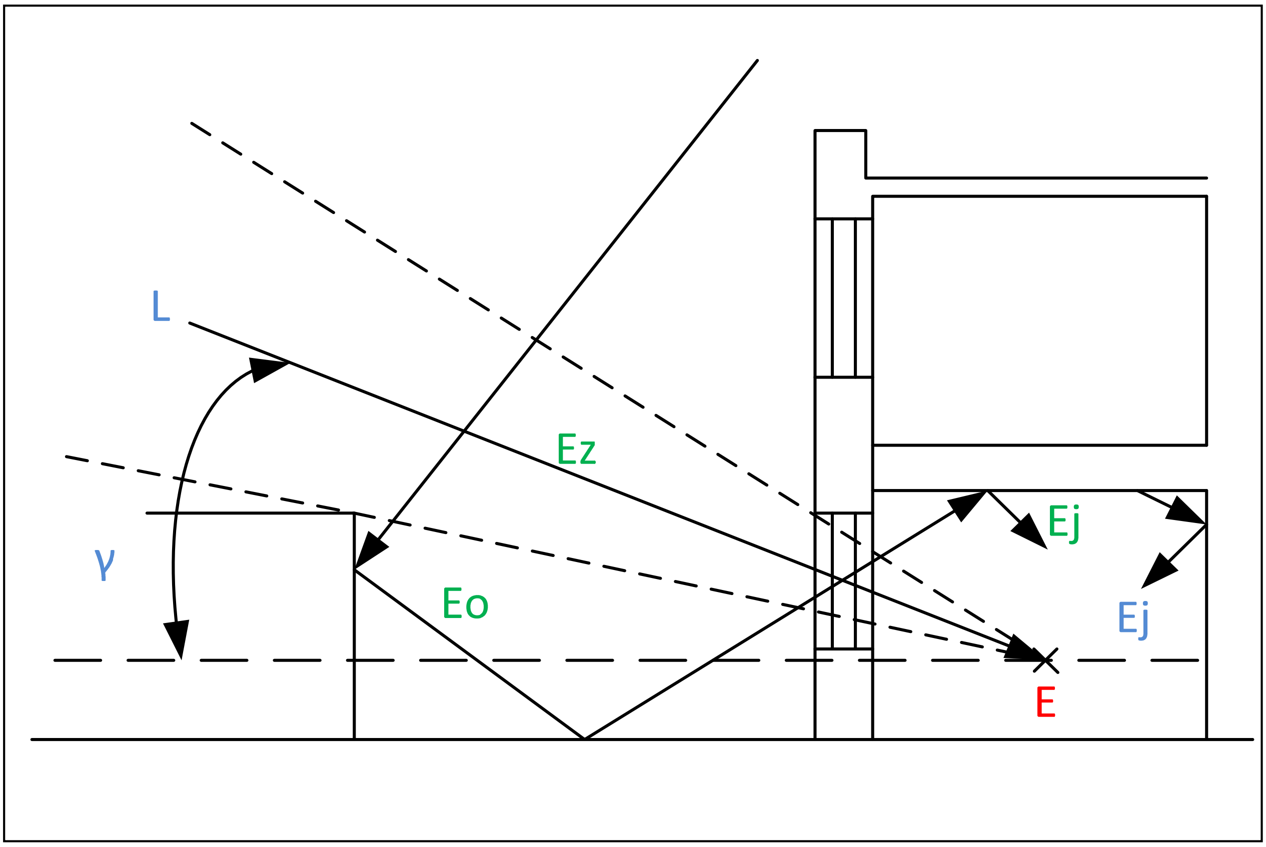

Figure 2. The interaction of the daylight components in the interior

Indirect component is determined from the contribution of incident rays in the assessment area. Elements whose angle of incidence is about 180° assessed on the plane can be neglected, fig. 3. Line coloured blue shows the direct rays from the sky light, fig. 3, line coloured red shows the predicted reflective surfaces in the indoor environment.

The calculation of indirect components take into account the surfaces where light falls from sky and which elements are capable of illuminating and thus affect the result level of illumination for the concerned area. Element for the indirect component is considered as lambertian source of radiation. In dependent on the accuracy of the calculation is choosing the number spectral reflections from the surfaces of the area. Irradiated areas by the individual elements of sky are considered as lambertian sources of radiation in the entire area. By experimental measurement of the spectral composition of the sky types can express the spectrum of daylight at any point in the monitored area. The spectral composition was calculated for the elements shown in fig. 4. Cut designed by blue line, fig. 4, is a decisive factor for sky light, which is falling into place of evaluation. Red line designed internal components that contribute to the determination of the spectral composition. They are not shown all.

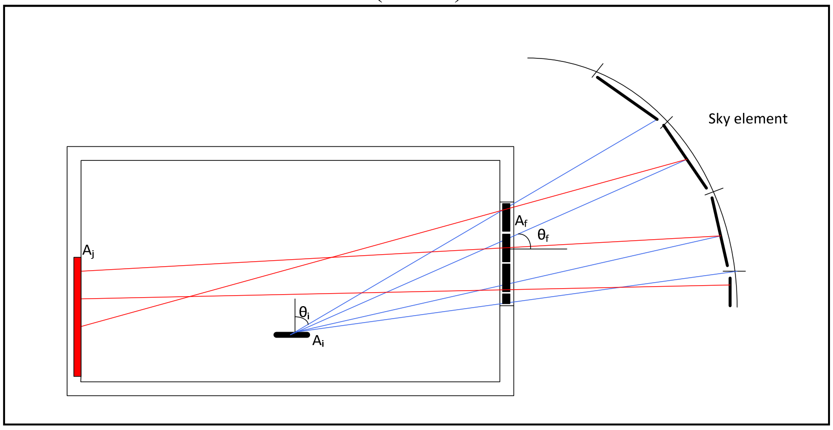

Figure 3. Illustration of rays which enter to the interior from sky patch

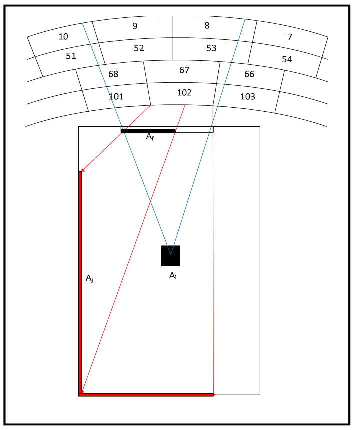

Figure 4. Geometry of the experimental room with illustrated sky patches

Measurement and calculation of the area shows considerable consistency in the results. Comparison was made for the measure of overcast sky and was used in the calculation of the spectral composition of the parameters of sky type I.1 according to [5]. By measurement was obtained value of illuminance for evaluating area to which it was compared calculated value of the overall illuminance.

Evaluated area was in the middle of the room with length 4,32 m, width 2,84 m, high 2,82 m and area was of 0,85 m above the floor. The window had a width dimension of 1,2 meters and height of 0,9 meters. Room had a standard reflectance of light from the walls ρ = 0,72, from ceiling ρ = 0,8 and floor 0,2. In the calculations of illuminance were considered values of spectral reflectance available from materials databases.

RESULTS

Spectral power distribution of light incidents to the control point Ai is shown in fig. 5 and it shows differences between measurement and calculation. Calculation contains a lower proportion of radiation energy in the wavelength range of 440 nm to 700 nm. Differences obtained by measurement and calculation can have several causes: atmospheric effects, uncertainty of measurement, lack of precision mathematical algorithm especially in the absence of exterior components, unavailability of catalogue spectral characteristics of material for the spectral reflectance. The average relative deviation between measurement and calculation from the reference value for the whole spectrum wavelengths represents 12,95%. Deviation of result has an acceptable value that is acceptable in view of the deviation of the original authors of equation (1). The calculation was performed for one reflection from the surfaces of the room. The current models use two or more reflections, these should be accurate in the calculation. The problem is that the software considers in the calculation code the transfer of energy, but information about composition and distribution of the spectral power distribution leave out.

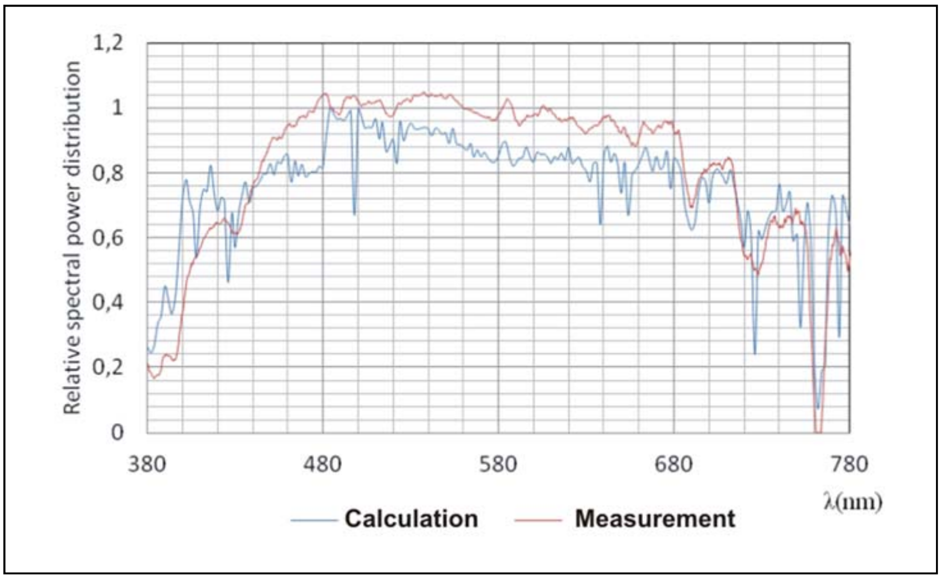

Figure 5. The relative spectral power distribution of daylight in the interior

Results were subsequently compared with the results of the calculation for illuminance in the simulated room in software Dialux and Relux [6][7], tab. 1. In the software was selected as the reference type of sky CIE uniformly overcast marked as I.1[8]. The measured sky was according to [8] describes as I.1.

In software Relux was set the same conditions as time, location, type of standardized sky, room geometry and elements of the room. The result has a significantly lower value of illuminance. The difference between calculation and measurement is explained as neglect exterior components.

TABLE I. THE RESULTS OF DAYLIGHT ILLUMINANCE DISTRIBUTED IN THE INTERIOR

Parameter	Measurement	Calculation	Software	
			Dialux	*Relux*
E_m (lx)	115,1	101,9	107,5	89,5
ΔE_m (%)	-	-11,46	-6,06	-22,24

CONCLUSIONS

The spectral composition of light and transfer information in lighting calculations will be in the future in the foreground. Currently it is valid the calculation of light transmission that is based on radiation energy. If we consider the calculation of spectral properties for artificial and natural light indoors, that opens a new approach to lighting. Mixing of these two light sources and expression of their common spectral composition, we could complement wavelengths, which are missing in lighting and choose a suitable source for lighting. Another aspect is select of healthy light for various groups of peoples, for various work and activities. Today these parameters are expressed by as CCT and CRI. For future work in field of light and illumination it can be source of lot information. Mainly we will blend the good and healthy light, in the area where we will work or make activities and there where it will be important.

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Preliminary Experimental Evaluation of Electrotropic Windows in a Full Scale Test Facility

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Abstract — **This paper reports the results of a preliminary study aimed to evaluate the visual performances of an electrotropic switchable glazing using a south oriented full scale experimental station. The internal daylight illuminance and luminance distribution acquired with electrotropic glazing in clear state have been compared with those in milk state. At the same time, quantities able to characterize the external weather conditions were measured. The results highlight that: (1) the milk state helps to prevent areas with high luminance peaks as well as to reduce the maximum luminance values at the observer's eyes, (2) the milk state allows to increase illuminance values in the points farthest from the window and (3) in terms of mean luminance values of the window, there are no remarkable differences between glazing states.**

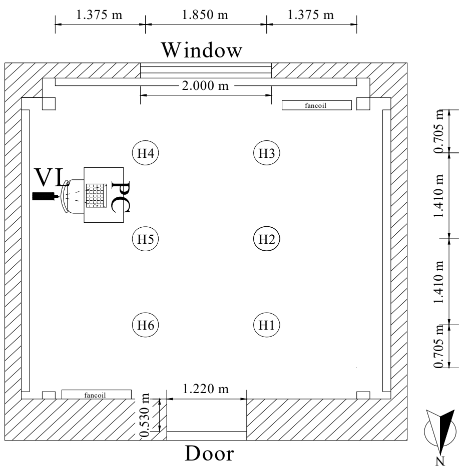
Index Terms—**Daylight, Electrotropic glazing, Experimental measurements, Smart windows, Visual comfort.**

INTRODUCTION

The energy efficiency and reduction of environmental pollutants represent a common objective towards which the efforts of researchers and politicians are focused. The correct use of daylight allows to reduce energy use for lighting in buildings as well as improve visual comfort [1]-[5]. In this scenario, smart windows, especially those electrically controlled, can play an important role in controlling the visual and thermal conditions inside a room. In fact, differently from conventional windows, these new typologies of glazings allow to vary their visible solar transmission and solar factor by applying an electric field; for the best use of these new technologies, on-site assessment and glare characterization are necessary for understanding their real behaviour upon varying internal and external conditions. With this aim, experimental and theoretical studies have been performed on a full scale smart windows. Lee et al. [6] conducted experimental studies to evaluate the performances of electrochromic (EC) window prototypes using a south oriented full-scale office test-bed. They found that EC windows were able to maintain a fixed constant illuminance value on a work plane as well as to reduce energy consumption for lighting, if compared with conventional windows. Piccolo et al [7], [8] evaluated the visual performances of an EC glazing prototype in a small test cell during the summer for different orientations; they found that, if controlled through dynamic strategy, EC window could maintain a constant illuminance level on a work-plane as well as preserve from discomfort glare for south orientation, while for east and west orientations, the control of glare effects were more difficult when using an EC window. Matusiak [9] investigated the problem of the glare sensation in buildings with translucent façades in the period March-November, using a physical test-model equipped with Nanogel glazing. From the main results it could be inferred that translucent facades may cause a sensation of glare as well as a reduction in speed reading in sunny days for those buildings situated at high latitudes and huge differences among the responses of subjects were detected. Ghosh et al. [10] examined the visual performances of a window equipped with a suspended particle device (SPD) switchable glazing in comparison with a conventional double glazing window. The study underlined that SPD switchable glazing with visible solar transmittance that ranges between 5% and 55% could be suitably used for controlling daylight and glare. All the studies suggested the need to perform further experimental analysis to evaluate the on-site performances of these type of smart windows. In this paper, the preliminary results of experimental studies aimed at evaluating the visual performances of an electrotropic (ET) glazing were presented. An electrotropic window is an electrically driven glazing that can be switched from a transparent (clear) to an opaque white (milk) state in the presence of an electric field. Its main advantages, in comparisons with other shading devices, are the possibility to dynamically vary its optical and thermal characteristics, a fast switching time (within 1 s) that allow to follow the sky condition changes and an high value of the visible solar transmittance in the milk state. The visual performances of the electrotropic glazing were evaluated by a full scale experimental station, comparing the internal daylight illuminances and luminance distributions acquired with ET glazing in the clear state and in the milk state. In order to define the weather conditions, external quantities were also acquired.

EXPERIMENTAL STATION AND MEASUREMENTS SET-UP

Starting from the need for additional experimental studies on full scale windows as well as for assessing on-site performances of "smart" solution for windows, an experimental station was designed and set-up at the Department of Engineering of the University of Sannio. The station consists of a main supporting steel structure, with an external size of 6.00 m x 6.00 m and height of 5.50 m that support three removable walls and one not movable wall. The test facility structure is placed on a turntable with the purpose of adjusting its orientation. The facility is equipped with a wood frame window with a total size of 2.000 m x 1.200 m, a ratio between glass area and total window area equal to 0.59 and a distance from the middle point of the window to the ground of about 2.750 m. For the present study, two electrotropic double glazing (each with size 0.785 m x 0.900 m), produced by Gesimat [11], were installed. From outside to inside, the glazings are composed of a 4 mm uncoated float glass, a 16 mm gap filled with Argon and an electrotropic (ET) layer between two 4 mm uncoated glass. According to the technical data declared by the manufacturer, the ET glazing is switched to the clear state by applying a electric field equal to 115 V within about 1 s and it is characterized by a visible solar transmittance (T_{vis}) equal to 72.5 %, a thermal transmittance (U_g) equal to 2.5 W/m^{2}K, a solar factor (g) equal to 0.72 and a power demand of about 10 W/m^2. Indeed, without the electric field, the glazing is in milk state and it is characterized by a visible solar transmittance (T_{vis}) equal to 60.7 %, a thermal transmittance (U_g) equal to 2.5 W/m^{2}K and a solar factor (g) equal to 0.67. During the experiments, the external conditions are evaluated acquiring the global and diffuse horizontal illuminance values on the roof of the experimental station (two illuminance-meters LP PHOT 03 manufactured by Delta OHM [12], with cosine correction, measuring range from 0 lx to 150,000 lx, relative spectral response (f1') < 6 % and accuracy < 4 % are used), as well as the vertical illuminance on the external surface of the window (by one illuminance-meter Konica Minolta T-10 [13], with cosine correction, measuring range from 0.01 lx to 300,000 lx and accuracy of ± 2 %). For measuring the horizontal diffuse illuminance, the illuminance-meter is equipped with a black painted shadow-ring. The daylight contribution inside the facility is evaluated acquiring the illuminance and luminance distributions. Fig. 1a reports the layout of the experimental station, the position of the illuminance sensors (points H1 to H6 in Fig. 1a) as well as the relative position of the notebook (PC), the imaging luminance measurement device (VL) and the window. The internal daylight illuminance distribution is evaluated through six illuminance-meters Konica Minolta T-10 [13] placed at 0.85 m from the floor level in horizontal position. The internal daylight luminance distribution is evaluated acquiring luminance maps using an imaging luminance measurement device LMK 98-3 Colour, manufactured by TechnoTeam [14]. The imaging luminance measurement device (VL in Fig. 1a) is positioned at the eye level of a person considered as seated at an office work station on the left side of the window, facing and looking at the screen of a notebook (size of the screen 0.38 m). The imaging luminance measurement device is equipped with a lens TT4.5, focal length of 4.5 mm, relative spectral response (f1') equal to 2.6 % and accuracy equal to ± 3.7 %. Fig. 1b shows an internal view of the experimental station and the window with the electrotropic glazing in the clear state (left) and milk state (right).



a)

b)

Figure 1. Layout of experimental station with position of illuminance-meters (from H1 to H6) and videoluminance-meter (VL) (a); internal view of the facility (b).

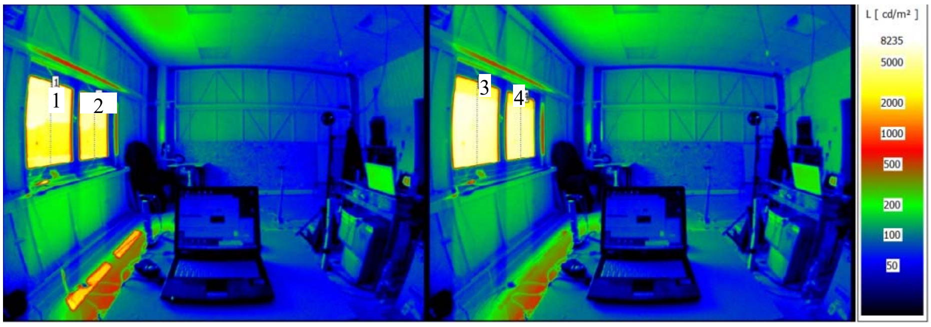
RESULTS AND DISCUSSION

The results are reported for the measurements performed on 11 May 2017, from 10:00 to 17:00. For each hour of measurement a set of data (pairs) were acquired; each pair was obtained acquiring the internal daylight distribution with glazings in the clear state and after one minute with glazings in the milk state. At the same time, the external quantities were also measured. Since the internal measurements were recorded in different moments, the analysis were made using only pairs characterized by almost identical external conditions; the threshold has been established in a variation of difference between outdoor horizontal and vertical illuminance levels lower than 4%. Fig. 2 shows the comparison between luminance maps acquired on May 11 at 13:57 with electrotropic glasses in clear state (a) and at 13:58 in milk state (b). The figure shows that:

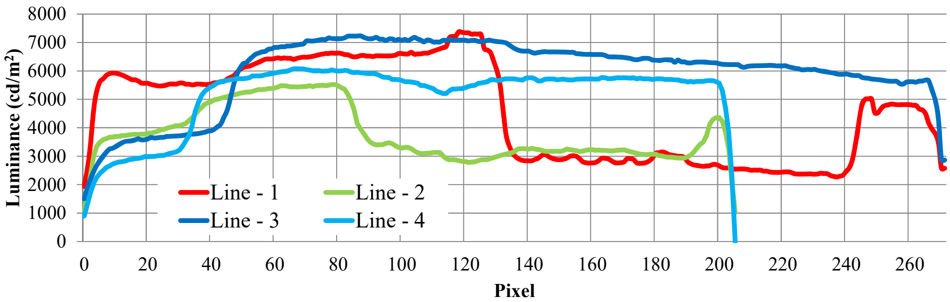
- the luminance values on the internal surfaces with the electrotropic glazings in the milk state are generally higher than those acquired with glazing in the clear state;
- the glazings in the milk state prevent the presence of the floor area with reflected sunlight that can often cause high localised luminance peaks;
- the milk state allows a greater uniformity in the luminance distribution on the glazings surface.

To evaluate the luminance distribution on the surface of the glasses, the luminance values along two vertical lines placed in the middle of each pane for the two states are considered. In the Fig. 2c, the luminance values observed along the vertical lines, moving from top to down, were reported. In particular, lines number 1 and number 3 refer to the luminance values on the left side of the window for the clear and the milk states, respectively. Lines number 2 and number 4 report the luminance values on the right side of the window for the clear and the milk states, respectively. The figure highlights that:

- the luminance values in the milk state are generally higher than those in the clear state;
- considering the line (red) number 1 (left side, clear state), it is possible to identify the visible area of sky at the observer's eyes, where the luminance values range from about 5500 cd/m² to about 7000 cd/m², and the visible area of obstructions, where the luminance values range from about 2300 cd/m² to about 3100 cd/m²;
- considering the line (blue) number 3 (right side, milk state), it is not possible to identify the different outside areas and the luminance values range from about 5600 cd/m² to about 7100 cd/m² with a smooth line pattern;
- lines number 2 (left side, clear state) and 4 (right side, milk state) underline a variation of the luminance values similar to that observed along lines number 1 and 3.



a) b)



c)

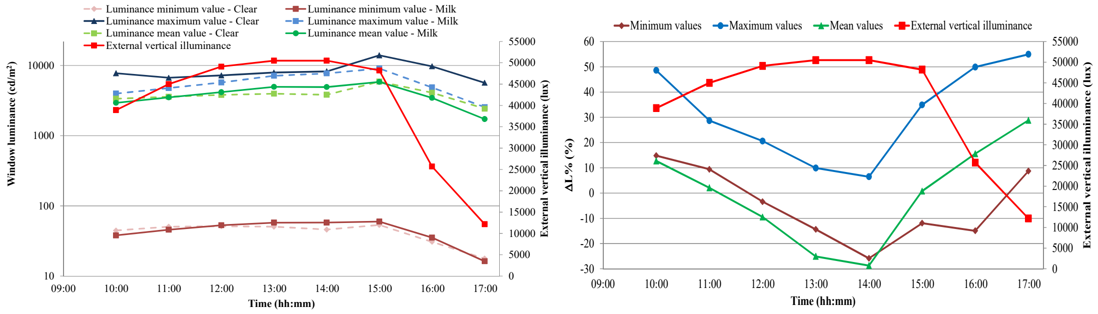
Figure 2. Comparison between luminance measurements captured with electrotropic glazing in the clear (lines 1 and 2) and milk state (lines 3 and 4).

Fig. 3a reports the maximum, minimum and mean luminance values measured on the glazings surface in the clear and milk state as well as the vertical illuminance on external window surface upon varying external conditions. In Fig. 3b, the external vertical illuminance values were jointly reported with the percentage differences ΔL% between minimum, maximum and mean luminance values acquired in clear (L_{clear}) and milk (L_{milk}) state. The percentage differences are calculated according to the equation:

$$\Delta L\% = \left(\frac{L_{clear}-L_{milk}}{L_{clear}}\right) x\ 100 \tag{1}$$

Fig. 3a and Fig. 3b show that:

- the minimum luminance values acquired in the milk state are generally higher than those in the clear state;
- whatever the external conditions are, the maximum luminance values acquired in the milk state are lower than those captured in the clear state;
- the mean luminance values observed in the milk state are generally lower than those in the clear state, except for data acquired at 12:00, 13:00 and 14:00;
- the percentage differences calculated for the mean luminance values of the window range from about -28.7% at 14:00 to 28.8% at 17:00;
- the percentage differences calculated for the maximum luminance values of the window range from about 6.5% at 14:00 to 54.9% at 17:00.



a) b)

Figure 3. Comparison between external vertical illuminance and minimum, maximum and mean luminance on glazing surfaces in clear and milk states in terms of absolute values (a) and percentage differences (b).

Fig. 4 shows the comparison between the vertical illuminance on the external surface of the window and the ratios between the mean luminance of the window and the mean luminance of the task area, in the clear and milk state. The task area was defined as a circular zone with an opening angle of about 0.53 sr. The task zone was chosen, so that it covers the most part of the computer screen as well as a part of the desk, while the window is not a part of the zone. The figure highlights that:

- glazing in the milk state allows for lower values of the above-mentioned ratio than those calculated with glazings in the clear state except for acquisitions performed at 12:00, 13:00 and 14:00;
- the percentage differences of the above-mentioned ratio calculated for the clear and milk state of the window range from about -35.0% at 13:00 to 20.7% at 17:00.

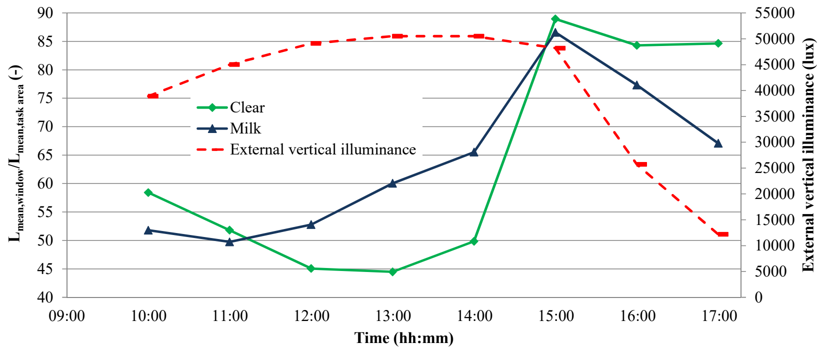


Figure 4. Comparison between external vertical illuminance and the ratio between the mean luminance values of the window and the mean luminance values of the task area, in clear and milk states.

With reference to the layout of the internal sensors, the Fig. 5 illustrates the comparison among the illuminance values acquired on each measurement point with the glazing in the clear and milk state. From Fig. 5 it can be noted that:

- both in the clear and milk state the highest illuminance values are observed for those sensors placed next to the window (H3 and H4);
- the illuminance values acquired by the sensors closest to the window depend on the sun position; during the morning (sun moving from east) the illuminance values acquired by sensors H3 are higher than those acquired by sensor H4, while in the afternoon (sun moving to the west) it can be noted an opposite trend;
- increasing the distance from the window the internal daylight illuminance values decrease;

- the illuminance values on the sensors farthest from window (H1 and H6) acquired with the glazings in the milk state are higher than those observed with the glazings in the clear state; glazings in the milk state allow for a better light distribution inside the test room.

CONCLUSIONS

The present paper reports the preliminary experimental results assessing the visual performances of a full scale ET switchable glazing. The comparison between daylight illuminance and luminance distribution inside the facility underlined the opportunity of using an ET glazing in the milk state to reduce the maximum luminance value, avoid internal areas with reflected direct sunlight as well as increase the illuminance values in the points farthest from the window. Nevertheless, due to the high visible solar transmittance value in the milk state, the mean luminance values of the window with glazing in the clear and milk states are still high and there are no remarkable differences between the glazing states.

ACKNOWLEDGEMENTS

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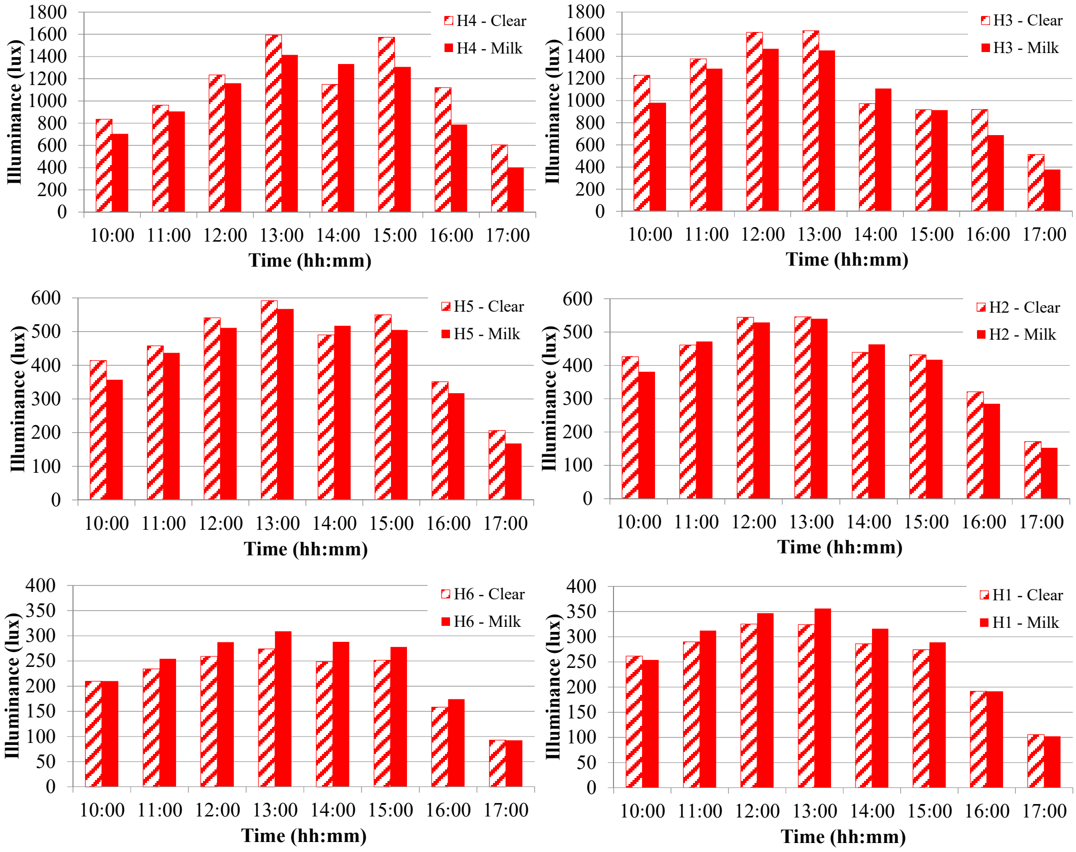

Figure 5. Daylight illuminance distribution for indoor acquisition points upon varying external conditions.

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The Optimal Luminous Intensity Curves of Luminaries for Roadway Lighting

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***Abstract*—This article describes method of reverse evaluation of luminous intensity curves which can be applied for roadway lighting. Input parameters are mainly classification of roadway, height of street light columns and their distance and output data are in form of luminous intensity curves of luminaries corresponding with standard EN 13201. Thus results can be applied as useful data for roadway administrators who design reconstructions of old roadway lighting systems.**

***Index Terms*--Optimal luminous intensity curve, road lighting,**

INTRODUCTION

Procedure of designing new lighting system for street illuminating is detailed formulated in standard EN 13201. Basically it used calculation, when luminous intensity distribution of specific luminaire is known and parameters such as optimal height of columns, their distance and angle of luminaire are calculated in order to comply specified standard parameters (street luminance, illuminance, threshold increment). Principally calculation is carried out on the representative raster field and algorithm only calculates direct contributions from luminaries. Therefore finding optimal parameters is task for optimising algorithms implemented in designing and computing software [2].

With mass LED utilization in general lightning started reconstructions of old lightning systems. Basically old luminaries are changed for new LED luminaries, however the columns parameters with old luminaries are kept the same. Therefore height of columns and their distance is not changed and thus it is necessary to calculate optimal luminous intensity distributions of luminaries in order to achieve specified standard parameters. There are simple optimising algorithms capable of selecting the most ideal luminous intensity curve from several offered variants. In order to calculate ideal luminous intensity curve with set conditions can be problematic and it requires sophisticated approach and complicated algorithms. One of these approaches is described in following text.

BASIC ASSUMPTIONS AND DESCRIPTION OF THE CALCULATION

A. Basic assumptions

Calculation of optimal luminous intensity curve for specific lightning system with set heights of columns and their distance and also with more luminaries can be difficult because exist of many mathematical solutions. Basically it is a reverse calculation from predefined street area and illuminance to luminous intensity curves of all luminaries, which contribute to street illuminance. Since there are many solutions it is very important to define boundary conditions in order to get only one optimal result.

- The first assumption is calculating only direct luminous intensity contributions from each luminaire. This condition is basically fulfilled because of minimal indirect contributions on the opened street roadway. However in city streets there can be indirect contributions which might influence street illuminance. Practically indirect contributions are not considered in calculations in order to greatly simplify calculations. Therefore indirect contributions are not calculated in the following algorithm.
- Next important assumption focuses on uniformly defined C planes of luminaries. In this calculations it is presumed orientation of C-planes according to the European standards, more precisely regulations of CIE and standards EN 13201. Therefore C-plane C90 is oriented perpendicularly [1], [3].
- The third assumption concerns calculation of illuminance as a superposition of each illuminance contributions of luminaire. However, including all luminaries into calculations make algorithm more complex. In this case it is defined a condition of calculating illuminance with the only **two** nearest luminaries to point of illuminance calculation. The only exceptions are points directly below each luminaire, meaning at their C90 and C270 planes. In this point it is assumed the most significant direct contribution from the luminaire above and equally divided contributions from nearby luminaries.
- It is assumed that all luminaries are able to light only border of columns of their nearby luminaries. See below in Figure 1.

- There is significant influence o incident light angle coming from luminaire to specific point (cosine law) and influence of distance between luminaire and this point, when illuminance decreases with the distance squared by two (square law).
- Moreover it is necessary to defined height of columns “h” and their constant distance “d”. These parameters are the same for all columns (luminaries).
- The luminaire can be also inclined from horizontal planes (tilt angle). However, this angle is equalled to zero in order to simplify the calculations. Therefore all luminaries are situated perpendicularly to the roadway.
- Very important assumption concerns dimensions of calculated area. For simplicity it is defined area with dimensions of width of roadway "s" and distance between columns "d". Moreover it is necessary to offset of luminaire to the border of roadway.
- The last condition focuses on placement luminaries along the roadway and required illuminance. In this case it is used system of one-sided placed luminaries along the roadway and all calculations are referred to required illuminance 10 lx.

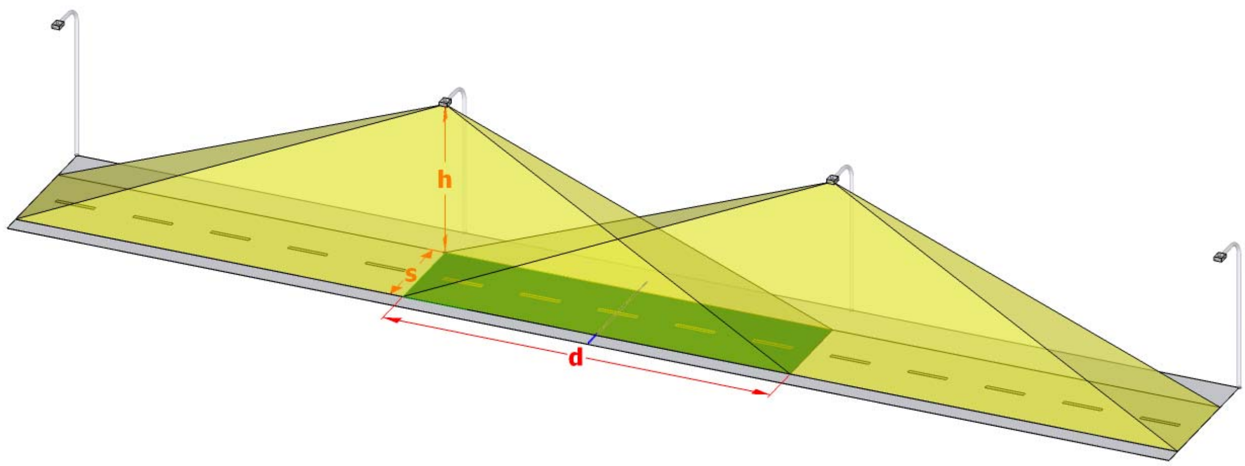


Figure 6. Placement lay-out of luminaries on the road (only two luminaires are on for better lucidity)

B.Description of the calculation

As it was already mentioned in the previous chapter, the calculation is carried out within the width of the roadway “s” and distance of columns “d”. In the Figure 1 this area is shown as a green area. The whole calculation has assumption of equally illuminated green area with the constant illumination “E”. The calculation can be expressed with following equation (1).

$$E = \frac{I}{l^2} \cdot \cos\beta \tag{1}$$

where I stands for luminous intensity

l is the distance between luminaire and the point in raster

β is incident angle of light from normal line (in case of tilt angle equals zero it is β=γ, where γ is angle from C- γ plane of luminaire used according to CIE and EN 13201)

In this configuration each luminaire is situated directly above the border line of the raster, meaning that offset is equalled zero. Thus the following equations are related for vertical plane on the border of the raster and plane of luminaries. These planes are the same as C0 and C180 of the luminaire. The extension of calculation with another dimensions in raster is a task of generalisation of equations into next dimensions, thus it is not considered anymore in calculations. According to the definition of final illuminance of the raster from chapter II. A it possible to evaluate illuminance of each point as a superposition with following equation (2)

$$E = \frac{I_1}{l_1^2} \cdot \cos\beta_1 + \frac{I_2}{l_2^2} \cdot \cos\beta_2 \tag{2}$$

With substitution applied (3)

$$\frac{\cos\beta_i}{l_i^2} = \frac{h}{l_i \cdot l_i^2} = k_i \tag{3}$$

It is able to modify equation (2) with equation (3) into following form (4)

$$E = I_1 \cdot k_1 + I_2 \cdot k_2 \tag{4}$$

Now it is appropriate to set condition how to divide luminous intensities I_1 and I_2 from two separate luminaries for each point of the raster. Previously it was defined that final illuminance is calculated only from nearest two luminaries. Thus in the middle of the raster (blue line) lies a point, where $k_1 = k_2$. In this point illuminance can by calculated with equation (5)

$$E = I_1 \cdot k_1 + I_2 \cdot k_1 = k_1(I_1 + I_2) \tag{5}$$

In case of symmetrisation of the planes C90 and C270 of the luminaire, there must be mutual mirroring between planes C0 and C180. Thus there is only one ratio between luminous intensities I_1 and I_2 in the middle of the raster in the following equation (6)

$$I_1 = I_2 \tag{6}$$

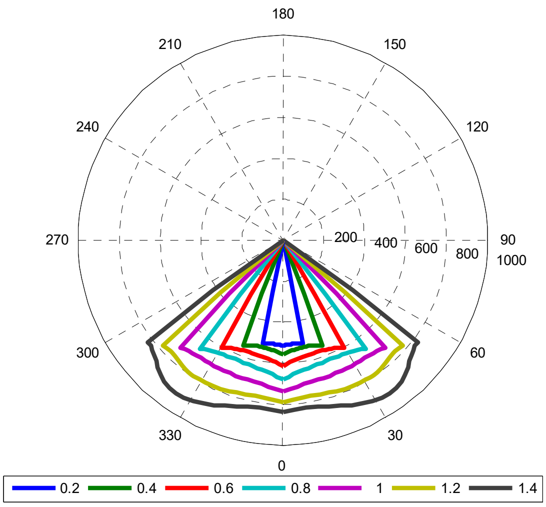
According to equation (6) will be final illuminance of blue line as followed (7)

$$E = k_1(I_1 + I_1) = 2I_1 \cdot k_1 \tag{7}$$

Using equation (7) it is possible to calculate luminous intensity of the blue line with equation

$$I_1 = I_2 = \frac{E}{2 \cdot k_1} \tag{8}$$

Equality (6) can be only applied in the middle of the raster when conditions from chapter II. A are fulfilled. However, outside the blue line this equality might not be valid. Therefore the ratio between I_1 a I_2 can result into infinity. In order to reversely calculate luminous distribution curves with particular solution it is necessary to define the ratio of luminous intensities outside the blue line.



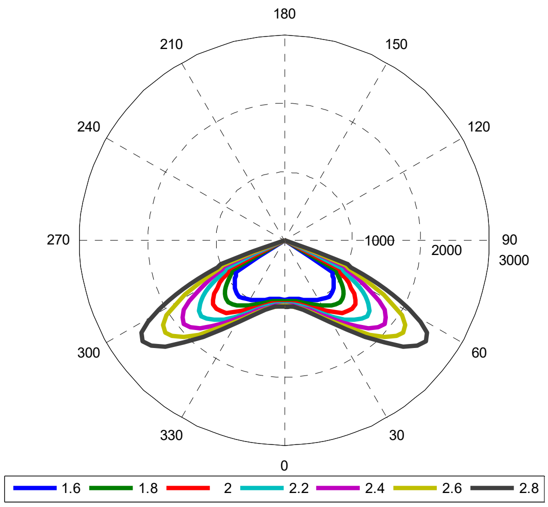


Figure 7. Luminous intesity curves for C0 and C180 planes with different ratios of "h" and "d" with condition of $I_1 = I_2$ for each point of raster

One of the definition of luminous intensity ratio might be extension of equation (6) on all points of the raster. With conditions from chapter II. A it is necessary to modify equation (6) under the luminaire, because there are points on the plane under the luminaire, where light incident from luminaire above and from two nearby luminaries from each side. Thus in these points equation (6) can be modified to equation (9)

$$I_1 = 2 \cdot I_2 \tag{9}$$

Final calculation of luminous intensity can be written with equation (10) for any point of the raster and with equation (11) for points situated in orthogonal plane under the luminaire.

$$I_1 = I_2 = \frac{E}{k_1 + k_2} \tag{10}$$

$$I_1 = 2 \cdot I_2 = \frac{E}{k_1 + k_2} \tag{11}$$

Resulted luminous intensity curves with respecting above mentioned conditions are calculated for different ratio of "h" and "d" in the Figure 2 at h = 10 m. Moreover the ratio can be expressed as followed (12)

$$r = \frac{d}{h} \tag{12}$$

As mentioned earlier, for all points outside the blue line the equation (6) might not be valid. The ratio between luminous intensities "I_1" and "I_2" can be various. In order to maintain constant illuminance in the green area (Fig. 1) it is necessary to guarantee compensations between luminaries in case of decreasing luminous intensity of one luminaire. Therefore equation (4) is modified to equation (13) as followed

$$E = I_1^{'} \cdot k_1 \cdot \varepsilon + I_2^{'} \cdot k_2 \tag{13}$$

where ε is decrement coefficient with definition (14)

$$\varepsilon = \frac{I_1}{I_1^{'}} \tag{14}$$

where I_1 is a nominal value of luminous intensity (6)

I'_1 is a actual value of luminous intensity.

A new value of luminous intensity I'_2 is defined with equation (15)

$$I_2^{'} = \frac{E - I_1^{'} \cdot k_1 \cdot \varepsilon}{k_2} \tag{15}$$

Decrement coefficient value "ε" always equals one in the middle of the raster (blue line). However, outside the blue line decrement coefficient "ε" can equal almost any value. In case of smooth decrement coefficient function, the resulted luminous intensity curve is also smooth. Thus with changing the decrement coefficient it is possible to form original luminous intensity curves from Figure 2.

In case of decrement coefficient function is linear to distance from the middle of the raster (blue line) and equals one in the middle of the raster and zero under the orthogonal plane of nearby luminaire, the luminous intensity curves get narrowed and forms curves showed in Figure 3.

These properties can be used in optimising of luminous intensity curves in terms of discomfort glare. Therefore width of luminous intensity curve has significant influence on glare index depending on threshold increment TI.

According to results it is obvious, that this customization has significant influence on luminous intensity curves in case of very high columns at close distance, when the ratio "r" is small.

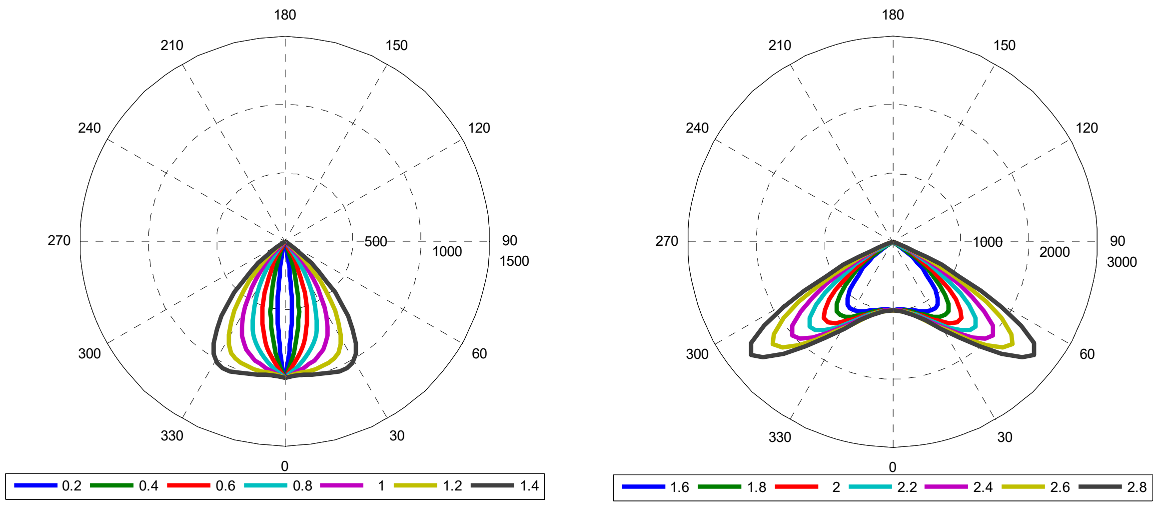


Figure 8. Resulted luminous intestity curves in C0 and C180 planes for different ratio of "h" and "d" with using decrement coefficient "ε"

As mentioned earlier used equations can be generalized with other dimension and it can include dimension of width of roadway “s”. As a result it is obtained complete luminous intensity curve in all planes. Therefore the resulted 3D surface of luminous intensity distribution can be expressed as it is shown in Figure 4.

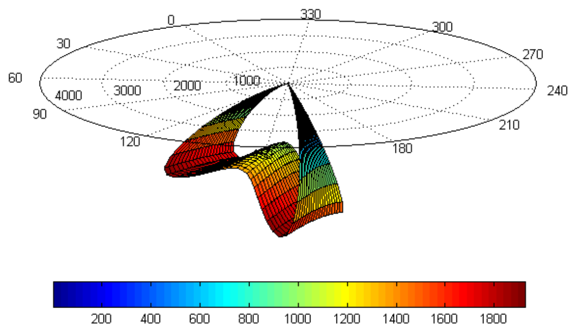


Figure 9. Luminous intensity in 3D for height h = 10 m, d = 28 m, s = 6 m and illuminance E = 10 lx with using decrement coefficient "ε"

CONCLUSION

The reverse calculation of luminous intensity curves (distribution) is the first step of calculating optimal luminous intensity curves for street lighting. The next step will followed in optimising luminous intensity curves in terms of discomfort glare. This issue is not covered in this article because of limit of maximum pages. However, for this purpose it is possible to use properties of decrement coefficient "ε" to ideally form luminous intensity curves. Moreover this article does not solve illuminance calculation of outside area of the roadway that certainly has a practical use. However, these practical needs can be added as extension to calculation in the future approach.

ACKNOWLEDGEMENT

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Lighting For Cyclists: an Eye Tracking Study in Natural Settings to Investigate Where They Look

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Abstract— **Little is known about road lighting conditions desirable for cyclists. Existing lighting standards are unlikely to be based on robust evidence of cyclists needs, and the requirements of cyclists are usually aggregated with those of pedestrians despite the two groups having very different needs. A first step towards identifying suitable lighting is to find out where cyclists tend to look. This article describes an eye-tracking study with 22 cyclists using an outdoor route in natural conditions. A secondary response task was used in conjunction with eye-tracking to identify moments when the cyclist may have been paying particularly close attention to the fixated object. Fixations during these critical moments were grouped into one of eight object categories. Observation of the path ahead appears to be the most significant visual behaviour, particularly when it is dark, suggesting road lighting should ensure cyclists can clearly see the path ahead.*Index Terms*— Driving; Fog, Peripheral detection**

Index Terms **- Cyclists; Eye-tracking; Obstacles**

INTRODUCTION

Encouraging more cycling has a range of health and environmental benefits. However, cyclists are defined as vulnerable road users because they have a higher risk of being involved in a collision and being seriously injured or killed compared with some other types of road user [1]. Darkness increases the risk of a collision or accident for all road-users but the after-dark risk is particularly heightened for cyclists [2]. This may help explain why there is a reduction in the number of people cycling when it is dark, even after accounting for other factors such as the time of day and year [3]. A key purpose of road lighting is to help cyclists and other road users see and be seen after-dark. By improving visibility, road lighting can reduce the numbers of cyclists involved in collisions after-dark. The requirements for road lighting set out in existing guidelines [e.g. 4] may not, however, provide adequate specifications to achieve these purposes: first, they tend to target primarily pedestrians, and second, the empirical basis even for pedestrians is somewhat lacking [5]. Road lighting guidelines frequently group cyclists together with pedestrians in terms of their lighting requirements, despite the likelihood that these two types of road users have different requirements.

To assess the adequacy of existing road lighting guidelines for cyclists we first need an understanding of the visual tasks carried out by cyclists. The effect of changes in lighting on these critical tasks can then be investigated to identify optimal lighting conditions. Such an approach has been adopted previously with pedestrians, to identify their critical visual tasks and use this information to suggest appropriate lighting specifications [6],[7]. It is likely that the visual tasks of cyclists will vary from those of pedestrians, due to differences in road position, speed, cognitive load, potential hazards and proximity to motorised traffic.

Eye-tracking provides the potential for understanding what cyclists need to see. Mobile eye-tracking uses two camera systems, typically mounted upon a pair of glasses, with one system recording the field of view and the second recording the wearer's eye movements. A calibration process enables the two recordings to be superimposed to identify the direction of gaze. The use of this method with cyclists in natural settings is rare. In one previous study, Vansteenkiste et al [8] used an eye-tracker with people cycling on high- and low-quality cycle tracks, the high-quality track being a recently renewed brick cycle lane, the low-quality track consisting of large tiles that had moved or were missing. They found an increase in looking towards the nearer part of the low-quality cycle track, compared with the high-quality cycle track. In another study [9], cyclists equipped with an eye-tracker rode around the urban centre of Bologna, Italy. One of the main conclusions from this study was that discontinuities of the path, such as intersections and crosswalks, and the presence of pedestrians appeared to attract greatest visual attention. However a major limitation with both these previous studies is that they had no way of distinguishing between significant or critical visual fixations, and non-critical fixations. Eye-tracking reveals the direction of gaze but not necessarily the focus of attention, as demonstrated by the phenomenon of inattentional blindness – the failure to process or be aware of something we are staring directly at [e.g. 10]. To overcome this limitation it is useful to link the allocation of attentional resources with where someone is looking. One method to do this is to ask the person wearing the eye-tracker to undertake a concurrent cognitive task, such as responding to a frequent but randomly occurring sound by pressing a button. Discrete instances when the person does not perform well on this task may indicate attention has been redirected away from the task potentially towards something significant in the visual environment. Such a method has been used to identify the critical visual tasks of pedestrians [6], and the method is also robust to a stimulus frequency bias that is likely to occur if all fixations were analysed rather than only those identified as critical [11].

This paper describes an experiment in which a secondary cognitive task was used in conjunction with eye-tracking to identify the critical visual tasks of cyclists in a natural setting.

METHOD

Twenty-two participants were recruited to take part in the experiment. They were equipped with a mobile eye-tracker (SMI Eye-Tracking Glasses) and asked to cycle a pre-defined urban route that was approximately 2.2 km in length, see Fig. 1. The route contained sections of main and minor roads, a car park and a park pathway, and took approximately 6-8 minutes to complete. Participants completed the same route during daylight and after-dark, on two separate days, the order these were done being counterbalanced within participants. A small speaker was attached to the underside of the cycle helmet participants wore, near their ear, which emitted an audible beep at random intervals between 1 and 3 seconds. Participants were instructed to press a handlebar-mounted button as quickly as possible, every time they head a beep. The button was positioned so that participants did not need to take their hand off the handlebars to press it, and they could still safely operate the brake lever at the same time.

Reaction times to each beep were calculated and this data used to define ‘critical moments’, instances when the participant may have diverted their attention away from this response task potentially to something significant in their environment. A critical moment was defined as an occasion when the participant either failed to respond to a beep, or provided a response that was at least two standard deviations slower than their mean reaction time during the whole of that trial session.

Fixations were defined from the recorded eye-tracking data using algorithms within the SMI BeGaze software (version 3.7). These initially identify undefined samples, blinks and saccades using thresholds about sudden changes in pupil diameter and velocities between gaze locations. The periods in between these undefined samples, blinks and saccades are denoted as fixations. Fixations occurring within a two-second window around every critical moment (one second before and one second after the associated beep) were placed into one of eight categories based on the object or area being observed (see Table 1). These categorisations were carried out by a single coder, with a second coder also categorising fixations in four of the eye-tracking videos to check inter-rater reliability. At 87%, agreement on the overall category of each fixation was high between the two coders.

Figure 1. Route cycled by participants.

TABLE I. DESCRIPTION OF FIXATION CATEGORIES

Object category	Description	Justification
Path	Fixations on the path surface ahead of bicycle	Previous studies on cyclists suggested the importance of fixating on the road path
Goal	Way finding fixations above street level	Essential for fixations related to navigating and planning action ahead. This category appeared in previous research.
Obstacles	Any object or irregularity on the path which may cause accident if not detected Including small posts	Used before in studies on pedestrians, it remains vital for cyclists safety on the roads, thus it is anticipated to influence gaze behaviour
Kerb	Pavement/edge of footpath	The hypothesis is being aware of kerb distance is vital for cyclists to prevent accidents
Cars	Moving and stationary cars participant encounter on the experiment route	Cars is a major source of cycling accidents on the roads, thus they are visually important objects to cyclists steering decisions. That is why we hypothesis it has an effect on gaze behaviour.
Cyclists and pedestrians	Either on shared path, distanced, or crossing the road	Cyclists usually encounter other cyclists and pedestrian while on the ride, thus fixations on this category will explain its visual criticality to cyclists
Buildings	Fixations on buildings facades	Separating buildings in an independent category could be of benefit to explain how cyclists observe built environment. A suggested hypothesis is increased number of critical fixations on 'non-safety' category like this one could indicate safety awareness level of cyclists.
Miscellaneous	All other objects or surfaces	All other fixations which do not fit the previous categories

RESULTS

Eye-tracking in real-world environments, particularly outdoor environments, can make the collection of reliable eye-tracking data more difficult due to factors related to sunlight, rapid changes in illumination, head and body movements, and motion blur [12]. Eye-tracking from the after-dark sessions of 2 participants and the daylight sessions of 9 participants were excluded from further analysis due to a loss of reliable eye-tracking signal. The remaining 20 after-dark and 13 daylight eye-tracking videos all achieved a minimum of 50% valid eye-tracking samples.

The median number of critical moments during daylight sessions was 21, compared with 36 recorded during the after-dark sessions. This may reflect greater attention required for the visual environment when it is dark, as it may be more difficult to see potentially significant objects such as obstacles and hazards, compared with the improved visibility provided by daylight. Fixations during the 2-second window that was around each of these critical moments were categorised into one of 8 categories, shown in Table I.

Fig. 2 shows the median proportion of critical fixations in each object category. Note that medians are reported in this analysis as the data are not normally distributed, according to examination of frequency distributions and the Shapiro-Wilks test.

The category with the highest proportion of critical fixations in both day and after-dark sessions is the Path, with a median of 41% during the day session (IQR = 13%) and 48% during the after-dark session (IQR = 21%). In one study it was found that pedestrians tended to look towards the path in 59% of fixations, this behaviour labelled travel gaze [13], and defined as where the gaze is held on the near path at a fixed distance slightly ahead of the pedestrian and is carried along at the speed of locomotion. Travel gaze may be associated with inattention. Fig. 2 includes only those fixations associated with critical moments, as defined by delayed response to the dual task, and this suggests that attention was being given to the fixated object.

Of the eight categories, note that for three of them (path, obstacles and kerb) the median proportion of fixations increases after dark compared with daytime whilst for the remaining five categories the after dark proportion is similar or less than that in daytime. Common to these three categories is the possibility of a surface hazard that may lead to an accident if avoiding action is not taken. Pedestrians are able to change gait, increase foot clearance, and change direction, all when very close to a hazard. Given that a cyclist has fewer options for hazard avoidance than a pedestrian, and given that the outcome of an accident for a cyclist on the carriageway may be more severe than for a pedestrian on the footpath, then it is not unexpected for cyclists to direct a significant proportion of cognitive and visual attention to the road surface.

Given that cyclists have a significant need to see the road surface to detect and identify potential hazards, then road surface should be lit after dark. The road can be lit using road lighting or cycle-mounted lighting. Research has shown, however, that hazard detection may be impaired by using both types of lighting simultaneously [14]. Road lighting enhances the visibility of an object using negative contrast – making the road surface brighter than the visible vertical surface of the object. Vehicle-mounted forward lighting enhances visibility by positive contrast – the object is brighter than its background. If both forms of lighting are used in parallel, and according to the luminance provided by each, then the contrast and hence visibility of the target is reduced.

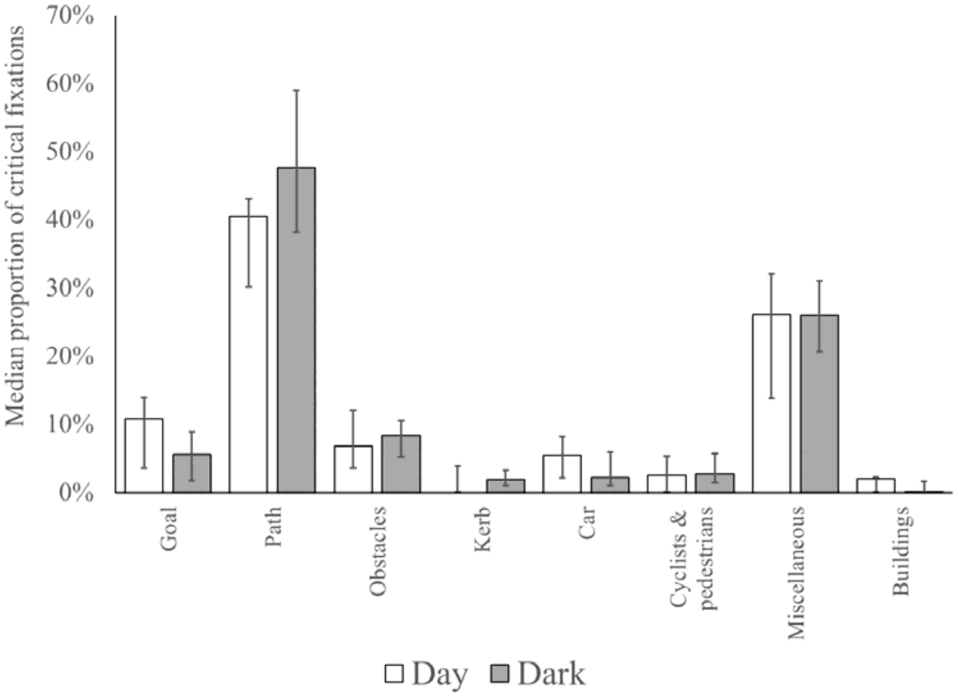

Figure 2. Median proportions of critical fixations towards different object categories, during day and after-dark sessions. N = 13 for Day, N = 20 for Dark. Error bars show interquartile range. Note that median value for Kerb in Day session is zero.

CONCLUSION

Road lighting has the potential to improve safety after dark and encourage more people to cycle. One reason for this is that it may improve a cyclist's ability to see during hours of darkness, although we do not currently know how well existing road lighting standards achieve this goal. A first step in addressing this gap is to identify the critical visual tasks of cyclists. This information can be used to investigate how lighting influences these tasks, with the end goal being to identify optimal lighting characteristics for cyclists. We carried out an eye-tracking experiment with cyclists in a real-world environment to record their visual behaviour. A concurrent secondary task was used to gauge levels of attention, and critical fixations were identified. Our results suggest observation of the path and scanning for potential surface hazards is of importance to cyclists, and may be even more important after-dark compared with during daylight. This may be due to greater difficulty in being able to see potential hazards when it is dark, leading to greater attention being paid to the path ahead, adjacent kerbs and potential obstacles, and for cyclists travelling in the carriageway alongside motorised vehicles, the outcome of an accident is likely to be more serious than for a pedestrian on the footpath.

ACKNOWLEDGEMENT

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The Role of Ambient Light Level in Accidents at Pedestrian Crossings

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Abstract— **Three quarters of road traffic collisions (RTCs) involving a pedestrian death or serious injury occur when they are crossing the road. Pedestrian crossings are designated transport infrastructure designed to make crossing the road more safe. We investigated whether the risk of an RTC involving a pedestrian at a crossing was greater after-dark compared with during daylight, using the biannual Daylight Saving Time clock changes to control for confounding factors unrelated to ambient light. Odds ratios were significantly greater than one for all crossing types, suggesting pedestrians are at greater risk when using a crossing after-dark compared with during the daylight, which shows that light matters. This after-dark risk is increased further during adverse weather conditions, compared with during fine weather. Visibility is likely to be a major cause of the increased risk after-dark and during adverse weather, and existing road lighting at crossing locations may not currently be adequate.**

Index Terms— **Accidents, Light Level, Pedestrian crossings**

Introduction

Pedestrians are defined as vulnerable road users as they have higher casualty and fatality rates relative to the distances they travel, compared with other road users. For example there were 2108 pedestrian casualties per billion miles travelled, compared with 273 casualties per billion miles travelled amongst car users [1]. According to UK data, 77% of road traffic collisions (RTCs) involving a pedestrian death or serious injury occurred when the pedestrian was crossing the road [2]. Pedestrian crossings are a design feature of transport infrastructure that aim to make crossing the road safer for pedestrians, by encouraging them to cross at the same location and by alerting the driver to their presence. However, crossings do not make pedestrians immune to injury or death, as UK statistics suggest that in 2015 97 pedestrians were killed, 1209 seriously injured and 4521 slightly injured whilst on, or within 50 metres, of a pedestrian crossing. One factor that may be related to the risk of a pedestrian being injured or killed when crossing the road is the light condition, as this could influence how visible the pedestrian is to the driver. A range of research demonstrates an increased risk of RTCs and resulting injuries and deaths after-dark (e.g. [3], [4], [5]). Evidence about whether this after-dark risk also applies at pedestrian crossings is currently lacking. Crossings are generally in areas that have road lighting, and supplementary road lighting is commonly used in an attempt to increase the visibility of a pedestrian crossing and anyone who is using it. However, further evidence is needed about how crossings should be lit, as illustrated by the fact that leading design guides from three different counties all disagree [6], [7], [8].

A first step towards identifying appropriate lighting for crossings is to first ask whether ambient light levels do have an impact on risk of an RTC at a pedestrian crossing. This can be confirmed by comparing the risk during daylight with after-dark. However, a simple comparison of RTC rates during daylight and after-dark may be unreliable due to a number of potentially confounding factors. For example, reduced traffic volumes after-dark can lead to increased vehicle speeds, which are associated with greater risk of an RTC and greater severity (e.g. [9]). Darkness may also be associated with increased intoxication amongst drivers as well as pedestrians which makes involvement in an RTC more likely, due to its association with evening times [10]. Darkness is also associated with colder and wetter weather, based on both time of day and time of the year, and these factors may increase the likelihood of an RTC due to poorer driving conditions. One approach to control for these confounding factors, and exposure rates, in terms of the numbers of pedestrians using the roads during daylight and after-dark, is to compare RTCs at the same time of day but under conditions of either daylight or darkness. Travel behaviour can be very habitual and often people travel the same route at the same of day, particularly when commuting [11]. Other potentially confounding factors such as motivation for travelling and intoxication levels are also likely to remain constant at the same time of day. One method for comparing different ambient light conditions at the same time of day is to utilise the biannual clock changes that occur in many countries as a result of the transition to and from Daylight Saving Time (DST) (e.g. [4]). Clocks are advanced one hour on a particular date in Spring and moved back one hour in Autumn. This creates create an abrupt change in ambient light conditions during the same time period before and after the clock change.

We used this DST method to compare RTCs involving pedestrians at crossings during daylight and after-dark. The aim was to identify if the risk to a pedestrian using a crossing is greater after-dark.

METHOD

The STATS19 database provides data for every police-recorded RTC in the UK. Details were extracted for RTCs that involved a pedestrian casualty and occurred at a pedestrian crossing (which includes zebra, non-junction pedestrian light crossings such as pelican and puffin, and pedestrian phases at traffic signal junctions). This data was filtered to only include records that occurred within a case hour, based on the time of sunset, and two control hours (14:00 – 14:59 and 21:00 – 21:59), for the 13 days before and after the 22 DST clock changes that occurred between 2005 and 2015. The case hour was selected to ensure the greatest change in ambient light condition before and after a clock change, and was defined as either the hour before sunset on the day of a Spring clock change, or the hour after sunset on the day of an Autumn clock change. The time of the case hour varied depending on the location of the RTC, because sunset times vary with latitude even on the same day. The two control hours provide consistent ambient light conditions both before and after a clock change – for example it will always be daylight between 14:00 and 14:59, and it will always be after-dark between 21:00 and 21:59, see Fig. 1. These provide a comparison with the case hour allowing factors to be accounted for that are unrelated to the change in light conditions, such as large public events, weather conditions or holiday periods. The frequency of RTCs at pedestrian crossings during the case hour when in darkness were compared against the frequency in daylight, and this ratio was compared against the same ratios but for the control hours. These comparisons produced an odds ratio (OR), as defined in Equation (1). An OR greater than one indicates a greater risk of an RTC at a crossing after-dark compared with during daylight.

$$\left(\frac{RTCs\ during\ case\ hour\ in\ darkness}{RTCs\ during\ ase\ hour\ in\ daylight}\right) / \left(\frac{RTCs\ during\ control\ hours\ when\ case\ hour\ in\ darkness}{RTCs\ during\ control\ hours\ when\ case\ hour\ in\ daylight}\right) \tag{1}$$

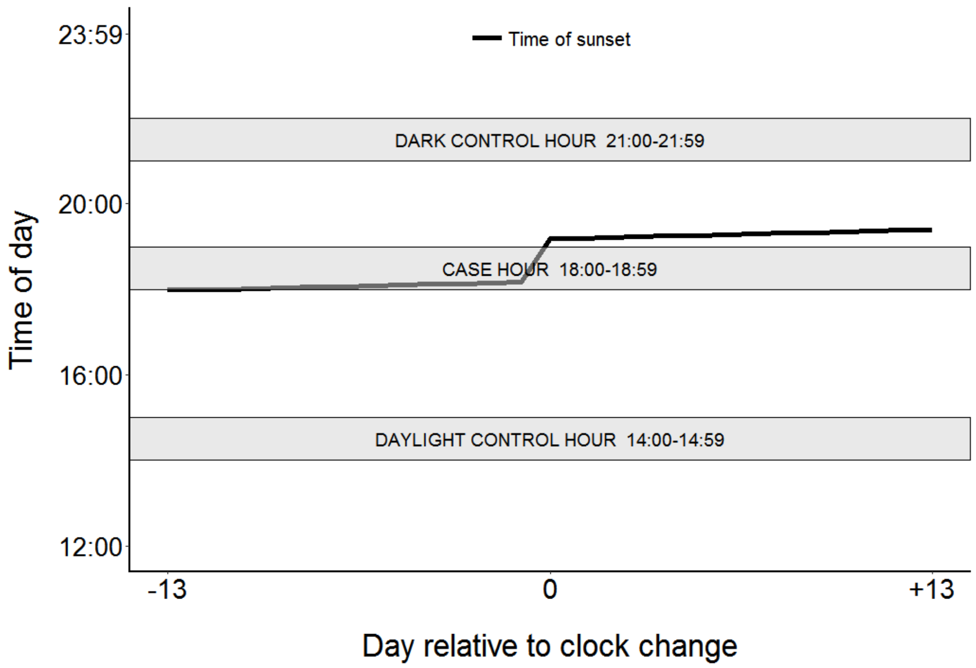

Figure 1. Time of sunset by day relative to the day on which clock change is carried out, in Spring. Case and control hours shown. Note that the case hour shown is illustrative and will change depending on location (latitude) of a specific RTC.

RESULTS

The frequency of RTCs involving a pedestrian casualty at a crossing in the case and control hours are shown in Table I. The frequencies in the case hour and in both control hours combined were used to calculate ORs that reflect the relative risk of an RTC after-dark compared with during daylight, based on Equation (1). These are shown in Table II. An OR above one indicates greater risk after-dark than in daylight. ORs for all crossing types were significantly greater than one ($p < 0.01$ for all crossing types).

The STATS19 database records what the lighting conditions were when an RTC occurred, including whether road lighting was present and lit. Such data is only relevant during after-dark conditions, so the records for RTCs involving a pedestrian at a crossing were filtered to only include those that occurred during the 13-day after-dark period of the case hour and the full 26-day period of the dark control hour. Road lighting was present and lit in 98% of these filtered records, suggesting RTCs at pedestrian crossings are not associated with a lack of lighting.

TABLE I. FREQUENCIES OF RTCS INVOLVING PEDESTRIAN CASUALTY AT A CROSSING DURING CASE AND CONTROL HOURS, 2005 – 2015.

Location of RTC	**RTC frequency, 2005 - 2015**							
	Case hour		**Day light control**		**After-dark control**		**Both controls**	
	Day	***After-dark***	***Case hour in daylight***	***Case hour in dark***	***Case hour in daylight***	***Case hour in dark***	***Case hour in daylight***	***Case hour in dark***
Zebra crossing	84	143	87	66	29	36	116	102
Pelican crossing	148	244	144	126	72	76	216	202
Traffic signal crossing	142	217	135	122	68	81	203	203
All crossings	374	604	366	314	169	193	535	507
No crossing	1037	1367	896	854	443	411	1339	1265

TABLE II. ODDS RATIOS AND 95% CONFIDENCE INTERVALS FOR RISK OF PEDESTRIAN RTC AFTER-DARK COMPARED WITH DURING DAYLIGHT, BY CROSSING TYPE

Crossing Type	**Odds Ratio**	**95% confidence intervals**	**Significance (p-value)**
Zebra crossing	1.94	1.33 – 2.83	< 0.001
Pelican crossing	7.76	1.33 – 2.33	< 0.001
Traffic signal crossing	1.53	1.15 – 2.04	0.004
All crossings	1.70	1.43 – 2.03	< 0.001

The STATS19 database also records details about the weather conditions at the time of the RTC. The relative risk of an RTC at a crossing after-dark compared with during daylight was compared between fine weather conditions and adverse weather conditions, which included rain, snow, fog and other adverse conditions. An OR was calculated using Equation (2). The resulting ORs for different types of crossings are shown in Fig. 2. All ORs were significantly greater than one ($p < 0.05$ for all crossing types).

$$\left(\frac{\substack{RTCs\ during\ case\ hour\ in\ darkness \\ and\ in\ adverse\ weather}}{\substack{RTCs\ during\ ase\ hour\ in\ daylight \\ and\ in\ adverse\ weather}}\right) \Bigg/ \left(\frac{\substack{RTCs\ during\ case\ hour\ in\ darkness \\ and\ in\ fine\ weather}}{\substack{RTCs\ during\ case\ hour\ in\ darkness \\ and\ in\ fine\ weather}}\right) \tag{2}$$

CONCLUSION

We have compared the risk of an RTC involving a pedestrian at a crossing after-dark compared with during daylight. Daylight Saving Time clock changes were used to control for potentially confounding factors such as exposure rates, vehicle speeds, weather and intoxication levels. Odds ratios for all crossing types were significantly greater than one suggesting a greater risk of an RTC at a crossing after-dark compared with during the day. This increase in risk can be attributed to the change in light levels, from daylight to darkness, since other factors were controlled for. This reduction in ambient light is likely to influence visibility levels, potentially making it more difficult for a driver to see the crossing or a pedestrian using it, but also making it more difficult for a pedestrian to see an approaching vehicle and judge its speed [12]. Visibility issues may also be heightened when there is adverse weather such as fog or rain which would explain the greater risk after-dark during such weather conditions, compared with the after-dark risk during fine weather. The role of visibility at pedestrian crossings suggests lighting may have a significant role to play in helping reduce RTCs. However, road lighting was present and lit in 98% of pedestrian RTCs at a crossing after-dark in the data we examined, suggesting there is not currently an issue about a lack of lighting at crossings, but more to do with the adequacy of the lighting. Further research is needed to identify optimal lighting conditions at pedestrian crossings to help reduce the increased risk of an RTC after-dark.

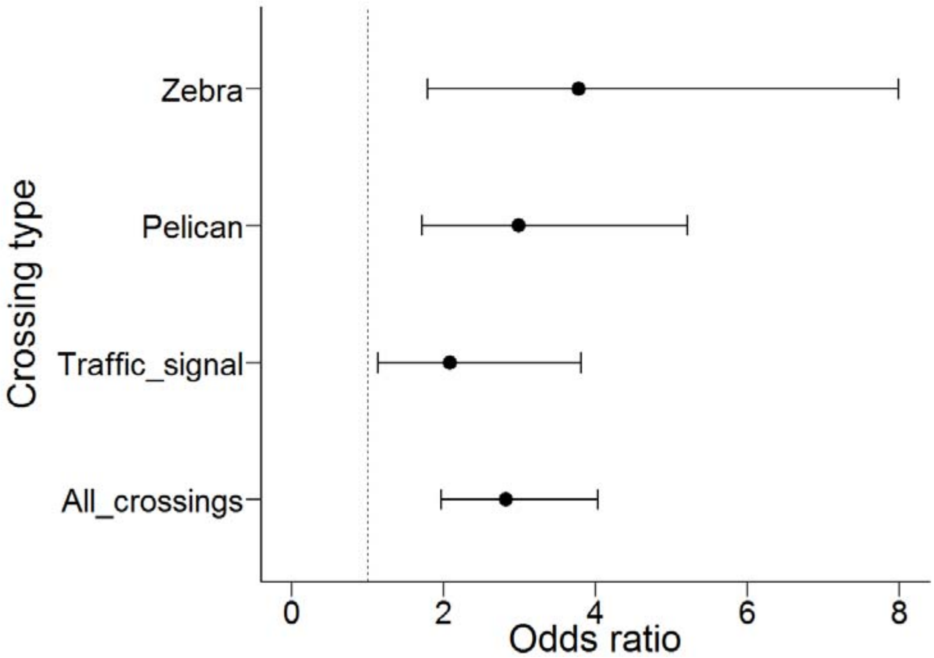

Figure 2. ORs of pedestrian RTC occurring after-dark compared with daylight, in adverse weather relative to fine weather. Lower and upper 95% confidence intervals are shown. Vertical line indicates OR of 1. An OR > 1 indicates increased risk after-dark in adverse weather, compared with fine weather.

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A Novel Method For Demonstrating That Light Encourages Pedestrian Activity

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***Abstract*—This paper describes a novel approach to establishing whether ambient light affects the decision to walk or cycle. Rather than asking people, a subjective approach likely to received biased response, we used objective data – counts of the numbers of cyclists and pedestrians passing a given location within specific periods of time. We describe three methods for capturing and analysing the data – automated counters vs on-road surveys and daylight-savings-transition vs an annual period. These data provide objective evidence suggesting that ambient light has a significant effect on the numbers of pedestrians and cyclists which has not previously been established**

***Index Terms*—ambient light, cyclist, pedestrian, travel choice.**

INTRODUCTION

Internationally, there are many government initiatives to promote walking and cycling for local journeys. This is done to improve public health through increased physical exercise and reduce the level of transport-related pollution in the environment. Reduced use of motorised transport also reduces the consumption of vehicle fuel, which is directly related to pollution in the environment [1].

One purpose of road lighting is to promote acceptable conditions for people to walk or cycle after-dark. How well does this strategy work? It is known that road lighting offers reassurance to pedestrians [2] but not whether this actually leads to more walking. One approach would be to ask people how lighting affects their decisions: such subjective evaluation is, however, likely to give a misleading opinion, either by leading the witness toward stating such positive outcome [2] or by misleading quantitative estimates [3].

In this article we report three methods we have carried out using objective data of behaviour to determine whether ambient light level has an influence on the number of people walking or cycling. These data are the counts of pedestrians and cyclists passing a certain point. In two cases these data were established using automated counters; in the third case we used manual counting by direct observation (Table I).

To isolate the effect of ambient light from other influences on walking and cycling, such as time of day and purpose of walking, we extended the daylight savings transition (DST) approach as used by others [4] to investigate the effect of ambient light on road traffic collisions. In the DST approach, data are examined for a specific hour (the case hour) in the days immediately before and after clocks are advanced or retarded, this hour being chosen as one in which the ambient light tends toward daylight one side of DST and tends toward darkness on the other side of DST. In other words, flow counts of pedestrians and cyclists were recorded in a test hour for an equal number of days before and after a daylight savings clock change, this hour being in darkness on one side of the clock change and daylight on the other side due to the one hour shift in local time.

One limitation of the DST approach for the current purpose is that pedestrian activity may be affected by issues other than ambient light level, such as changes in weather. To account for this we also considered activity in one or more control hours. These control hours are those for which it is either continuously daylight (or darkness, according to the choice) both sides of the DST clock change.

Changes in pedestrian and cyclist frequencies were analysed using an odds ratio (OR) (equation 1) following Johansson et al [5]. An odds ratio greater than 1.0 indicates an increase in activity in daylight compared with that after dark.

$$\text{Odds ratio} = (A/B) / (C/D) \quad (1)$$

For the Spring clock change:

A = Frequency during experimental period after clock change

B = Frequency during experimental period before clock change

C = Frequency during control period after clock change

D = Frequency during control period before clock change

Note that for the Autumn clock change, A and B are reversed, as are C and D, to ensure the daylight side of clock change is always the denominator.

TABLE I. SUMMARY OF METHODS FOR COUNTING PEDESTRIAN AND CYCLIST FREQUENCIES

Method	Data capture	Period	Control hours	Data analysis
1	Automated counters	5 years (Autumn 2011-Spring 2015): 13 days before and after DST.	4 (two daylight and two dark)	DST
2	Automated counters	4 years (2012-2015): whole year data	2 (daylight and dark)	Annual
3	On-road observation	1 year (2016); 5 days before and after the spring clock change	1 (daylight)	DST

METHOD 1

This used flow data recorded by 29 automated counters located across a US district (Arlington County, Virginia) which were installed since 2009. Flow counts of pedestrians and cyclists were extracted for a test hour for 13 days before and after the spring and autumn DST in each year, the case hour being 18:00-19:00 (dark to day transition) in Spring and 17:00-18:00 (day to dark transition) in Autumn. There were four control hours, these being 1.5 and 3.5 hours before and after the case hour: multiple control periods were selected to explore whether this choice affects the results.

The results (Table II) show odds ratios of greater than 1.0 for all control hours and for pedestrians and cyclists. Odds ratios are themselves indications of effect size, but for reference it may be useful to note that odds ratios of 1.22, 1.86 and 3.00 have been equated to Cohen's small, medium and large effect sizes [6],[7]. These data therefore suggest that more people choose to walk or cycle when it is light rather than dark.

METHOD 2

Method 2 employed the same data set as for method 1 (the automated counters in Arlington, Virginia) but used an alternative method of analysis (Figure 1). Johansson et al [5] noted, with regard to traffic accident studies, that the DST approach may introduce bias attributable to seasonal variation in transport decisions, for example, conditions are likely to get worse as winter approaches, and by considering only a small number of days before and after clock change reduces the data set. In the Johansson et al method a case hour is chosen which, according to the seasonal change in daylight, tends towards daylight for one part of the year and towards darkness for the remaining part of the year. Here the case hour was 18:00 to 18:59. Two control hours were employed, defined such that they would always have the same light condition throughout the year (either daylight or darkness) and these were 15:00 – 15:59 (daylight control hour) and 21:00 – 21:59 (dark control hour).

An odds ratio was again used to compare pedestrian and cyclists frequencies in day and dark periods. The results (Table II) again show OR>1.0 in all cases, and thus the increased likelihood of people walking or cycling when it is light compared with dark.

METHOD 3

Method 3 used the same analysis as for method 1 (the DST approach) but with a different data set - pedestrian and cyclist flow data captured by on-road observers, an approach needed to study locations where automated counters are not installed. This was done for five evenings before and after clock change in two locations (suburban and city centre) of one city (Sheffield, UK). The City location was approximately 1.2 km from the city centre and had a high number of shops and commercial properties. Local knowledge also suggested there would be a relatively high number of pedestrians and cyclists. The Suburban area was approximately 4.2 km from the city centre and in a residential neighbourhood, with housing being the dominant building type in the immediate area. There were separate observers at the two locations and their positions were kept constant throughout both weeks. The frequency of pedestrians and cyclists was recorded during the control (17:30-18:00) and case (18:30-19:30) periods. This included any pedestrian or cyclist who was visible on the street from the observer's location, passing in either direction, but did not include pedestrians who were seen getting out of or into a vehicle.

The results of the on-road survey, as shown in Table 2, are mixed, with OR>1.0 for pedestrians and cyclists each at one location only. Where the OR is not suggested by these data to depart significantly from 1.0 means that the changes in flow were similar in the case and control periods, and in the latter the light condition did not change. This mixed finding may be due to the specific control period used or to the small sample of locations.

TABLE II. RESULTS OF PEDESTRIAN AND CYCLIST FLOW ANALYSES: ODDS RATIOS COMPARING CASE AND CONTROL HOURS AND 95% CONFIDENCE INTERVALS (CI)

Method	Control hour	OR pedestrian (95% CI)	OR cyclists (95% CI)	Different from OR=1.0?
1	Late dark	1.59 (1.54-1.63)	1.37 (1.33-1.41)	Yes**
	Dark	1.17 (1.15-1.2)	1.37 (1.34-1.39)	Yes**
	Early Day	1.75 (1.72-1.77)	1.43 (1.41-1.45)	Yes**
	Day	1.73 (1.71-1.76)	1.36 (1.34-1.37)	Yes**
	Overall	1.62 (1.60-1.63)	1.38 (1.37-1.39)	Yes**
2	Day	2.25 (2.23-2.27)	1.75 (1.74-1.76)	Yes**
	Dark	1.08 (1.06-1.09)	1.22 (1.20-1.24)	Yes**
	Overall	1.93 (1.92-1.95)	1.67 (1.66-1.68)	Yes**
3	Daylight (location 1: city)	0.94 (0.89-0.99)	1.27 (1.04-1.54)	No (pedestrians) Yes* (cyclists)
	Daylight (location 2: suburban)	1.62 (1.33-1.99)	1.07 (0.58-1.99)	Yes** (pedestrians) No (cyclists)
	Overall	0.98 (0.92-1.03)	1.26 (1.04-1.51)	No (pedestrians) Yes* (cyclists)

* p<0.05, ** p<0.01

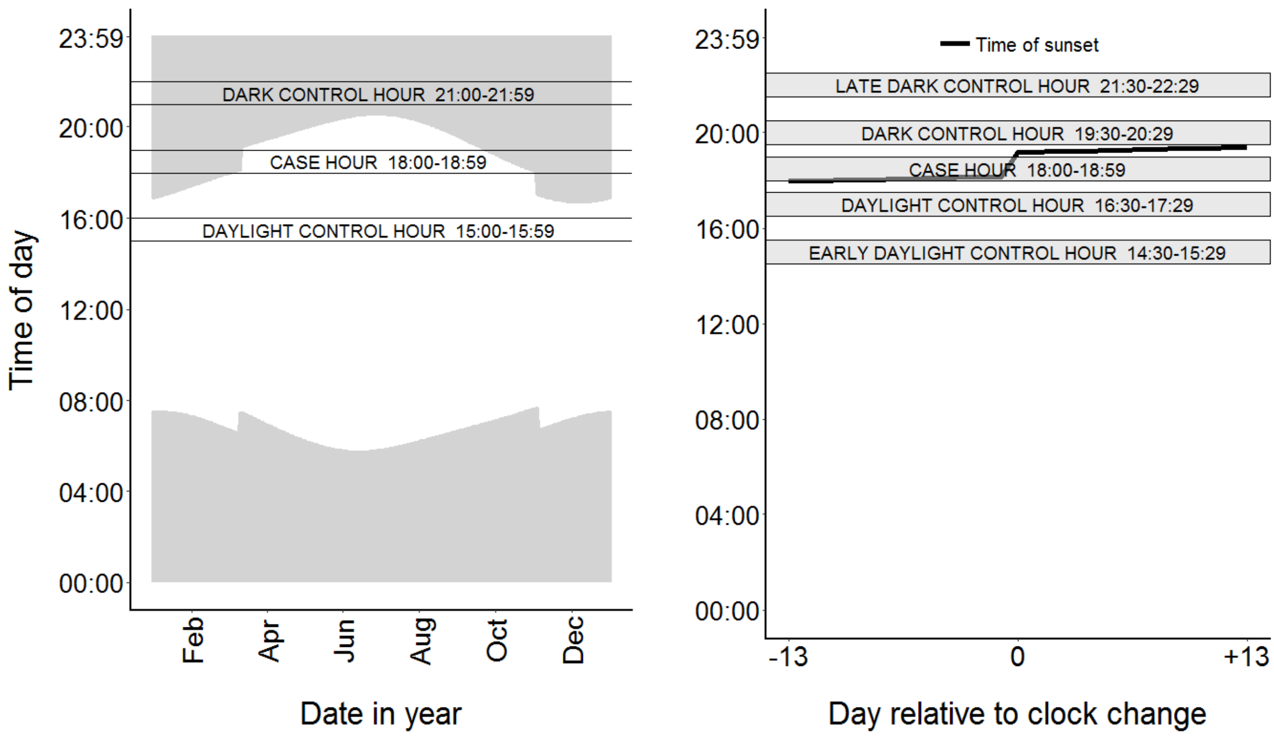

Figure 1 illustration of approaches to using time of day to filter the travel flow data: annual approach used in method 2 (left); dst approach used in methods 1 and 3 (right).

CONCLUSION

Three conclusions are drawn from this work. Taken together, results from all three methods tend to show an odds ratio significantly greater than 1.0, indicating that more people choose to walk or cycle in light rather than dark. In other words, the level of ambient light has a significant effect on travel choice. The magnitude of the OR varies depending on whether it relates to pedestrians or cyclists, which control period is used and which analysis method is used. However, the majority of ORs lie between 1.2 and 2.3, which represents a small to medium effect size based on Olivier and Bell's definitions [6].

Generally, both the annual and DST approaches agree that effect of daylight is greater for pedestrians than for cyclists. The observer counts from Method 3 are slightly ambiguous, but this is likely due to small sample of data, observer error, and smaller control period (30 minutes rather than 1 hour). Our preliminary conclusion regarding the choice of control periods is that there should be at least two, a day and a dark period, these scheduled to be at least 2 hours away from the case hour to reduce spill-over effects (i.e. counting a traveller who commenced their journey long before the observation hour) but this remains to be validated.

This work shows that ambient light matters for travel choice. The next step is to determine whether changes in illuminance after dark also affect travel choice. In further work this approach will be used to investigate the influence of changes in road lighting on pedestrian and cyclist counts, specifically, whether this method is able to detect variations in pedestrian and cycling frequencies due to changes in illuminance and spectral power distribution.

ACKNOWLEDGEMENT

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Spectral Reflectance of Argentinean Road Surfaces

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***Abstract*— CIE publication No 30-2 notices that road surfaces are not completely spectrally unselective, nevertheless, incandescent lamps are recommended for standardized road sample measurements used in road lighting. In this way, the effects on reflection of luminous sources spectra used on the road are disregarded. Recently, Argentinean studies carried out from standardized simultaneous measurements of illuminance and luminance found an inverse dependence between white to yellow lamp spectra. The study found an increase of average luminance coefficient "Qoo" of around 20 percent for led (white) luminaires against High Pressure Sodium (HPS) lamps.**

A spectral study on samples of Argentinean draining road surfaces is presented in this paper. Size standardized samples were measured using a focused spectra meter as detector. A traditional high pressure sodium lamp (HPS) and a street led luminary were used as light sources. A specially built diffuse surface was used as reference in order to compare the spectral differences in reflection.

As a result, color selectivity was found. The spectral samples selectivity produced a photopic absorption between 5 to 15 percent greater in HPS lamp spectra than led source.

***Index Terms* — Led, Road Lighting, Road Reflection, Spectra.**

INTRODUCTION

In road lighting, the visual perception of the driver is conditioned by the luminance distribution on the surface of the lit road. In this model, known as Luminance Technique, reflection properties of the road surface are characterized by the luminance coefficient "q", proportionality factor, for each road point, between its illuminance and the luminance reflected in the observation direction. The integer of luminance coefficient "q" on a solid angle that underlies a road element is called average luminance coefficient Qo, useful factor for evaluating the degree of "lightness" of the road surface.

A. Luminance Coefficient

The luminance L of an elementary surface ΔS on the road (Fig. 1) is determined by (1):

$$L = \frac{I(C,\gamma)}{H^2}\, q(\alpha,\beta,\delta,\gamma)\cos^3(\gamma) \tag{1}$$

I(C,γ) is the lighting intensity of the luminary in direction to the point where luminance is calculated, H the height of the luminary installation and q the road luminance coefficient.

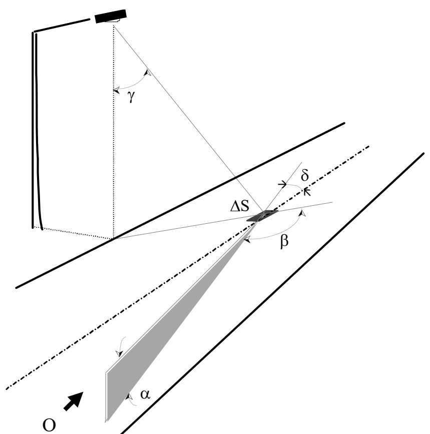


Figure. 1. Basic geometry for the vision analysis in roads

The luminance coefficient depends completely on the road surface: basic material, binder composition, application method final texture, time of use, etc. Far from being a constant, its value depends on the positions of the observer and on the lighting source with respect to the point under consideration. Studies showed that a valid simplification is to fix the observation angles: it has been standardized the driver's vision line parallel to the road axis ($\delta = 0°$) and its elevation so that it has an impact on the vision point with a slope $\alpha = 1°$. Thus, the standardized conditions for vision on road consider q dependent only on β and γ [2].

If E is the exact illuminance on the road, (1) can be rewritten as:

$$L = q(\beta;\gamma)E \tag{2}$$

The luminance coefficient complies with the function of proportionality factor, for each road point, between illuminance and luminance. Thus, it is defined the average luminance coefficient Qo, which quantifies the degree of "lightness" of the road surface:

$$Q_0 = \frac{1}{\Omega_0}\int_{\Omega_0} q d\Omega \tag{3}$$

In (3), Ωo represents the solid angle that underlies the element Δs of Fig. 1. As it was mentioned in previous paragraphs, higher values of Qo, associated with "lighter" surfaces, will allow obtaining an increase in average luminance, for a same system of lighting (thus, increasing the installation efficiency).

B.Coefficient Qoo

If there is an enough amount of simultaneous evaluations of accurate luminances and illuminances on several sections of a road surface, it is possible to use factor Qoo, relationship between average luminance and average illuminance, as an empirical approximation of the road degree of lightness:

$$Q_{00} = \frac{Lm}{Em} \tag{4}$$

Although there is no theoretical relationship between Qo and Qoo definitions, the low dispersion obtained in the analysis of an important number or luminance and illuminance evaluations allows inferring a good performance of this coefficient as marker of the road lightness degree [1]-[4].

Figure 2 summarizes the results obtained in the mentioned studies. In this figure, M1, M2, etc. correspond to different sectors or motorways with homogeneous surfaces, being HPS and LED the light system of the studied installations.

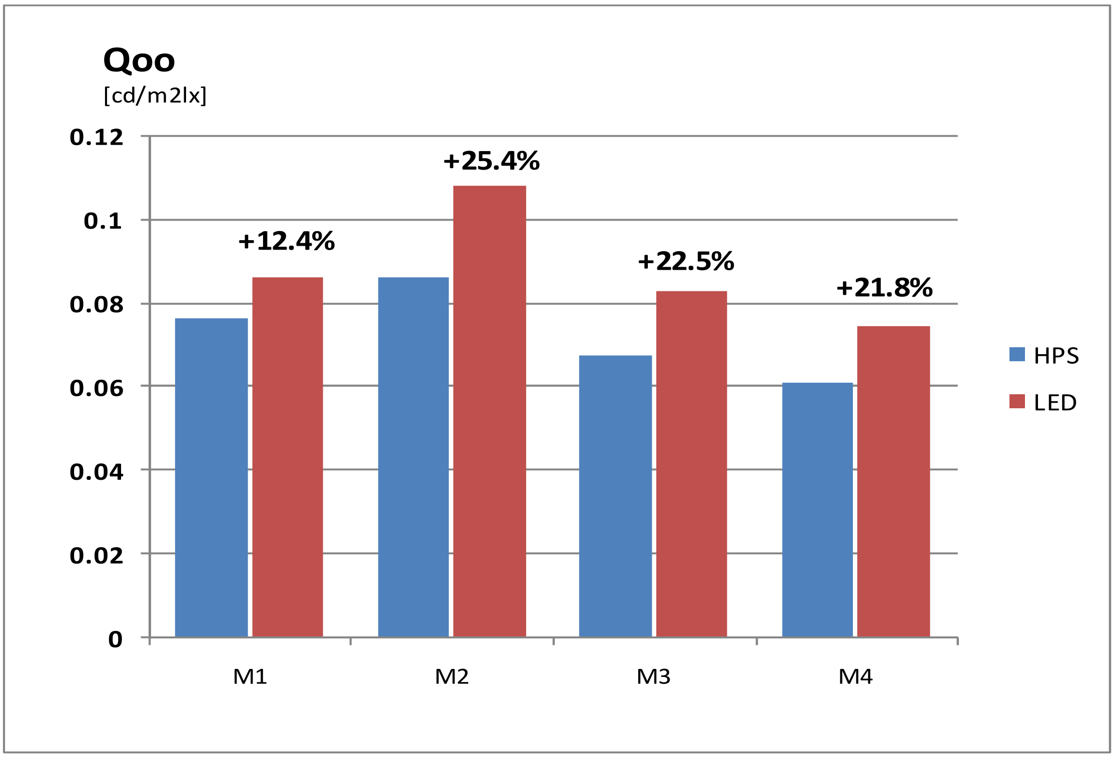


Figure 2. Qoo values (extracted from [4])

DEGREE OF LIGHTNESS UNDER LED LIGHTING

The aim of the present work is to verify whether there is any change in the average luminance coefficient assignable to white led light. In other words, it is intended to find some kind of spectral selectivity in the reflection on the surface.

A. Background.

Ekrias [6] studied the spectral reflection of eleven types of asphaltic compounds from Finland, combining samples of "natural" surfaces and with aggregates of color pigments for clarifying them. His measurements were based on circular samples, of 100 mm in diameter, incidence angles β= 20º and elevation γ=55º. The observation angle α was 35º, larger than standard CIE of 1º. Figure 3 allows observing some samples used in such research. In the image, it can be observed an important size of stone, with a much smaller proportion of binding asphaltic compound than that of surfaces in use in our country. Besides, some of the samples presented a reddish tone, possibly due to coloring aggregates.

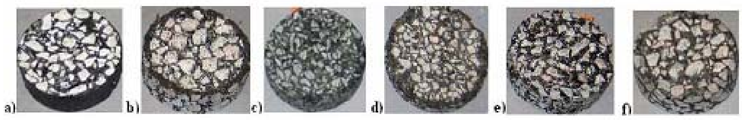


Figure 3. Samples of surfaces used in [6]

The mentioned tone is shown in the spectra obtained by Ekrias, which evidences a slight increment in their reflectance towards the red zone of the spectrum.

Adrian's studies [7] show similar results. In this case, the studied samples were asphaltic concretes or concretes, without specifying the use of any type of coloring aggregate. Figure 4, extracted from [7], shows a growth in the reflectance for growing wave lengths, similar to that found in [6].

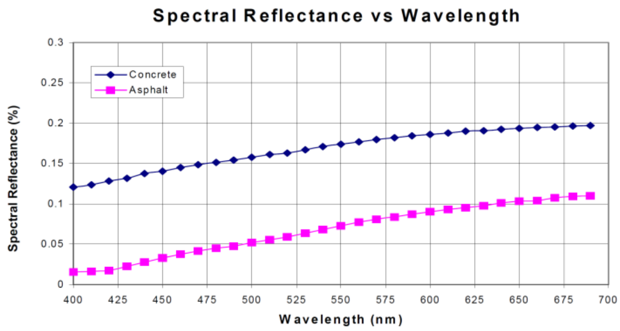


Figure 4. Results of Adrian's spectral studies

American studies [8] show an increase in the reflectance towards the red, more evident on surfaces worn out due to several years of use. It is noteworthy the coincidence among studies from distant places (USA – Europe), despite the high regional influence on the surface composition and the use or non-use of coloring aggregates.

SPECTRAL STUDY

A. Measurement diagram

Works were carried out on three samples, shown in Fig. 5, of standardized dimensions for evaluation of road samples [2]. The samples were extracted from access motorways to Buenos Aires City in the period 2003 to 2007. The three studied samples were of asphaltic concrete, draining type, cold application.

Figure 5 also shows a diagram of the measurement system. The light source was placed in β=0º, using three angles of vertical incidence: γ = 0º, 15º and 30º. The spectrum reflected by the sample was recorded with a spectrometer Avantes Starline, AvaSpec 2048 [9]. The optic fiber entrance slit was adjusted to 5° observation angle, higher than CIE standard.

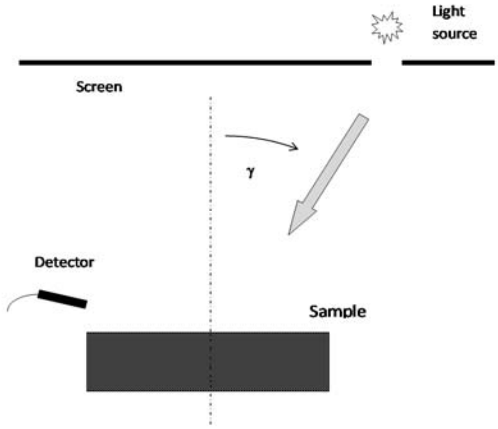
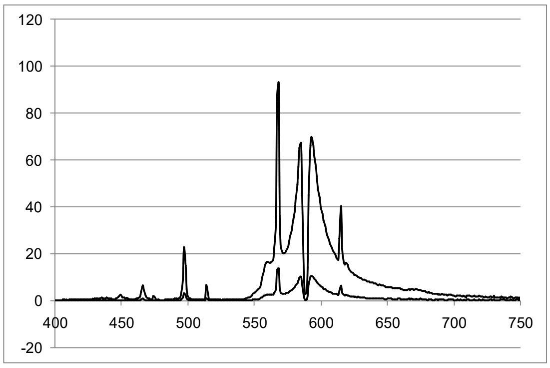


Figure. 5. Studied samples and set up of measurement system

Two light sources were compared. On one hand, HPS lamp, tubular clear bulb type was used. On the other, a plate with Surface Mounted Devices (SMD) led components, with road lighting refracting lens, chromatic features x= 0.328, y= 0.350, CCT= 5697 K was used as led source. The spectral reflection of road samples was obtained for both lighting sources, by using a reference diffuse surface built with a wooden board painted with *integrating sphere paint* (barium sulfate pigment in water with Carbo methyl cellulose as adherent).

B.Results

Figure 6 presents the reflected spectra of the reference diffuse surface and sample 1, for γ=15º, for both lighting sources. The diffuse reflectance coefficient for the reference was 0.85.



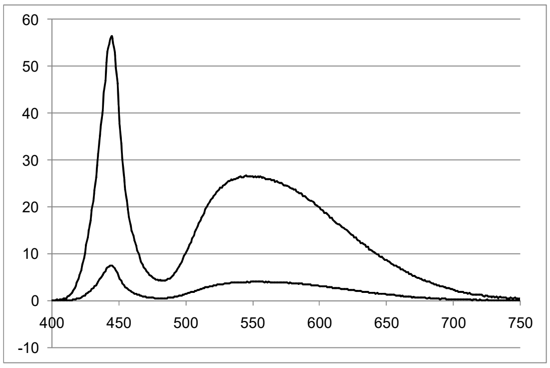


Figure. 6. Reflected specters: HPS lamp (left), Led (right). Intensity in [mw/cm2 nm], wavelength in [nm]

The relationship between sample and reference reflection, weighted by 0.85 reference reflectance, was used as indicator of spectral reflectance of each sample. These values, for the lighting condition before mentioned and for the three samples, are shown in Fig. 7. No significant differences were found for the γ = 0º and 30º illuminating conditions.

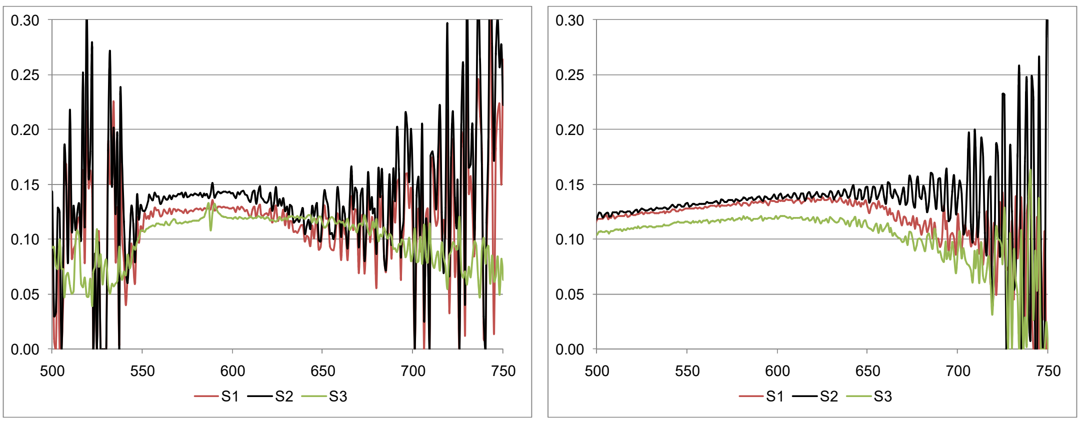


Figure. 7. Spectral reflectancies under HPS and led luminous sources

At the beginning and at the end of the drawn spectrums, with very low reflected intensity values and depending on spectrometer resolution, the relationship resulted in no coherent numbers. These spectral sectors were disregarded in the analysis.

B.Result analysis

A soft growth with wavelength growing tendency can be observed, similar to that found in Adrian´s study. Nevertheless, Fig. 7 evidences a tendency change starting approximately from 620 nm. As HPS lamp has an important portion of its spectra between 600 to 650 nm, it is predictable a relative decrease in the average luminance coefficient compared with led lighting.

For evaluating the "photopic" effect of these differences and being able to quantify with a unique number, representative of the average reflection in the visible zone (value only valid for the measuring conditions of our experiment), factors F1 and F2, proportional to photopic reflection, were defined and calculated as:

$$\mathrm{F1} = \int \varphi\mathrm{HPS}(\lambda)\, \mathrm{V}(\lambda)\mathrm{d}\lambda \tag{5}$$

$$\mathrm{F2} = \int \varphi\mathrm{led}(\lambda)\, \mathrm{V}(\lambda)\mathrm{d}\lambda \tag{6}$$

In (5) and (6), V(λ) is the standardized curve of the spectral sensitivity of the human eye and φ(λ) are the measured spectral reflectancies, "HPS" for sodium and "led" for led lighting in the already mentioned conditions.

Table I summarizes the result of the performed calculation. It is observed a difference in favor of led reflection ("gain") close to an average of 10% for the studied surfaces, for the observation and lighting conditions already mentioned. The calculation range was limited from 500 to 700 nm.

TABLE III. RESULTS OF PHOTOPIC COMPARISON

Sample	**Spectrum**	**F =** $\int \varphi(\lambda)\,\mathrm{V}(\lambda)\mathrm{d}\lambda$	**Relative difference** (F2-F1/F1)
S1	HPS	11.2	15 %
	Led	12.9	
S2	HPS	13.0	1.5 %
	Led	13.2	
S3	HPS	10.0	15%
	Led	11.5	

CONCLUSIONS

The results found are in agreement with previous studies carried out in this laboratory and the research performed in Europe and USA regarding the existence of a soft dependence of the reflection on surfaces with the incident light spectrum. This implies a slight coloring towards reddish green that appears in all studies despite the different research techniques used and the type and composition of surfaces studied.

The study with actual surfaces, in use in the metropolitan area of Buenos Aires (Argentina) allowed correlating this "spectral selectivity" with an increment (gain) in the lightness degree when leds are used compared to the high pressure sodium spectrum. The Qoo improvement found in motorways were of an order of 20% average, whereas in the spectral study on three samples, the increment could be estimated up to 10%. It is worth mentioning here that in the last case the samples were surfaces not necessarily similar to the actual ones in use nowadays. However, the agreement, at least in tendency, indicates a new advantage of led technology and its link to energy efficiency.

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Refurbishment of Lighting Systems in Kindergardens – Case Studies for Bratislava

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***Abstract*— The paper is aimed at aspects of refurbishment of obsolate lighting systems by installation of modern T5 high-performance lighting and DALI based lighting control. Refurbishment does not cover solely classrooms and similars but concerns the whole buildings including also management offices, corridors and stairs, kitchens, dining rooms, storage rooms etc. The paper illustrates the solutions of lighting refurbishment in five kindergardens in Bratislava as case studies. Energy balance is evaluated as well although energy saving was not the leading motivation for refurbishemt – it was as it should always be in such cases – creation of healthy lighting environment for humans, our children.**

***Index Terms*-- energy efficiency of lighting , interior lighting, lighting in kindergarden, lighting system, refurbishment of lighting.**

INTRODUCTION

Educational buildings, in general, are buildings with complex functions comprising diverse visual tasks and requirements. Quality of lighting is crucial as lighting system users are growing children whose eyes are yet in development. This concerns pre-school facilities in particular: young kids between 3 and 5 of age are very sensitive to visual conditions and insufficient or otherwise improper lighting may irreversibly harm their eyes. On the other hand, visual comfort significantly contributes to the friendlyness of the environment, decreasing the stress of being parted from their parents for a while what is one of the social aspects of education in kindergardens.

Good lighting in classrooms or playrooms must balance visual performance and visual comfort for diverse activities during different periods of day and for various external conditions (like daylight availability). Lighting must be intensive enough but the same time emphasize of other aspects of illumination must be regarded, including uniformity, glare prevention, light colour, modelling etc. Unlike in primary schools, activities in kindergardens are half oriented to learning and half to guided or unguided playing games, individually or in groups, an hour or two for afternoon sleeping. Environment has still remind a home. Lighting must fulfil and cover all these different requirements.

Situation in buildings with old (> 25 years) lighting systems is well studied in Slovakia. Studies are based on audits of a number of buildings throughout the country. The paper will publish summary of the findings. There are still buildings (1950 - 1970) where incandescent bulbs make almost 100 % of all the lighting. Newer buildings (1970-1990) are typical for T12 or T8 fluorescent lighting and luminaires equipped with conventional magnetic ballasts. It is a miracle that fluorescent tubes made before 1990 (now 27 years old) are still in operation. The paper presents an average structure of rooms in kindergardens and average figures of the state-of-the-art.

NORMATIVE REQUIREMENTS FOR ILLUMINATION OF KINDERGARDENS VERSUS REALITY

Requirements for lighting in schools and educational buildings are established in legislative documents and technical standards, mainly in EN 12464-1 which is oriented to illumination of workplaces. In Slovak Republic, kindergartens are managed and financed by municipalities. This leads to situations when allocation of budget for improvement of buildings' infrastructure often do not belong to main priorities or is simply insufficient, moreover, dependant on political decisions. New buildings are built very rarely, kindergardens occupy older buildings with very obsolete lighting systems. In most of buildings age of these systems is more than 20 years and in many cases even much more. Lighting levels are deeply under any standard, maintenance is insufficient or ignored at all, big number of incandescent lamps is just a waste of energy, but also installations with fluorescent lamps are very inefficient. In spite of this fact, modernisation of lighting systems cannot be supported solely by energy savings, because current illuminance is very low (often less than a fifth of required values) and new systems have to fulfil current standards. This is a serious complication towards decision makers. Therefore, modernisation activities are supported by different approach – appeal on hygienic aspects of lighting.

State-of-the-art of lighting of kindergardens in Slovakia

A.Major Problems Of Lighting Systems

Bad condition of lighting systems is inherited from the past. Buildings have been constructed decades ago and age of lighting systems correspond with the age of buildings. Luminaires mounted before 1990 are usual, though luminaires from 60’s are not so rare as well. New or reconstructed systems are mostly exceptional. Overview of dominant lighting solutions in kindergardens built in different periods of time is in Table I.

TABLE I. Dominant lighting solutions in kindergardens

<table>
<tr><th>Period</th><th>1950 – 1960</th><th>1960 – 1970</th><th>1970 – 1980</th><th>1980 – 1990</th><th>1990 – 2000</th><th>2000 – 2016</th><th>2016 +</th></tr>
<tr><td>Lamps</td><td>Incandescent lamps</td><td>T12 fluorescents</td><td>T12/T8 fluorescents</td><td>T8/T12 fluorescents</td><td>T8/T5 fluorescents</td><td>T5/T8 fluorescents</td><td>LED</td></tr>
<tr><td rowspan="4">Luminaires</td><td colspan="2">pendant with a shade or globe diffuser</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">ceiling-mounted with plastic louvres or opal diffuser</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">ceiling-mounted with opal or prismatic diffuser</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="3">ceiling-mounted or built-in with aluminium louvres or prismatic diffuser</td></tr>
<tr><td>Control gears</td><td></td><td>EEI = D</td><td>EEI = D/C</td><td>EEI = C/D</td><td>EEI = B/C/A3</td><td>EEI = B/A3</td><td>–</td></tr>
<tr><td>Lighting control</td><td colspan="4">Manual</td><td>Manual + sensors</td><td>Manual + DALI</td><td>DALI + diverse functions</td></tr>
</table>

B.Lamps

Share of inefficient light sources is extremely high (Fig. 1). Surprisingly big number of incandescent lamps are still operated (Fig. 2). They are prevalently used in round-shaped surface mounted or pendant luminaires with diffuse globe, both for 60 W lamp. Such luminaires can be still found in many classrooms, offices, kitchens etc. Situation with fluorescent lamps is not better (Fig. 2). It is common to find 20-years and older tubes in luminaires, mainly T12/40W types. Until they are not blinking or stopped to lit, remain to be operated in spite of their low luminous output. Thanks to disregarded maintenance the lumen losses are often below 40 % of their initial value, consuming the same amount of energy. Usually, the cheapest tubes with standard luminophor are used, colour rendering is therefore not satisfactory. Lamps of different colours are sometimes in the same luminaire side by side (Fig. 3).

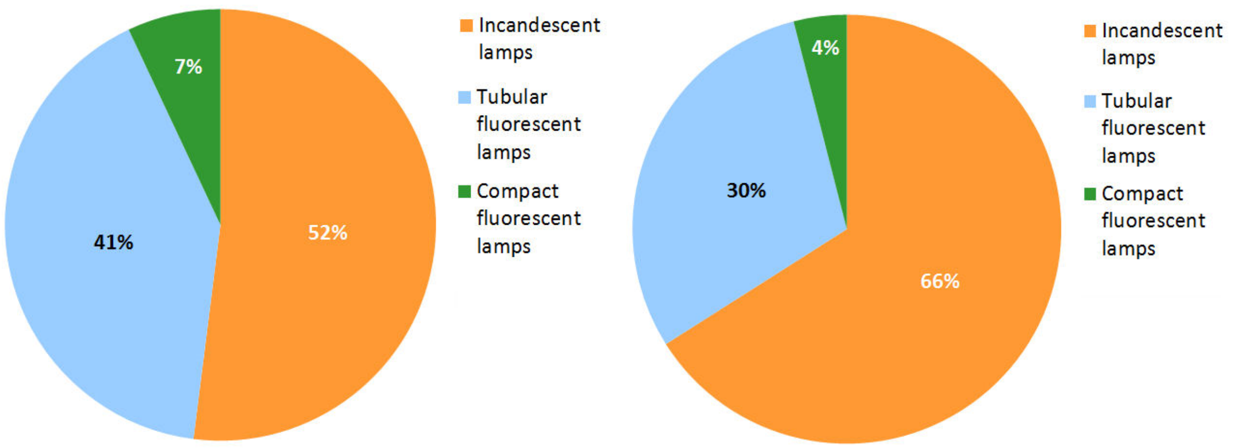
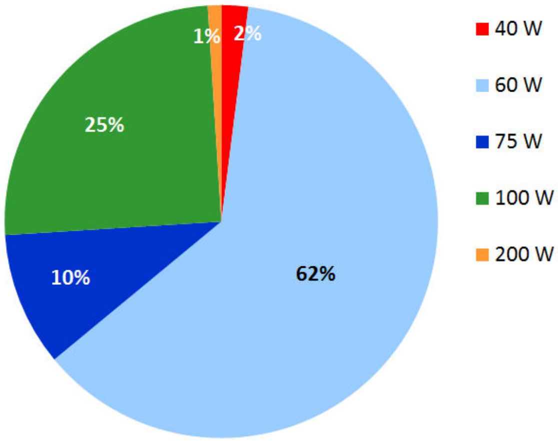


Figure 1. General lamp structure in kindergardens – piece share (left) and power share (right)

C.Luminaires

Perhaps the biggest problem is an inadequate choice of luminaire type for particular applications. Most of luminaires, both for incandescent bulbs or fluorescent tubes, are equipped with a white diffuser. This provides highly uniform illumination but absence of directional light leads to uninspiring monotonous environment and visual fatigue – and it is not easy to attract and keep a constant attention of children during the educational process. Condition of luminaires corresponds to their age and maintenance quality. While in some kindergardens with extra old luminaires these are kept functioning in a relatively good state, in others there are many luminaires with broken covers or bodies, broken or dirty diffusers, rusty reflectors, damaged or non functional sealing in luminaires of higher IP class (fig. 4). Electrical efficiency of fluorescent luminaires is low due to conventional magnetic ballasts with energy class D or C. Flickering of light usually acts subconsciously and it is perceived unintentionally, what in combination of long time influence and young growing organism may cause psychological problems (neurosis).



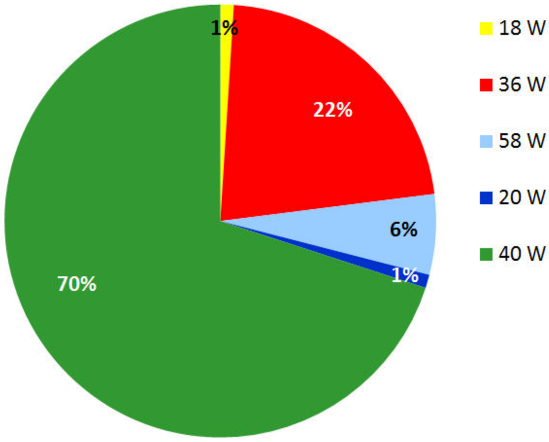


Figure 2. Structure of incandescent lamps (left) and fluorescent lamps (right) of different wattage in kindergardens – power share

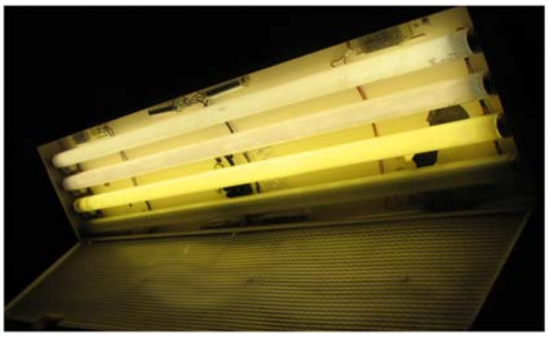


Figure 3. Fluorescent lamps with different light colours mixed in the same luminaire

Figure 4. Dirt and dust inside of a luminaire with IP 54 ingress protection class

D.Lighting Systems

Geometry of lighting systems often provide no preconditions for good lighting as well. Number of installed luminaires is not sufficient to cover the needed quantitative lighting parameters even if these luminaires are of most efficient and modern types. But some other classrooms are overlit (regarding the control of groups of luminaires) and there are real options to reduce the power consumption and keep the required lighting level. For analyses of lighting systems it is useful to know the area share of different kind of rooms. In average the largest area of kindergarden is taken by classrooms (33 %). Share of corridors is 18,2 %, dressing rooms 8,3 % and storage rooms 5,2 %. Other kind of rooms individually do not make more than 5 % but in total they make 35,3 %. Room types can be grouped together according to the required horizontal illuminance as per EN 12464-1. Results of this statistical evaluation are depicted in Fig. 5. The graph shows that half of the area has to be illuminated to at least 300 lx.

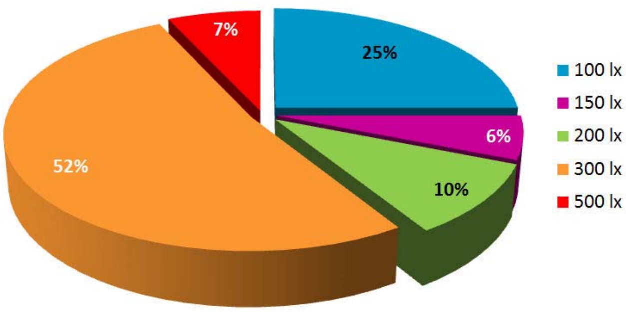


Figure 5. Structure of rooms in kindergardens according to the required illuminance level

CASE STUDIES FOR THE CAPITAL CITY BRATISLAVA

This paper aims to present refurbishment of six kindergardens in the capital city Bratislava as the case-study. All the kindergardens are located in the Petržalka quarter which was built in the period of half 70's till the half 80's (see Table I) according to unified project documentation, i.e. the buildings as well as the lighting systems are very similar to each other, though with minor modifications and minor changes during the lifetime. The similarity is a good starting point for evaluation and comparison. Some classrooms were equipped with pendant luminaires for incandescent lamps with a globe diffuser (Figure 7), some with luminaires for fluorescent lamps T8/36W and D class ballasts with prismatic diffusers ((Figure 6). Many other rooms have installed small luminaires for incandescents E27/60W (Fig. 8).

Figure 6. A classroom (playing room) before and after reconstruction (Turnianska)

Figure 7. A sleeping room before and after reconstruction (Turnianska)

Figure 8. Stairs before and after reconstruction (Turnianska)

It is very important to emphasize that in many rooms the illuminance level is very low and do not satisfy current normative requirements. For example, in classrooms the illuminance is about one third to one quarter of the required, in corridors one quarter to one sixth of the required. When refurbishing the lighting system, first it is necessary to bring the illuminance level to the desired value and the potential energy savings can be only the positive side-effect of the measures.

Kindergardens with refurbished lighting systems are listed in Table II, they are sorted according to the energy balance in the right-most column. First three objects were refurbished in the period of 2015 without lighting control. The other three objects were refurbished in 2016 with lighting control. Lighting control comprised DALI based switching and dimming with combined sensors with presence and daylight control and constant light output (CLO). In corridors, stairs and social rooms sensors control the lighting by presence and switch by daylight availability. The results show that due to low lighting level of the old system, energy balance without lighting control is often positive.

TABLE II. OVERVIEW OF KINDERGARDENS IN BRATISLAVA WITH REFURBISHED LIGHTING SYSTEMS

Object	R_T	R_C	A (m²)	N_O	N_N	$N_\%$	P_O (kW)	P_O (kW)	$P_\%$	$W_\%$
Bulíkova	72	8	1 029,3	192	147	-23,4	11,3	13,5	+19,4	+19,4
Bradáčova	72	8	1 009,3	190	144	-24,2	10,2	10,6	+4,3	+4,3
Iľjušinova	126	17	2 259,0	409	290	-29,1	24,3	23,9	-1,8	-1,8
Strečnianska	112	16	2 071,0	397	269	-32,2	24,0	22,2	-7,6	-16,4
Bzovícka	90	13	1 803,9	336	247	-26,5	21,0	18,3	-12,9	-18,8
Turnianska	112	15	2 175,5	428	275	-35,7	29,2	20,6	-29,3	-32,1

Key:

R_T rooms total
R_C classrooms (playing and sleeping rooms)
A total area in m²
N_O luminaires before refurbishment
N_N number of luminaires after refurbishment
$N_\%$ balance of luminaires in %
P_O input power before refurbishment
P_N input power after refurbishment
$P_\%$ balance of input power in %
$W_\%$ balance of lighting energy consumption in %

Lighting control helps significantly to achieve energy savings whilst good lighting quality is provided. On the other hand, upgrade of the lighting system was not always felt by the users (teachers/educators) as comfortable and they complain about automatic control – they prefer manual only and just the simple switching. This opinion can be explained as an older custom, what is a question of time to get over. For lighting operator, however, the energy savings are important to reduce the electricity bills.

Energy savings are not high enough to result in short payback times. Total costs for refurbishment for the objects with lighting control are between 45 000 to 50 000 euros while the savings of costs for electricity make around 2 000 euros; the simple payback time is then around 20 years (or more) what is comparable with the predicted lifetime of the refurbished lighting system. Anyway, this measure must be deemed as necessary to satisfy adequate lighting levels and also because the old lighting system is simply obsolete – almost 40 years old luminaires are twice of their nominal lifetime.

CONCLUSIONS

Status quo and conservation of the situation in lighting is given by legislative changes related to the governmental decentralisation when priorities have been focused particularly on basic functionality of educational buildings. Today this is changing and kindergardens as well as other educational buildings concentrate on various development programmes. Financial funds and mechanism for renovation of buildings and their infrastructure as well as improvement of conditions for education are more and more available. Role of lighting is of high importance and should belong to highest priorities within renovation programmes. Auditing lighting systems should help the process significantly.

Energy savings can be achieved only by conscious and complex reconstructions of lighting systems and significantly depend on starting point described by audit for each individual building. Situation varies from positive energy savings of about – 30 % to increase of energy consumption after reconstruction when old systems are underdimensioned (energy balance up to + 20 %). But the same time it is necessary to mention that possibly energy savings have to be understood as a positive side effect and hygienic aspects should be the motor of lighting reconstruction, i.e. creation of high quality lighting environment in accordance with relevant regulations and standards. Overall rationalisation of lighting and increase of its efficiency and performance should be the result. Here the lighting control helps significantly, even for objects with insufficient lighting levels the energy balance is always positive.

Today there is a huge potencial in implementing the raising LED technology. In 2017 there are some new projects of the refurbishment of lighting systems in kindergardens in Bratislava in preparation, all with new LED luminaires. Interim results say that the energy savings can be around 40 – 50 % in the case of objects with insufficient lighting levels. Primary schools and high-schools in the same region and time period of installation have this potential yet higher, up to about 70 % bacause here the illumination in classrooms often exceeds the requirement. These results are, however, just preliminary and will be published in future papers.

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Concept of Lighting System for Experimental Studies in Interiors

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***Abstract*—In this paper a concept of lighting system for experimental studies was presented. Two luminaire types were proposed for the illumination of a given interior. Numbers and layouts of each luminaire type were tested and specified. Luminous flux levels for luminaires in each type were calculated to provide the following average illuminance levels on horizontal working plane in the room: 100 – 200 – 500 – 1000 lx. According to these illuminance levels, the average luminance levels on vertical (wall) planes in the interior were calculated either and were in the range from about 5 cd/m^2 (for 100 lx) for direct lighting use up to about 150 cd/m^2 (for 1000 lx) for asymmetric lighting use.**

***Index Terms*—Interior lighting, luminance distribution**

INTRODUCTION

The results presented in this paper are a part of bigger research, conducted at the Lighting Division of the Warsaw University of Technology, devoted to the impact of lighting conditions on people. The main objective of the study presented in this paper is to introduce a concept of interior lighting system for experimental studies, by proposing the light intensity distributions of luminaires, their layouts and luminaires luminous flux levels to provide wide range of illuminance levels on horizontal plane and luminance levels on vertical planes in interior. The concept of lighting system presented corresponds to one interior at our university, where we will conduct experiments later, and it bases on the results of computer calculations.

Luminous environment in interior can impact on people. Lighting can affect human performance, visual comfort and perception of space and objects [1]. To explore lighting impact on people field or laboratory studies are undertaken. Laboratory studies give opportunity to create various lighting conditions and control them properly. That's why we decided to create an experimental room first.

Even in a laboratory environment, one can afford to provide a limited combination of lighting conditions only. The way of illumination and lighting conditions provided should correspond to the room purpose and main activities. Our studies are connected to typical office and school activities – reading, writing and computer work. For this reason, we have assumed that the system will provide general lighting conditions created with uniformly arranged luminaires of two types, for independent illumination of the horizontal and vertical planes in the room. To some extent, our inspiration for the lighting of the experimental room was Flynn's research, e.g. [2]-[5]. Such way of illumination should also enable us to study the perception of space and the psychological impact of lighting on people.

Among the others, the two ways of illumination were studied by Flynn, e.g. [2], provided by overhead and peripheral lighting. Overhead-uniform lighting system should provide high illuminance and uniformity levels on horizontal plane in interior and create visual clarity impression, expected e.g. in offices, conference rooms, classrooms. The second, peripheral-uniform lighting system should provide high uniformity on vertical (wall) planes in interior and create spaciousness impression, expected e.g. in circulation zones in buildings. High wall luminance should strengthen not only spaciousness impression but also visual clarity impression in interiors. From the other point, wall luminance should not be too high as it may reduce visual comfort. It means that luminance distribution in interior should be properly balanced to provide comfortable conditions for users.

EXPERIMENTAL ROOM

To perform the calculations a computer model room, based on an existing room at our university, was defined. The room is simple rectangular cuboid one and has: length 6 m, width 6 m and height 3 m. For the purpose of calculations some simplifications were made. It was assumed that the room was empty, windows were covered and daylight was excluded from calculations. In the future the room can be furnished and arranged depending on purpose. Reflectances for ceiling 0,7, walls 0,5 and for floor 0,2 were assumed either.

The first experiment that is planned assumes performing typical office and school activities as in real interiors, such as writing and reading printed materials, and computer work. To study influence of lighting conditions on such activities, ranges of the average horizontal illuminance on working plane and the average wall luminance were assumed:

- the average horizontal illuminance on working plane: 100 – 1000 lx,

- the average luminance on walls: 10 – 150 cd/m^2.

Both, horizontal illuminance and vertical luminance levels in most cases represent the typical levels in interior lighting practice [6][7]. In our studies the importance of wall illumination, in relation to other lighting metrics, will be studied in detail.

The realisation of such horizontal illuminance and vertical luminance levels can be achieved in practice in many different ways. In our studies, it was decided to apply two ceiling mounted luminaire types for illumination:

- direct lighting, ceiling mounted luminaires whose aim is to provide effectively the uniform illumination on the horizontal plane (0,75 m above floor) in interior;
- asymmetric lighting, ceiling mounted luminaires whose aim is to provide effectively the uniform illumination on the vertical (wall) planes in interior.

Light intensity distributions of the luminaires for the experimental room are shown in Fig. 1.

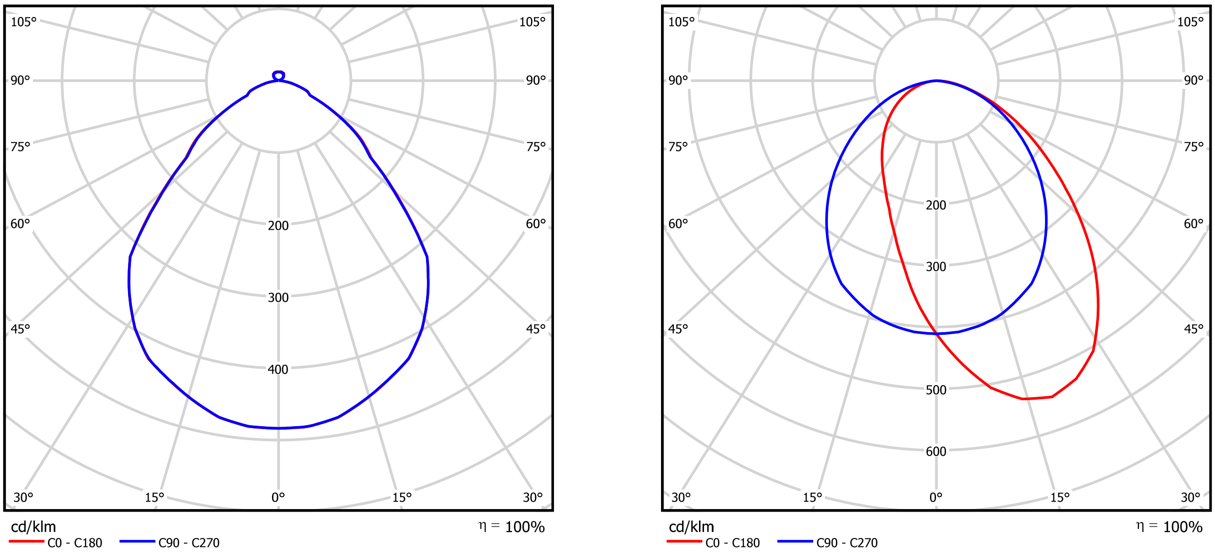


Figure 1. Light intensity distributions of the luminaires for the experimental room illumination.

Number of luminaires and their layouts were tested to provide the average illuminance level on horizontal working plane 1000 lx. For direct lighting system, the luminaires were arranged in a regular way (3x3 array) and for asymmetric lighting system, the luminaires were arranged in four lines – five luminaires per each line. The lighting system layout is shown in Fig.2. Maintenance factor 0,8 was assumed for calculations that were performed in DIALux software.

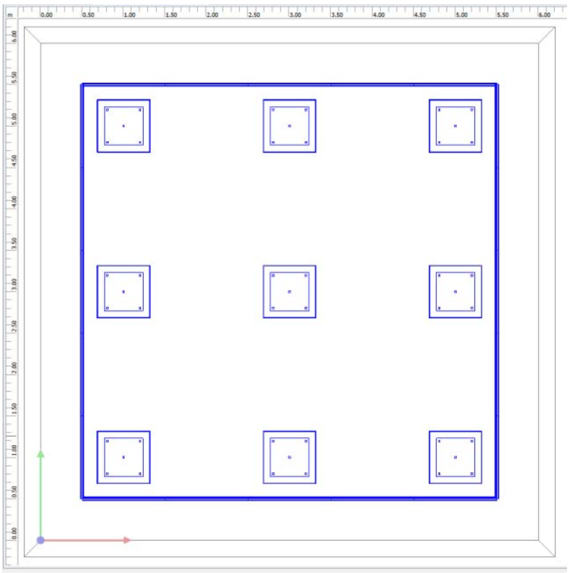


Figure 2. Schematic floor plan presentation of direct and asymmetric lighting systems in the experimental room.

LIGHTING CONDITIONS

When only one luminaire group works, the maximum luminous flux of luminaires is necessary to provide the average illuminance level 1000 lx on horizontal working plane. 50%, 20% and 10% of the maximum luminous flux of luminaires is necessary to provide the average illuminance levels on horizontal working plane 500 lx, 200 lx and 100 lx respectively. The results, presented in Tab. 1., show the luminous flux per one luminaire for each group to provide the average illuminance levels on horizontal working plane 1000 lx, 500 lx, 200 lx and 100 lx respectively and resultant average luminance levels on walls.

TABLE I. LUMINAIRE LUMINOUS FLUX, AVERAGE HORIZONTAL ILLUMINANCE ON WORKING PLANE AND AVERAGE WALL LUMINANCE IN THE EXPERIMENTAL ROOM.

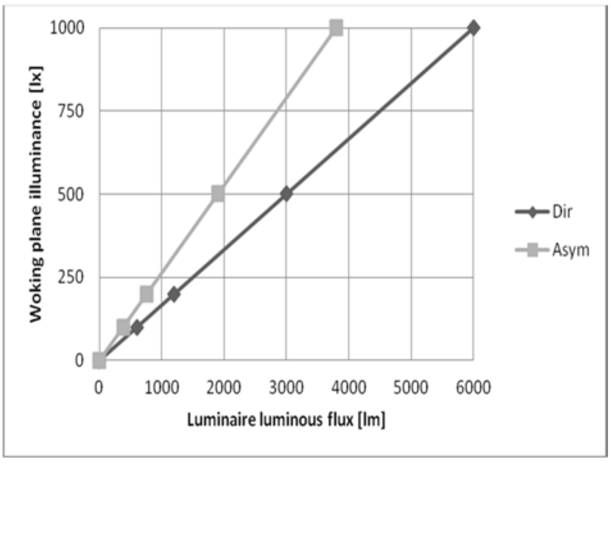
Luminous flux level per one direct lighting luminaire [lm]	Luminous flux level per one asymmetric lighting luminaire [lm]	Average illuminance level on horizontal working plane [lx]	Average luminance level on walls [cd/m^2]
6000	0	1000	68
3000	0	500	34
1200	0	200	14
600	0	100	7
0	3800	1000	146
0	1900	500	73
0	760	200	30
0	380	100	15

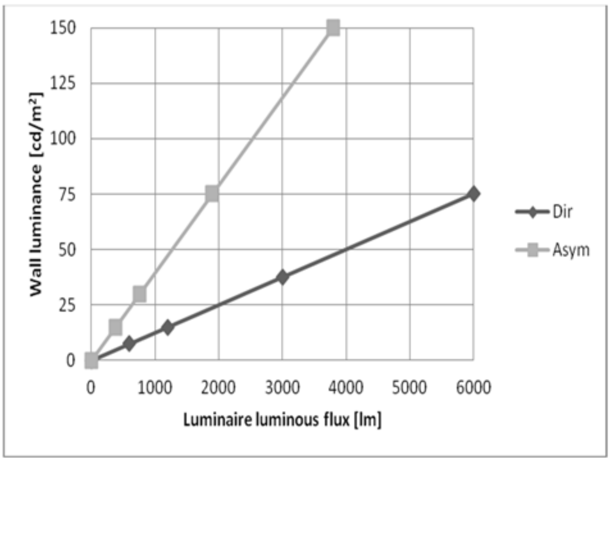
In this way we specified eight lighting scenarios in the room. An important conclusion comes from the results presented in Tab. 1. For the analysed system, there are limits in wall luminance level for given average illuminance level on working plane. The limits are the following:

- for 1000 lx on working plane, the average wall luminance is in the range: 68 – 146 cd/m^2,
- for 500 lx on working plane, the average wall luminance is in the range: 34 – 73 cd/m^2,
- for 200 lx on working plane, the average wall luminance is in the range: 14 – 30 cd/m^2,
- for 100 lx on working plane, the average wall luminance is in the range: 7 – 15 cd/m^2.

In our studies we are going to investigate how the change of wall luminance level, for given illuminance level on working plane, influences people perception of lit environment and abilities of visual system. That's why we included more than 2 lighting scenarios for each average illuminance level on horizontal working plane. These scenarios result from the operation of the two luminaire group together. Share of each system in the total illumination was determined.

The relationships between the average illuminance level on working plane, the average wall luminance and luminaire luminous flux level are linear and presented in Fig. 3.





Taking into account these relationships, we determined three additional scenarios for each illuminance level on working plane. The scenarios are differentiated by the share of illuminance level from direct and asymmetric lighting luminaires. The results are presented in Tab. II.

TABLE II. THE LIGHTING SCENARIOS FOR THE EXPERIMENTAL ROOM.

Direct lighting system			**Asymmetric lighting system**			**Lighting system**	
Φ_D* *[lm]	***E_D* *[lx]***	***L_D* *[cd/m²]***	***Φ_A* *[lm]***	***E_A* *[lx]***	***L_A* *[cd/m²]***	***Φ_S* *[lm]***	***L_S* *[cd/m²]***
Total illuminance level on working plane 1000 lx							
0	0	0	3800	1000	146	76000	146
1500	250	17	2850	750	110	70500	127
3000	500	34	1900	500	73	65000	107
4500	750	51	950	250	37	59500	88
6000	1000	68	0	0	0	54000	68
Total illuminance level on working plane 500 lx							
0	0	0	1900	500	73	38000	73
750	125	9	1425	375	55	35250	64
1500	250	17	950	250	37	32500	54
2250	375	26	475	125	19	29750	45
3000	500	34	0	0	0	27000	34
Total illuminance level on working plane 200 lx							
0	0	0	760	200	29	15200	30
300	50	4	570	150	22	14100	26
600	100	7	380	100	15	13000	22
900	150	10	190	50	8	11900	18
1200	200	14	0	0	0	10800	14
Total illuminance level on working plane 100 lx							
0	0	0	380	100	15	7600	15
150	25	2	285	75	11	7050	13
300	50	4	190	50	8	6500	12
450	75	5	95	25	4	5950	9
600	100	7	0	0	0	5400	7

Φ_D, Φ_A – luminous flux level per one direct and asymmetric lighting luminaire respectively;
Φ_S – total luminous flux level of all luminaires;
E_D, E_A – average illuminance level on working plane resulting from direct and asymmetric system respectively;
L_D, L_A, L_S – average luminance level on walls resulting from direct, asymmetric and both systems respectively.

CONCLUSIONS

In this paper a concept of interior illumination for experimental studies that would be conducted at the Lighting Division of the Warsaw University of Technology was presented. The concept was based on two general lighting, ceiling systems: direct and asymmetric, providing the assumed levels of illuminance on horizontal working plane and luminance on vertical (wall) planes in the interior.

The maximum use of asymmetric lighting only enables to provide the average luminance level on vertical wall plane about 150 cd/m^2, at 1000 lx level on horizontal working plane in the interior. Keeping 1000 lx level of average illuminance on horizontal working plane in the interior enables to reduce the average luminance level on walls up to about 70 cd/m^2 (the maximum use of direct lighting only).

Independent regulation of the two luminaire groups working together enables smooth adjustment of the average illuminance level on working plane and luminance level on walls according to the planned experiment needs. In the paper the ranges of average wall luminance levels for typical average working plane illuminance levels were presented, and were as follows: for 500 lx average illuminance on working plane the luminance on walls was about 35 – 75 cd/m^2, for 200 lx average illuminance on working plane the luminance on walls was about 15 – 30 cd/m^2, and for 100 lx average illuminance on working plane the luminance on walls was about 5 – 15 cd/m^2.

ACKNOWLEDGEMENT

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Indoor Lighting: How a Reflector Can Improve Performance and How To Assess It

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***Abstract*— HumbleBee is an innovative lighting system, based on LED with remote phosphors technology and customized smart lighting control system: the goal is to realize a prototype system, useful for tertiary / industrial sector, able to reduce energy consumption and improve the lighting quality and the visual comfort in working places. After the installation, the commissioning and a first monitoring campaign, the system has been improved through the application of very efficient reflectors, to optimize the light distribution. The present paper describes the experimental activities aimed to characterize the improved system and the comparison with the previous situation: photometric, spectroradiometric, electric parameters and thermal behaviour. Specific measurement procedures have been developed and applied, and are described. Computer simulations with lighting design software show the performance of the improved system in comparison with the original one. This experimentation has been developed in a graduation thesis with the University of Insubria (Varese).**

***Index Terms*— in situ measurements, interior lighting, industrial lighting, LED luminaire.**

INTRODUCTION

The HumbleBee lighting system is installed at ENEA Ispra building, in a laboratory structured as a typical industrial hall. It has been conceived as flexible and modular system, relatively easy to modify during time, according to the technological developments and / or better understanding of human needs: for example, luminaires have been suspended with pulley, to facilitate movement and manipulation.. The system is operative since few years and a first monitoring campaign assessed the performance of the installed system. While good results have been achieved, in comparison with the old lighting system, including compliance with the standard requirements, a need for a better light distribution and less glare lead to the idea of a reflector. The first design of the reflector has been made by Politecnico di Milano Dip.Design. With the time, reflectors have been redesigned and assembled with a new material by Almeco and are now part of the real system [1] – [3].

THE HUMBLEBEE COMPONENTS

The typical HumbleBee luminaire, high bay shaped, is composed by royal blue LEDs in a mixing chamber, a remote phosphor glass, which emits light at 4000K CCT, a thermal dissipation unit and auxiliaries. The system is dimming according to light levels and presence of persons: every luminaire can be dimmed individually. Emission, without reflector, is rotosimmetric and lambertian. Reflector is made of preanodized aluminium with a silver highly reflective layer (total reflectance ≥ 97%, diffuse reflection 95%, material Almeco Vega V98127). In the future, a protective shell will also be realized. In Fig. 1 the rendering of HumbleBee with reflector and the photometric distribution, together with the picture of the sample used for testing purposes.

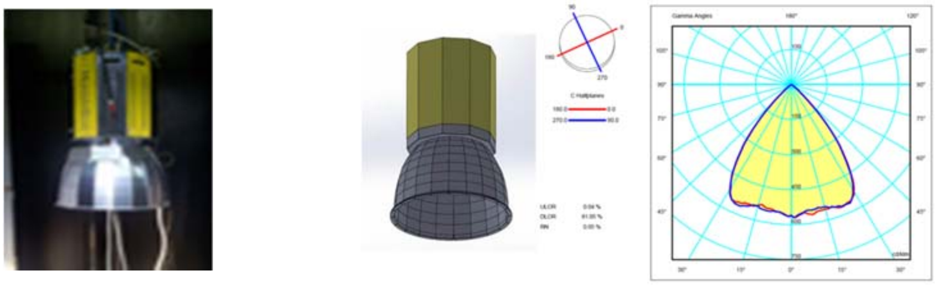


Fig. 1: HumbleBee

- thermal: temperatures of different components at different environmental conditions and dimming
- spectroradiometric: spectral radiance at different emission angles

MEASUREMENT METHODS AND RESULTS

A. Photometric Tests

The illuminance map on a working plane has been measured to assess illuminance distribution. A test cell (called CORVO) has been employed, as in Fig. 2.

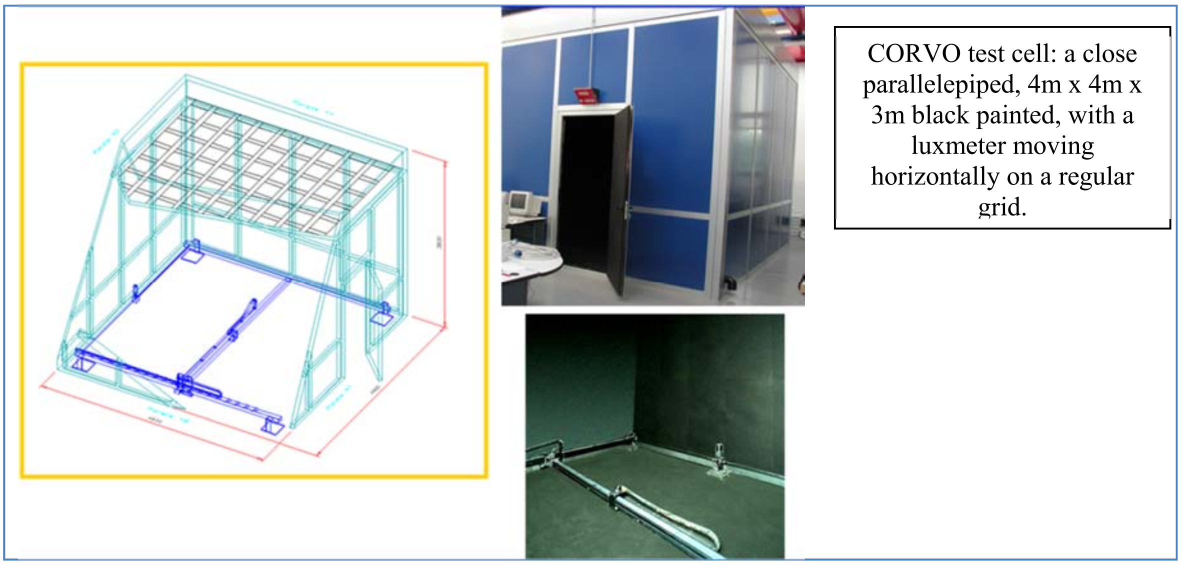


Fig. 2: The CORVO test cell

HumbleBee luminaire has been suspended at 2,6 m height, in centre of the ceiling. Measurement grid: 50 x 50 points over a 4 x 4 m surface. Tests have been performed at 25°C, with the luminaire in stable state. The height of installation is not really representative, because the true installation in the laboratory is 6m, but it is imposed by the physical size of the test cell and it is suitable for the purpose of the test.

The distribution of intensities (photometric solid) of a luminaire is usually obtained with a goniophotometer, in far field photometry conditions. In our case, an alternative method has been defined to obtain the distribution of intensities using the test cell. In principle, instead of a sphere, where the intensities are measured at a regular grid of angles (e.g. C-gamma coordinates), it is possible to use a cube, with simple trigonometric calculations to take into account incidence angle (which is always 0 in the sphere) and distance sensor-luminaire (which is constant in the sphere). Furthermore, as measurements on a plane are usually based on grids regular in "distance", a second calculation, with spatial interpolation, is necessary to determine intensities in regular grids of angles.

The method has been implemented in the test cell using the full grid on the horizontal plane (where the rotosimmetry hypothesis has been confirmed) and a selected number of point on 4 vertical axes passing from the centre of each vertical wall. The Eulumdat file of the luminaire has been produced, allowing computer simulation.

In Fig. 3, the result of the measurements, in terms of photometric solid. It is visible a non-perfect symmetry, due mainly to the non-perfect alignment of the elements in the test cell (which is not as accurate as a goniophotometer): in any case the method is suitable for the objectives of the study and allows easy and fast parametric tests.

The original distribution of the luminaire, without reflector, was lambertian, so that the advantage of the reflector is evident. Another test has been made, simulationg a wrong mounting of the reflector: the reflector has been shifted "upward" of 2 cm. Result is also shown in Fig.3 and shows the importance of a careful assembling of the luminaire.

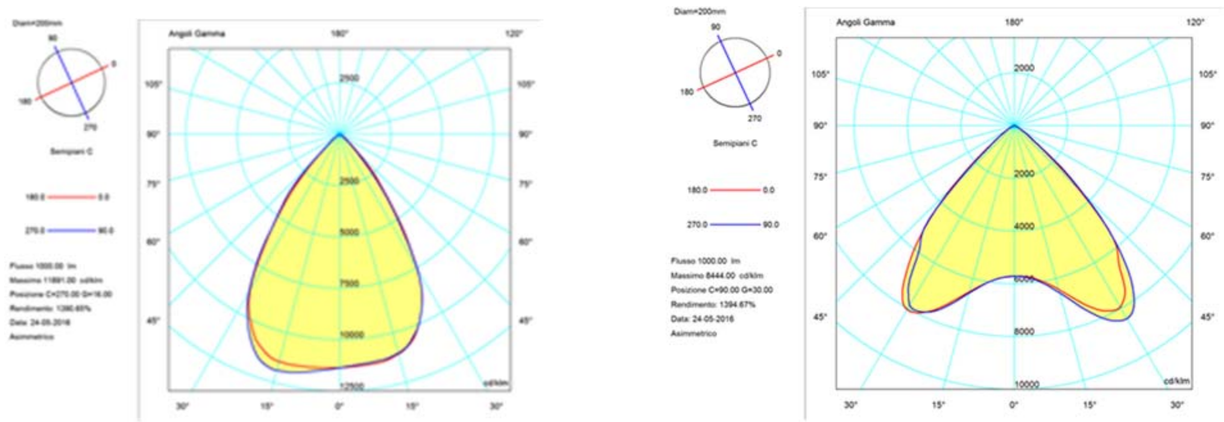
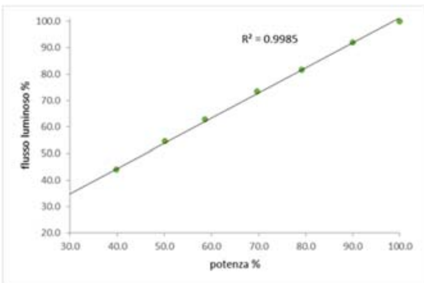


Fig.3: photometric solid of HumbleBee (left) and with the reflector in a wrong positions (right)

B.Electric Tests

Dimming curve has been calculated, starting from a number of illuminance reduced maps (9 points) and related electtric parameters (Voltage, Power, Current). The reduced maps have been chosen in the hypothesis that the intensities distribution does not depend on power. In Fig. 4 the results, where it is confirmed, as in te past, the linear behaviour of the systems.

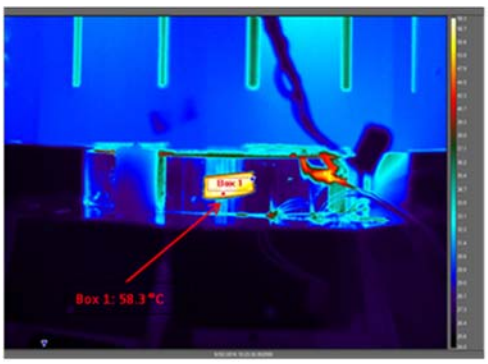


Dimming	100	90	80	70	60	50	40	30
Av. illuminance [lx]	1672	1540	1367	1229	1052	911	734	543
Power [W]	139,4	125,5	110,3	97,2	81,8	69,9	55,5	40,4
Voltage[V]	396,9	398	394,7	396	392,4	392,5	389,7	387,4
Current [mA]	353	317	281	247	210	180	144	106

Fig. 4: electric tests

C.Thermal Tests

A numner of thermal tests have been performed on the luminaire, in a climatic test cell, to obtain information on opertive conditions in typical "static situation: e.g. 25°C ambient temperature, reference and common situation, or 50°C, the ceiling of an industrial building during summer. The inside of the mixing chamber, where LED operative, the outside surface of remote phosphore glass, the external surface of the metal ring surrinding the mixing chamber, the external surface of the heat sink, the surface of the control system and ballast have been equipped with flat thermoresistances and also an infrared camera has been used: as many surfaces are metallic (with a high infrared reflectance), smal paper targets have been applied on order to correctly measure the thermal emission and the temperature of the surface. In Fig. 5 the maximum of the temperatures reached under different testing conditions, togheter with an example of igae taken with infrared camera.



Ambient temp, [°C]	*25*	*50*	*25*	*50*
Dimming [%]	*100*	*100*	*20*	*20*
Temp, reflector [°C]	25,3	49,5	24,4	48,3
Temp, remote phosphors[°C]	120,5	136,4	49,6	70,4
Temp, mixing chamber inside [°C]	58,2	82,4	32,8	56,6
Temp, metal ring [°C]	58,0	81,3	32,5	56,1
Temp, heat sink [°C]	39,4	63,5	28,2	52,5
Temp, DALI / ballast [°C]	46,5	72,2	35,5	58,3
power[W]	160,3	156,2	37,7	35,8

Fig. 5: thermal tests

The surface of the glass with remote phosphors reaches very high values (more than 120°C already at 25°C) and also the space where LEDs operate, represented by the inside of the mixing chamber, may be problematic: it remains under 60°C at 25°C ambient, but trespass 80°C at 50°C ambient (junction temperature has not been measured). Furthermore, the luminaire exhibits a long stabilization time, so that it will be difficult to foresee the thermal conditions under real operations, i.e. with continuous dimming due to natural lighting and presence variation with time.

D.Spectroradiometric Tests

Spectral emission of the HumbleBee sample has been measured at different emission angles. A small white target, with very high and uniform diffuse reflectance, has been used, attached in different positions on one of the black walls inside the CORVO test cell, at a proper distance from the luminaire: this test is possible because the black surfaces are very low reflective, so that emission spectrum from the luminaire is not biased.

Spectral radiance on the target has been measured, from which irradiance has also been calculated (the target is a lambertian surface). Values have been normalized. Results are shown in Fig. 6. The amount of light falling on the target decreases as the emission angles increases, while the spectrum does not vary.

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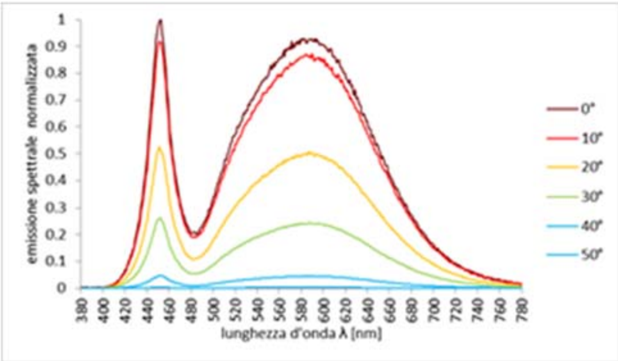

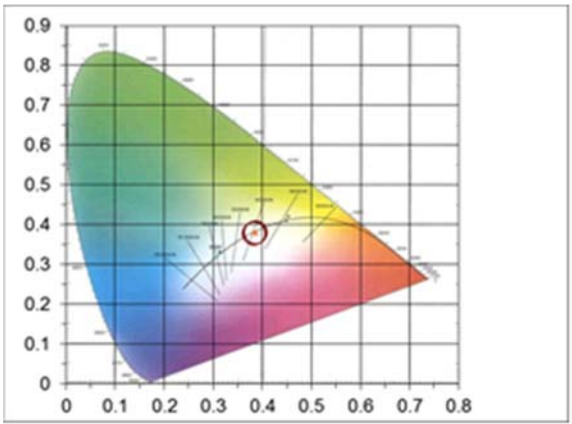

Angolo	0°	10°	20°	30°	40°	50°
CCT (K)	3882	3862	3831	3864	3822	3895

Fig. 6: spectroradiometric tests

The luminaire has been measured in the past, without reflector: CCT was 4100K. Measuring directly the spectrum on the remote phosphor glass leads to 4032K, and on the reflector surface leads to 3884K. The presence of the reflector, with its own spectral reflectance, slightly modifies the CCT.

CONCLUSION

The Almeco reflector, applied to the HumbleBee luminaire, produces great improvement to the intensities distribution, optimizing illuminance on the working plane, provided that the assembling is sell done.
Electric characteristics are the same as the previous situation, without reflector. The linear dimming curve is confirmed. There is still space for improvements for the thermal management of the system.

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Effects of High-Purity LED Light Colors on Time-Sense Perception

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***Abstract*— The use of light-emitting diode (LED) lighting has now become widespread. Such light sources emit light in the primary colors of red, green, and blue, and are thus capable of reproducing most chromatic colors. In this study investigated the effects of white and high-purity red, green and blue light LED light sources on medium-interval time sense perceptions. In our experiments, subjects were asked to declare when they believed that 600 seconds has passed since the start of a task, after which their time perception was compared to the actual elapsed time. The results showed that declaration times were longer than 600 seconds for all light colors during the reading task, which indicates that the subjects' attention was tightly focused on the reading material. For the chair-resting task, only green lighting induced shorter declaration times than white lighting, and green was the only color with declaration times shorter than 600 seconds.**

***Index Terms*-- chromatic colors, green lighting, LED, time sense, 600 seconds.**

INTRODUCTION

The use of light-emitting diode (LED) lighting has now become widespread. Such light sources emit light in the primary colors of red, green, and blue, and are thus capable of reproducing most chromatic colors. However, chromatic lighting has been found to have both physical and psychological effects on human beings [1], [2], [3]. For example, a previous study [4] reported that experimental participants judged 180 seconds to be shorter in a red lighting environment than in a blue lighting environment. On the other hand, no comparisons with white color lighting have been studied to date, and if waiting time is assumed, 180 seconds is too short to be considered as an appropriate waiting time. Accordingly, this study investigated the effects of white light and high-purity red, green, and blue LED lighting on medium-interval time-sense perceptions.

EXPERIMENT

In this experiment, high-purity red, green, and blue LED light sources were used to create desktop illuminance conditions of 500 lx, which was deemed suitable for a waiting room environment. Partitions were created by pasting white wallpaper on white styrene boards that were installed around the desktop. Table I shows a breakdown of the experimental conditions.

At the start of the experiment, test subjects were asked to begin performing a task, and then declare when they believed that 600 seconds has passed since the task start. Their time perceptions were then compared to the actual elapsed times. From electrocardiogram (ECG) data, which were recorded throughout the experiments, the low-frequency/high-frequency (LF/HF) values that act as sympathetic nervous function indicators were extracted. The selected tasks were reading a prepared document and resting in a chair.

The following procedure was used in the experiment:

1) The subject was provided an explanation about the nature of the experiment.
2) The subject was given a subjective examination that included a measurement of salivary amylase.
3) The subject was given 11 minutes to adapt to the chromatic lighting of the experimental environment.
4) Another amylase measurement was taken from the subject.
5) The subject was instructed to read a prepared document for 14 minutes, and to declare when he felt 600 seconds had passed since the start of task.
6) The subject was instructed to rest in a chair for 14 minutes and asked to declare when he felt 600 seconds had passed.
7) Another amylase measurement was taken from the subject and the subjective examination was repeated.
8) The ECG data of the subject was recorded between steps (3) and (6).
9) Steps (1) to (7) were repeated for each light color, which were chosen at random to avoid order effects.

The salivary amylase measurements were taken because it is thought that stress stimulates the excitatory signals of the sympathetic nervous system, and that salivary amylase activity is enhanced as a bodily self-defense reaction.

The subjective examination was provided in the form of a "*Jikaku-sho shirabe*" questionnaire that asked about work-related feelings of fatigue. This questionnaire consists of 25 subjective fatigue symptoms that are categorized into five factors of feeling: (i) drowsiness, (ii) instability, (iii) uneasiness, (iv) local pain or dullness, and (v) eyestrain. For each item, subjects were requested to estimate the intensity of their feelings using the following scale: “totally disagree,” “agree scarcely,” “agree slightly,” “agree considerably,” and “agree strongly.” These five intensities were assigned scores of 1–5 points, respectively [5].

TABLE I. EXPERIMENTAL CONDITIONS

Light source	LED
Illuminance of work space	500 lx
Uniformity ratio of work space	Over 0.8
The height of light source	0.5m
Desk size	H:0.75m×W:0.95m×D:0.71m
Chromaticity	White: (0.33, 0.32) Red: (0.70, 0.30) Green: (0.22, 0.72) Blue: (0.14, 0.06)
subjects	8 males in their 20s

RESULTS AND DISCUSSION

One-factor analysis of variance (ANOVA) was performed in this study. The factor was light color, and multiple comparisons were performed using Fisher’s least significant difference (LSD) method. Analyses were conducted to determine significant differences between white light and the other colors. The results are shown in the following figures, in which the error bars represent the standard error.

Figure 1 shows the time-sense measurements for the reading task. As can be seen in the figure, the subjects’ declared times were over 600 seconds for all colors. This result indicates that the subjects felt that time spans were shorter, which in turn indicates that their attention was tightly focused on the reading material. Here, it should be noted that time passage under green light was felt to be longer than that perceived under white light, but no significant difference was observed in the reading task for each light color.

Figure 2 shows the time-sense measurements for the resting task. It shows that the declaration times were over 600 seconds except under green light. This result indicates that the subjects only felt that time passage was longer only under green light conditions. A significant difference ($p<0.05$) was observed between the white light and green light conditions, thereby suggesting that high-purity green lighting tends to lengthen time perception.

Figure 3 shows the average of LF/HF values during adaptation and each task. Here, it can be seen that the LF/HF values tended to decrease during the reading task, as compared with that during the adaptation period, for all light colors. Additionally, the results show that the LF/HF values tended to increase more during the resting task than during the reading task for all light colors. Furthermore, it was shown that the LF/HF values were low for red light color during the adaptation phase.

As the results of the subjective examinations, it can be seen that drowsiness values under green light conditions, and eyestrain under both red and blue light conditions, were higher than the values recorded for other light color conditions. This seems that drowsiness increased because the color of green has a relaxant effect. As for eyestrain, it is considered likely that the highly-pure light color and strong radiant energy imposed loads on the subjects’ eyes.

No stress reaction was observed for any of the light colors from the results of the amylase measurement.

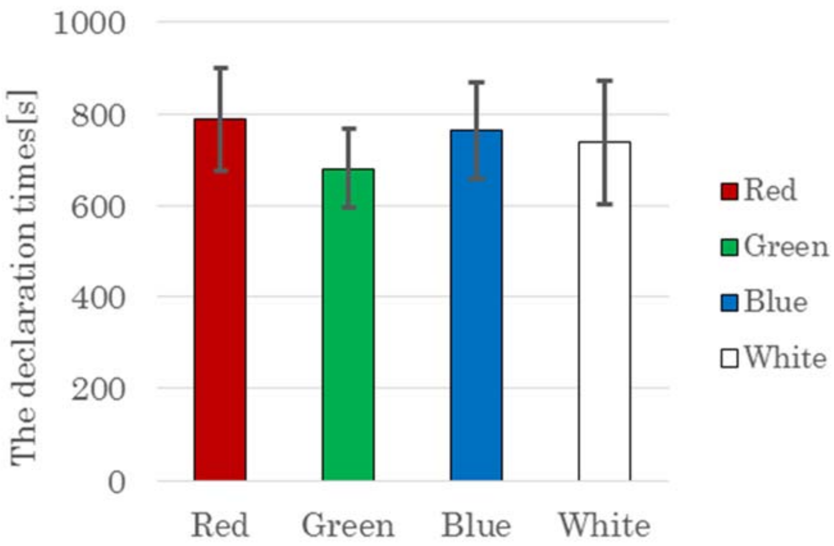

Figure 1. Declaration times for reading task.

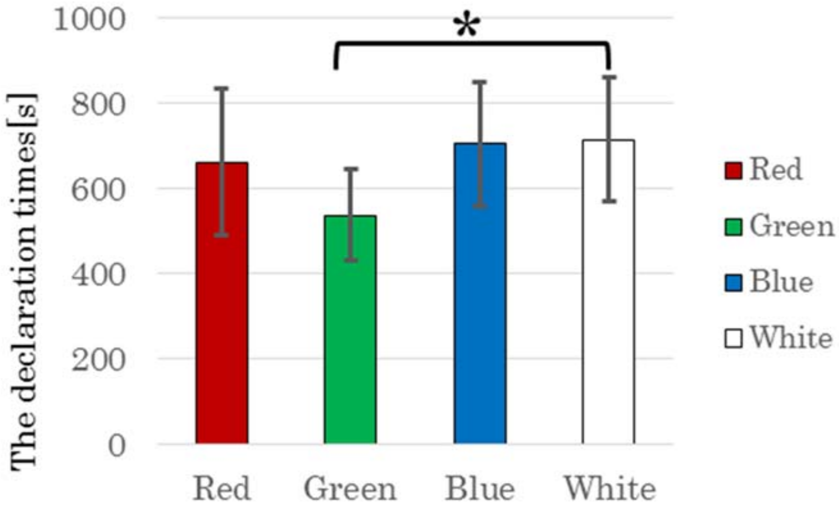

Figure 2. Declaration times for resting task. (*represents a P<.05)

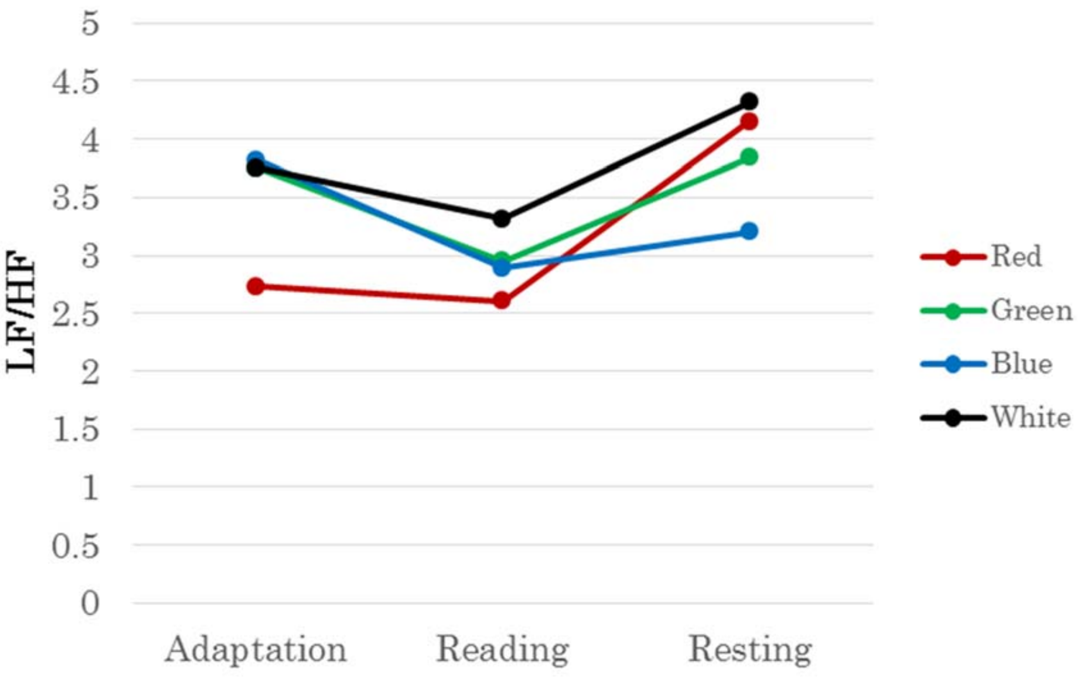

Figure 3. Average of LF/HF values.

CONCLUSION

In this study, time sense was measured for the purpose of clarifying the effect of high-purity LED light colors on time-sense perception. The results are summarized as follows:

(1) It was suggested that high-purity green lighting tends to lengthen time perception.

(2) There was no relationship between light colors on time-sense perception and LF/HF values.

This study was approved by the Ethical Review Board for the use of human subjects of Kanagawa Institute of Technology (No. 20160920-10).

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On the Correlation Between SQM Data and Zenith Brightness

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***Abstract*—Sky Quality Meter (SQM) is a portable and easily available device widely used to measure a night sky brightness. It is normally directed toward zenith and data recorded are often interpreted in terms of zenith brightness. However, SQMs have different opening angles, thus the relation between zenith luminance and luminance detected is not linear. The coefficient of proportionality also depends on other factors such as distance to a light-emitting city, its radiant intensity function as well as atmospheric conditions. We have performed mass computations of sky luminance patterns, while altering atmospheric conditions, distances between ground-based light source and a hypothetical observer, city emission functions, etc. The synthetic optical data obtained this way for SQM and SQM-L were compared against theoretical zenith luminances to reveal the correlation between them. The results are useful in better understanding of SQM data and also allows for remediation of long-term data series obtained earlier.**

***Index Terms*--atmospheric effects, numerical modelling, skyglow, SQM, zenith brightness.**

INTRODUCTION

Light pollution can have adverse impacts on human beings and the natural places situated in a vicinity of large cities and towns. Usually, the long term measurements of a night sky brightness are necessary to assess a correlation between skyglow and night lighting. Basically, the large data sets offer not only the information on light pollution in a given locality, but can also reveal relation between the night sky brightness and optical characteristics of the atmosphere. The zenith brightness is traditionally used to assess the quality of the night sky at given location and determine the impact of artificial skyglow [1]. The SQM devices are often used for its measurement they are easily available and simple to operate [2]-[4]. Sky Quality Meter (SQM) is a portable device that is normally directed toward zenith and data recorded are typically interpreted in terms of zenith brightness. However, SQMs are known to have different opening angles, thus the photons entering the aperture of SQM device do not necessarily travel vertically before reaching a photosensitive sensor. This is why relation between zenith radiance and signal detected is not perfectly linear. The coefficient of proportionality also depends on other factors such as distance to a light-emitting city, its radiant intensity function as well as atmospheric conditions. This is the aim of our paper to estimate an uncertainty of such correlation. For this purpose we have performed mass computations of sky luminance patterns, while altering atmospheric conditions, distances between ground-based light source and a hypothetical observer, city emission functions, etc. The synthetic optical data obtained this way for SQM and SQM-L were compared against theoretical zenith luminances. The results are useful in better understanding of SQM data and also allows for remediation of long-term data series obtained earlier.

SQM BRIGHTNESS

SQM is a wide-field photometer with different response on beams incident at different angles with the detector axis. Therefore, the luminance measured by SQM is the weighted average of luminance over the device's field of view. In general,

$$L(SQM) = \frac{\int_0^{\frac{\pi}{2}} \int_0^{2\pi} L(\vartheta,\varphi) D(\vartheta) \sin\vartheta \, d\varphi \, d\vartheta}{\int_0^{\frac{\pi}{2}} \int_0^{2\pi} D(\vartheta) \sin\vartheta \, d\varphi \, d\vartheta}, \tag{1}$$

where $L(SQM)$ is the measured average luminance, $L(\vartheta,\varphi)$ is the luminance of the sky and $D(\vartheta)$ is the angular response of the device. The incidence angle ϑ is identical to the zenith angle in our case. Although SQM output values are in mag/arcsec2 we will work with the linear scale and so all luminances are taken into account in cd/m2. The angular response functions for SQM and SQM-L were measured by Cinzano and can be found in [5]-[6]. The half width half maximum of SQM angular response function is approximately 42° and screening of the detector begins at roughly 60°. It covers the large part of the sky and in a vicinity of a city the measured luminance can significantly differ from the zenith value.

MODEL OF NIGHT SKY LUMINANCE DISTRIBUTION

The total luminance $L(\vartheta,\varphi)$ of the clear night sky is in general the sum of the natural diffuse light luminance $L_N(\vartheta,\varphi)$ and the artificial diffuse light luminance $L_A(\vartheta,\varphi)$. Thus we need to model both these two components.

A. Natural Background

The natural background luminance of the night sky originates from many sources. Ignoring the moonlight, the most important ones are the natural airglow (AG), zodiacal light (ZL) and integrated starlight (IS) [7]. Integrated starlight forms a constant sky background in the absence of the atmospheric extinction while the airglow grows with increasing zenith distance. The natural zenith luminance of the clear sky during moonless nights and besides the Milky Way and zodiacal light is usually taken to be equal to 22 mag/arcsec2, that is 0.171 mcd/m2. According to the Garstang model [8] the luminance (formed by IS and AG) measured at the zenith distance 60° can be roughly about 40% greater than the zenith value. It means that $L_N(SQM)$ calculated according to (1) should be slightly greater than the zenith luminance $L_N(zenith)$. The approximate calculations imply $L_N(SQM) \cong 1.07 L_N(zenith)$ and $L_N(SQM - L) \cong 1.02 L_N(zenith)$. But the wide field of view of SQM can involve also some stars brighter than magnitude 7 and/or other natural light sources so the given coefficient could be yet little bit greater. However, for simplicity we will consider the uniform sky luminance pattern $L_N = 1.71 \times 10^{-4}$ cd/m2. This uniformity assumption imply that the resultant ratios of the total luminances $L(SQM)/L(zenith)$ presented thereinafter are just some lower estimates of more realistic values.

B.Artificial Light

The calculation of diffuse skyglow originating from artificial ground-based light sources is in general a very complex problem. The certain standard simplifications are necessary to be done. The stratified plane-parallel model of the atmosphere is considered. Further, we suppose that each surface element of a model city area radiates according to the same emission function and this function is azimuthally symmetric. The luminance of the diffuse light incoming from a given point of the sky vault is calculated within the frame of the single scattering approximation. This approximation is relevant in an urban area or in its surrounding where optical paths of the light beams are not too long. In larger distances from a city or at higher turbidity conditions also the multiple scattering processes can contribute more significantly to the diffuse light. But these processes do not play an important role in our case.

We will not specify the exact equations of the theoretical model here. For more technical details see e.g. [9] or [10]. The particular skyglow patterns have been simulated using the software SkyGlow ver. 5.0 [11]. It enables to calculate the scattered light intensities originating from various irregularly shaped cities, with various emission functions, and at various atmospheric conditions.

NUMERICAL SIMULATIONS

The SkyGlow simulator contains a few optional parameters characterizing aerosols spread in the air as well as parameters determining directional and spectral characteristics of city radiation. The input parameters specifying aerosol properties are: single scattering albedo (SSA), asymmetry parameter (ASY), aerosol optical thickness (AOT) and Angström parameter. Single scattering albedo and asymmetry parameters are considered to be constant over the visible spectrum and AOT value is taken for the reference wavelength 500 nm. As the emission function we chose the standardly used Garstang function [12], hence the further couple of the optional parameters are the uplight fraction *F* and the ground albedo *G*. The spectral distribution of emitted radiation is given by a lamp type which makes the final input.

The simulations consisted of two parts. The first one involved the calculations of the ratio $L(SQM)/L(zenith)$ as a function of a distance from one specific city but at various aerosol parameters and emission characteristics of the city. In the second part we compared the investigated relation for three cities with different luminous area and population.

A.SQM-like data – Sensitivity on Model Parameters

At the beginning we investigated the SQM to zenith luminance ratio in different distances form the centre of the city Martin. The city has population about 56000 and the equivalent radius $R_{eq} = 2.4$ km (equivalent radius is the radius of a circular surface with the same area as the irregularly shaped city). The basic setting of the input parameters was the following: SSA = 0.85, ASY = 0.9, AOT = 0.1, Angström parameter = 1, Garstang parameters *F* = 0.15 and *G* = 0.15, and lamp type = HPS (high-pressure sodium). To examine the sensitivity of $L(SQM)/L(zenith)$ function on individual input parameters we performed consequently triples of calculations in which one of the input parameters could have three different values whereas the other ones remained unchanged. The resultant luminance ratios $L(SQM)/L(zenith)$ and also $L(SQM - L)/L(zenith)$ as the functions of distance r from the city centre are depicted in Fig. 1-6.

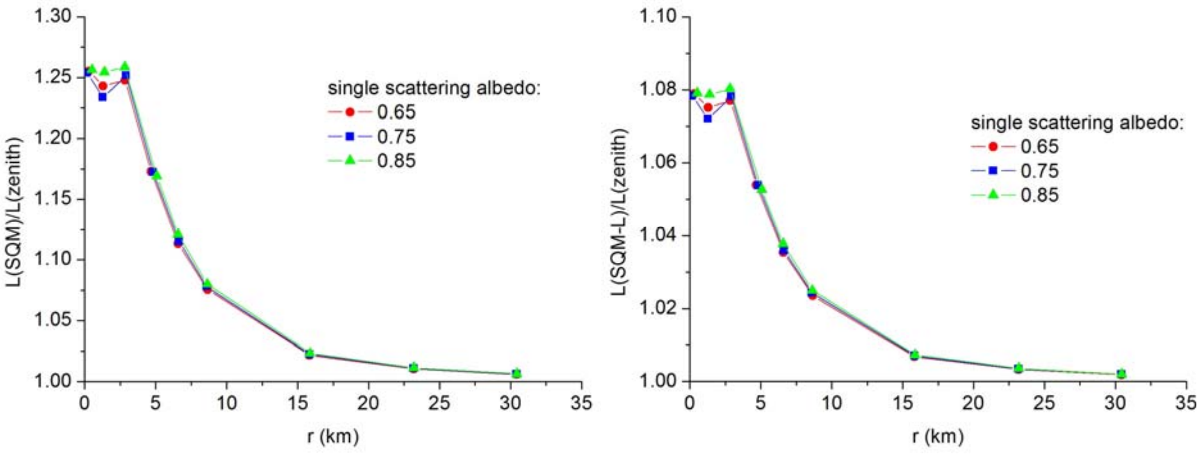


Figure 4. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance r from the centre of city Martin ($R_{eq} = 2.4$ km). The aerosol single scattering albedo is changing, the other input parameters correspond to the basic setting.

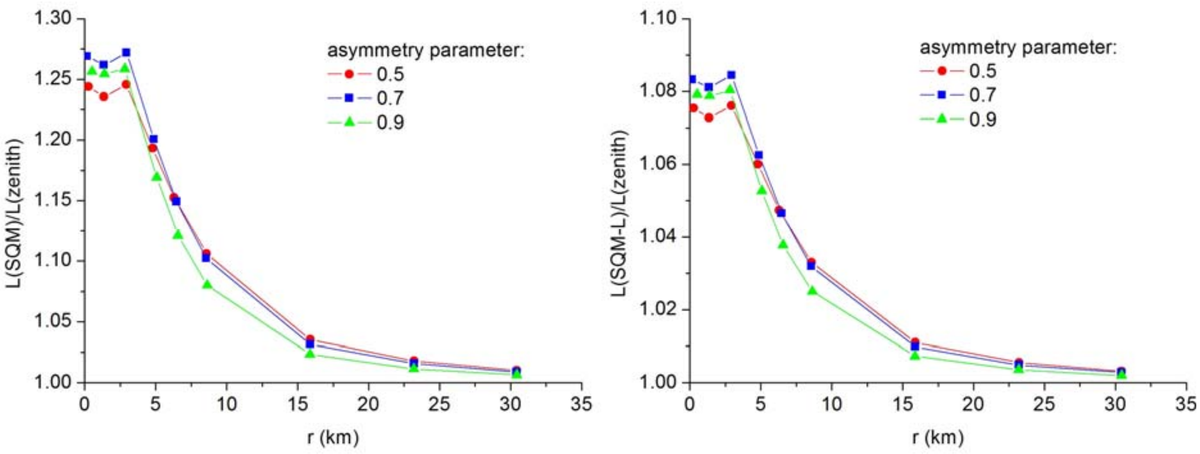


Figure 5. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance r from the centre of city Martin ($R_{eq} = 2.4$ km). The aerosol asymmetry parameter is changing, the other input parameters correspond to the basic setting.

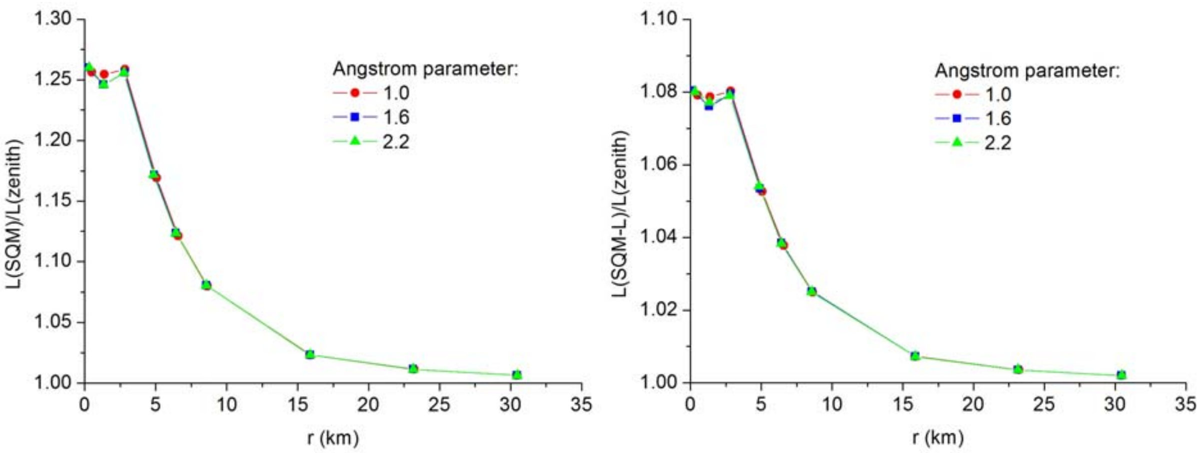


Figure 6. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance r from the centre of city Martin ($R_{eq} = 2.4$ km). The Angström parameter is changing, the other input parameters correspond to the basic setting.

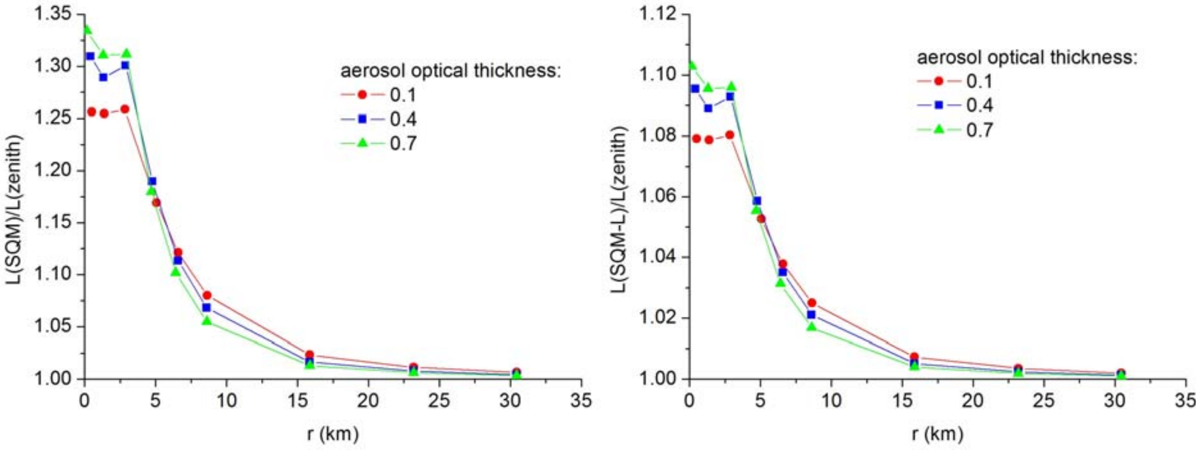


Figure 7. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance *r* from the centre of city Martin ($R_{eq} = 2.4$ km). The aerosol optical thickness is changing, the other input parameters correspond to the basic setting.

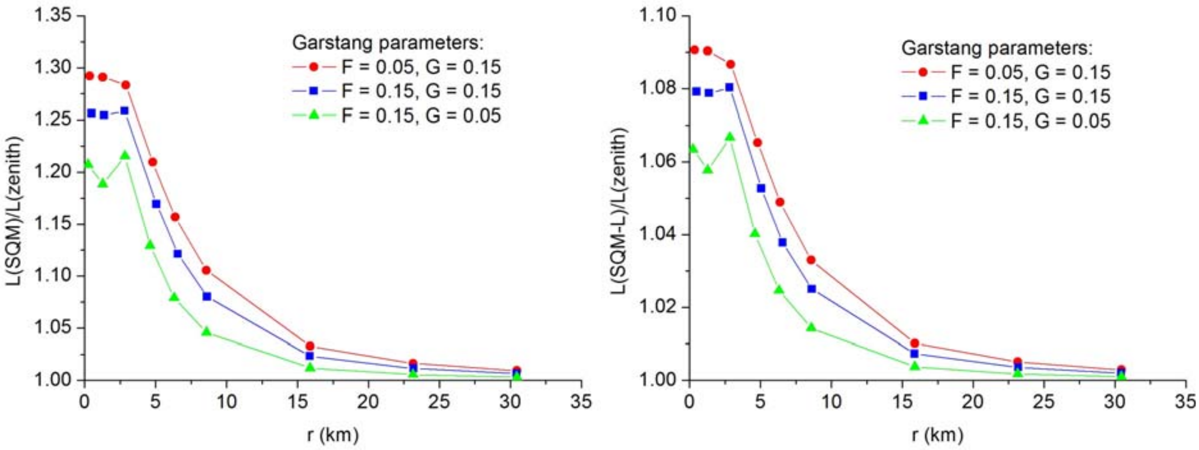


Figure 8. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance *r* from the centre of city Martin ($R_{eq} = 2.4$ km). The couple of Garstang parameters *F* and *G* is changing, the other input parameters correspond to the basic setting.

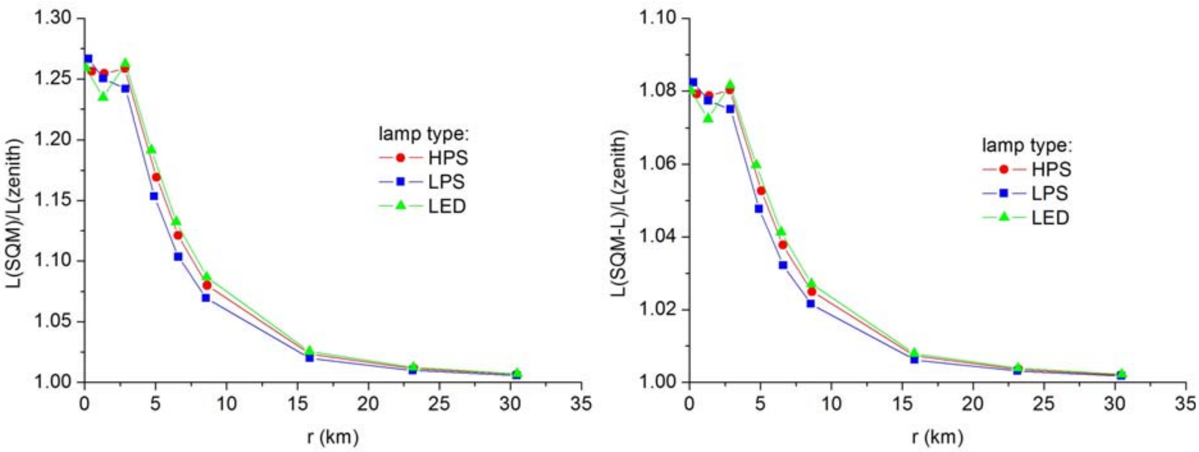


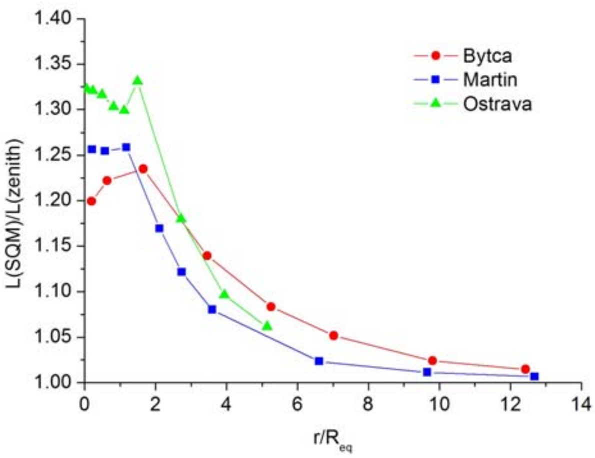
Figure 9. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of distance *r* from the centre of city Martin ($R_{eq} = 2.4$ km). The lamp type is changing, the other input parameters correspond to the basic setting.

We see that in most of the cases the ratio $L(SQM)/L(zenith)$ holds the value about 1.25 "inside" the city ($r < R_{eq}$) and then asymptotically decreases to 1. It seems that except the Garstang parameters and aerosol optical thickness the examinated input model parameters have no significant influence on the resultant curves. As Fig. 4 indicates, the relative deviation of $L(SQM)$ from $L(zenith)$ inside the city at higher atmospheric turbidity can be about 5% greater than the same deviation at low turbidity. But outside the city the difference is practically eliminated. In the case of various angular distribution of city emissions, the deviations can be yet more significant (see Fig. 5). However, it seems that a lower value of F implies a higher value of $L(SQM)/L(zenith)$ and, in contrary, a lower value of G causes a lower value of $L(SQM)/L(zenith)$. If we assume that F = 0.1 and G = 0.07 represents the most common situation ([13], [14]), the given curve might be close to the curve corresponding to the basic Garstang model F = 0.15 and G = 0.15.

The equivalent behaviour we observe also in the case of SQM-L, but due its narrower field of view the investigated ratios are, of course, smaller. Within the city $L(SQM-L)/L(zenith) \cong 1.08$. It means that the difference between the SQM-L luminance and the punctual zenith value is just about 0.08 mag/arcsec2 inside the city and yet smaller outside. Such difference lays in the device accuracy range ±0.1 mag/arcsec2. Thus, it is not relevant in practice.

B.SQM-like data – comparison of various towns

After the examination of the luminance ratios sensitivity on the input model parameters we made the next simulations in order to compare $L(SQM)/L(zenith)$ functions for differently large cities. Except the already presented city Martin we investigated yet one smaller town Bytča (population 11000, R_{eq} = 0.81 km) and one bigger town Ostrava (population 338000, R_{eq} = 5.86 km). The basic setting of the input model parameters, introduced in the previous subsection, was considered in all cases. The resultant curves of $L(SQM)/L(zenith)$ and $L(SQM-L)/L(zenith)$ as functions of the relative distance r/R_{eq} from a city centre are shown in Fig. 7.



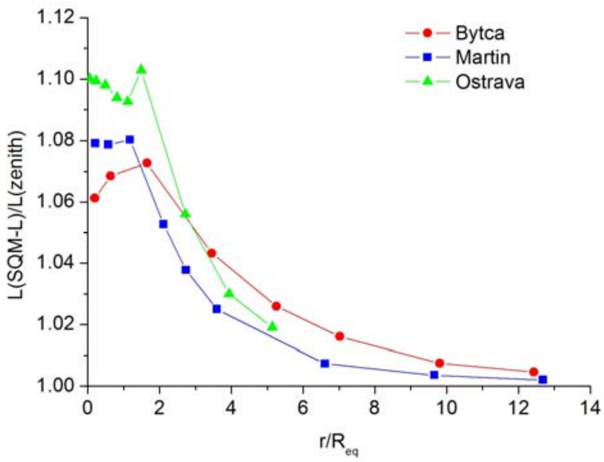


Figure 10. The ratios of SQM (left) and SQM-L (right) luminances to the punctual zenith luminance as the functions of relative distance r/R_{eq} from the centre of the city.

The bigger the city is the higher deviation of $L(SQM)$ from $L(zenith)$ we find in its interior. In the case of Ostrava, the relative deviation can be up to 33% what constitutes 0.31 mag/arcsec2. It is understandable forasmuch as in the greater town we can expect more intensive artificial skyglow at higher zenith distances that contribute to the SQM measurements. In general, there is the plateau extending to the distance $r \cong 1.5R_{eq}$ where the ratio $L(SQM)/L(zenith)$ remains approximately constant and consequently rapidly decreases. The calculated values for some relative distances are presented in Tab. 1. The results indicate that at the distance of roughly five equivalent radii of a town we can consider the night sky as dark because the artificial light does not influence SQM measurements significantly. Closer to a town we should be more careful in the interpretation of SQM measurements in the term of zenith brightness. At the distance of two equivalent radii $L(SQM)$ can be over 20% greater than the zenith luminance, it represents approximately 0.2 mag/arcsec2. It can be, of course, yet slightly increased or in contrary decreased by the device inaccuracy.

TABLE 1. VALUES OF $L(SQM)/L(zenith)$ IN DEPENDENCE ON RELATIVE DISTANCE r/R_{eq} FROM CITY CENTRE.

r/R_{eq}	$L(SQM)/L(zenith)$			
	Bytča	Martin	Ostrava	average
0.5	1.21	1.25	1.32	1.26
1.0	1.23	1.26	1.30	1.26
1.5	1.23	1.23	1.33	1.26
2.0	1.22	1.18	1.27	1.22
2.5	1.19	1.14	1.21	1.18

3.0	1.16	1.11	1.16	1.14
3.5	1.14	1.08	1.13	1.12
4.0	1.12	1.07	1.09	1.1
4.5	1.11	1.06	1.08	1.08
5.0	1.09	1.05	1.07	1.07

C.Luminance meters as indicators of SQM applicability

If an observer dispose of a sufficiently sensitive luminance meter with narrow field of view, certain assesment of SQM applicability as the zenith brightness indicator can be obtained from luminance ratios at different zenith distances. The maximum luminance $L_{max}(\vartheta)$ over the almucantar corresponding to the zenith angle ϑ is taken into account. The natural sky luminance is $\sim 10^{-4}$ cd/m2, so this should be the lower bound of a luminance meter measuring range. Otherwise the zenith luminance would not be detectable already at small relative distances. Also the values of $L(\vartheta)$ for higher ϑ within the SQM field of view appear to be $\geq 10^{-3}$ cd/m2 just op to the distance about $(1-2)R_{eq}$.

The ratios $L(\vartheta)/L(0)$ for some values of ϑ and also $L(60°)/L(30°)$ have been calculated for cities Martin and Ostrava and the results are illustrated in Fig. 8. When we compare the plots in Fig. 8 and in Fig. 7, we see that there is evident correlation between them. The end of $L(SQM)/L(0)$ plateau clearly corresponds to the maximum of $L(\vartheta_i)/L(\vartheta_k)$. This fact could help to estimate the border at which the $L(SQM)/L(0)$ begins to asymptotically decrease to 1. Mainly the curves $L(60°)/L(30°)$ appear to be mutually close for both the cities, so this ratio could offer approximate assessment of SQM applicability as the zenith brightness indicator when we compare its dependence on the relative distance with the data in Tab. 1.

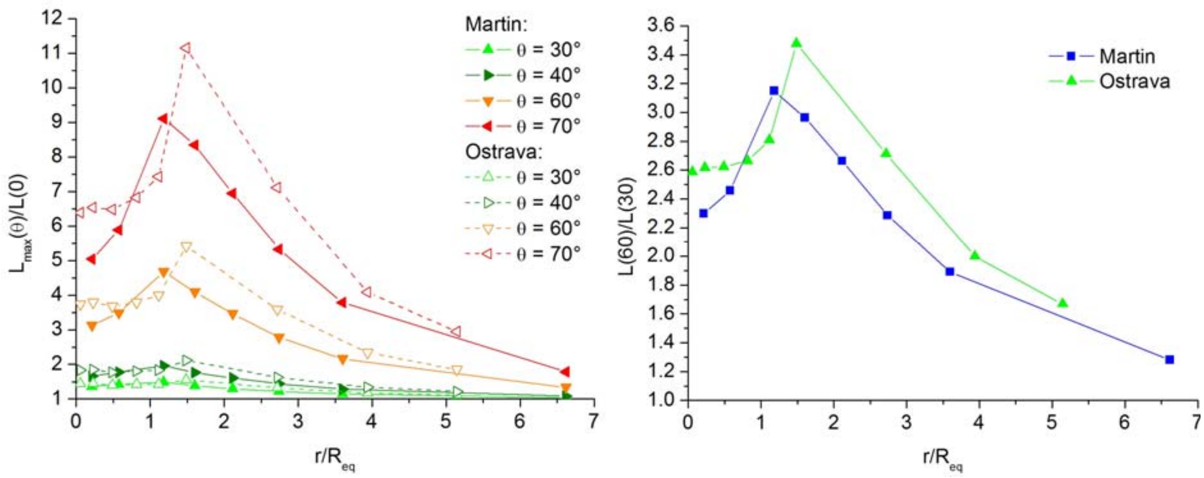


Figure 8. Ratios of maximum luminances at different zenith angles as functions of relative distance from the cities Martin and Ostrava. On the left: ratios of maximum luminance at zenith angle θ to the zenith luminance. On the right: ratio of the luminance at zenith angle 60° to the luminance at zenith angle 30°.

CONCLUSIONS

The paper deals with the convenience of SQM measurements interpretation as the zenith brightness. For this purpose we performed a set of simulations of artificial luminance sky patterns in different distances from selected towns and at various input model parameters. These computed artificial luminance distributions over the night sky together with the simplified model of the natural clear night sky luminance formed the input for calculations of luminance values "measured" by SQM and SQM-L.

The obtained results suggest that in a city interior and in its close surrounding the SQM luminance is in average about 26% greater than the punctual zenith luminance. It corresponds to the difference approximately 0.26 mag/arcsec2. This value can slightly vary according to the city population. Further the ratio $L(SQM)/L(0)$ decreases asymptotically to one (if we assume the uniform natural sky brightness). At the distance of five city equivalent radii it has still the value roughly 1.07. Thus one should be careful in interpretation of SQM-like data in the sense of the zenith brightness. The corresponding ratios achieved for SQM-L were not greater than 1.1. So the difference of the luminances is less than 0.1 mag/arcsec2 and hence not too relevant in practice because of the device accuracy.

Some information about the relation of SQM-like data to the zenith luminance can be obtained also from punctual luminances at higher zenith distances measured (if they are measurable) roughly in the direction of a city center. The clear correlations exist between the convenient ratios $L(\vartheta_i)/L(\vartheta_k)$ and $L(SQM)/L(0)$.

We hope that the results could be useful for experimenters because they allow to simply estimate the deviation between the zenith brightness and SQM data recorded in a given locality and thus to better plan measurements of light pollution in a surrounding of particular light sources.

ACKNOWLEDGEMENT

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Reducing of Blue Light Hazard

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***Abstract*—Paper deals with theme of blue light hazard and photobiological safety. Paper will be focused on eye protection against blue light. It will be measured photobiological safety for cool white LED without safety filter, with blue light blocking filter for glasses and with safety glasses. Measuring will be done on double monochromator according IEC EN 62471 and it will be calculated blue light hazard radiance and exposure limit for each eye protection. All measured values will be comparised.**

***Index Terms*—photobiological safety; blue light hazard; LED; incandescent bulb; blue blocking filter.**

INTRODUCTION

The creation of light has been in the hands of man forever. First they were used to illuminate the fireplace, the torches and the candles. The history of lighting has changed until the invention of a light bulb. In this time, the production and development of light bulbs were taking place swiftly. No one was looking at whether light sources (mainly bulbs) emit radiation that could damage the viewer's eyes. There were no standards that would allow light sources to be evaluated for safety. At present, light safety needs to be addressed, as poor quality sources can emerge on the market that emit UV radiation and large amount of blue light. Checking light sources that shine on a very wide spectrum is far more complex than to evaluate the radiation of monochromatic sources (lasers). The evaluation is performed with wide-spectrum sources by means of radiometric measurements. This measurement may be affected by the environment, the luminaire in which the source is installed, the optical elements of the luminaire or the background. Measurement may also be interfered with by a measuring optic that causes filtration and may change the measured spectrum. Measurements require special sophisticated devices and methods that can measure the desired results with high precision.

PHOTOBIOLOGICAL SAFETY

Standard IEC EN 62471 deals with the photobiological safety. The standard provides the knowledge to evaluate the light sources with regard to the security related to their effects on living tissue. It specifies the limits of radiation exposure, the reference methods of measurement and measuring techniques for full-spectrum light sources used in the light technique. This standard works with a range of wavelengths from 200 nm to 3000 nm. This standard provides knowledge to evaluate actinic UV hazard for skin and eye, near-UV hazard for the eye, retinal blue light hazard, retinal thermal hazard, infrared radiation hazard for the eye, thermal hazard for skin. The hazard values of light sources should be given as irradiance or radiance values of a distance in which an illuminance of 500 lx is produced, but not in less than 200 mm distance [1,2, 3].

If we want to prevent photochemical injuries of eye due to exposure to blue light, the weighted radiance L_B may not exceed the limit indicated by the equations 1 and 2. These equations can be applied to for sources subtending an angle more than 0,011 radian:

$$L_{\mathrm{B}} \cdot t = \sum_{300}^{700} \sum_{t} L_{\lambda}(\lambda, t) \cdot B(\lambda) \cdot \Delta t \cdot \Delta\lambda \leq 10^{6}\ \mathrm{J.m^{-2}.sr^{-1}} \quad \text{(for t} \leq 10^{4}\text{ s)} \tag{1}$$

$$L_{\mathrm{B}} = \sum_{300}^{700} L_{\lambda}(\lambda) \cdot B(\lambda) \cdot \Delta\lambda \leq 100\ \mathrm{W.m^{-2}.sr^{-1}} \quad \text{(for t} > 10^{4}\text{ s)} \tag{2}$$

where $L_\lambda(\lambda,t)$ is the spectral radiance in $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$, $B(\lambda)$ is the blue-light hazard weighting function, $\Delta\lambda$ is the bandwidth in nm, t is the exposure duration in seconds.

The equations are for a light source subtending an angle less than 0,011 radian simpler. These equations are based on spectral irradiance. Weighted irradiance E_B must not exceed the limit indicated by the equations 3 and 4 for small sources:

$$E_{\mathrm{B}} \cdot t = \sum_{300}^{700} \sum_{t} E_{\lambda}(\lambda, t) \cdot B(\lambda) \cdot \Delta t \cdot \Delta\lambda \leq 100\ \mathrm{J.m^{-2}}$$

(for t ≤ 100 s) (3)

$$E_{\mathrm{B}} = \sum_{300}^{700} E_{\lambda}(\lambda) \cdot B(\lambda) \cdot \Delta\lambda \leq 1 \,\mathrm{W.m^{-2}}$$

(for t > 100 s) (4)

where $E_\lambda(\lambda,t)$ is the spectral irradiance in $W \cdot m^{-2} \cdot nm^{-1}$, $B(\lambda)$ is the blue-light hazard weighting function, $\Delta\lambda$ is the bandwidth in nm, t is the exposure duration in seconds.

There are four groups of safety limits – the exempt group, the low risk group, the mod risk group, the high risk group. Limits for blue light hazard are mentioned in Table 1. The limits of irradiation express conditions under which people are expected not to have negative health effects during repeated irradiation. The determined values cannot be seen as the last values between safe and unsafe zone. These values can influence the observers in a different way. No negative health effects do not have to be found in healthy population. These areas cannot be used for people with high sensitivity to light and the setting limits suitable for these individuals would be difficult. The pupil diameter of the observer, the measured angular range of sources and visual angle for measurement are the specific factors influencing the determination and use limits exposure of the retina [1].

TABLE I. LIMITS OF BLUE LIGHT HAZARD [1]

	Symb.	Units	Exempt	Low Risk	Mod Risk
Blue light	L_B	$W.m^{-2}.sr^{-1}$	100	10 000	4 000 000
Blue light - small source	E_B	$W.m^{-2}$	1	1	400

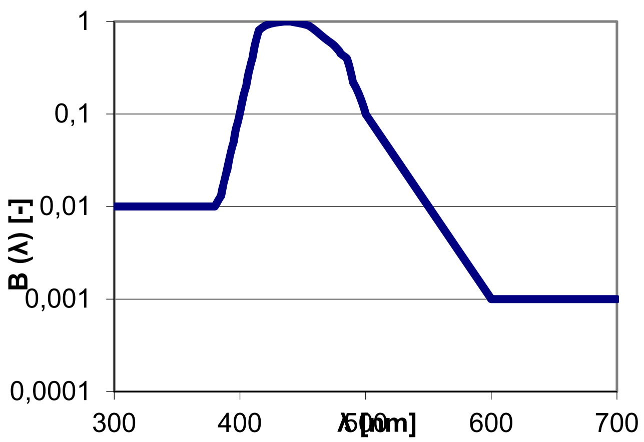

Figure 1. Blue-light hazard weighting function [1]

MEASUREMENT AND METHODS

For measurement was used double monochromator which is accurate instrument for photobiological safety measurement. It was used instrument OL 750D from Gooch & Housego. The instrument is capable of measurement after the step of 0,5 nm in the range of wavelengths. Measurement of wavelengths also depend on the type of detector which is used - silicon in the range of 200 to 1100 nm and lead-selenium in the range of values 1000 to 5000 nm. The instrument was calibrated for measuring with the spectral halogen lamp on the measuring range of 250 to 1100 nm by measurement step 1 nm. For the measurement it was used only silicon detector. It has been used integrating sphere as an optical input device.

They were used two light sources for measurement. The first source was LED 40 W with reduced power 17 W. Diameter of this source was F = 16,15 mm and color temperature was 6500 K. Measuring distance for LED was 200 mm. The second used source was incandescent bulb Tungsram 500 W, which was used in projectors. Dimensions of lighting area of the bulb were 7 x 7 mm. Color temperature was 3200 K. Measuring distance for incandescent bulb was 364 mm. For all measurement was used circular field stop to reduce parasitic reflections from the table and surrounding area. It was done three measurements for each source. In the first measurement the source was measured without any filter or glasses. In the second measurement the source was measured Essilor Crizal® Prevencia™ filter and in third measurement the source was measured with laser safety glasses LSG09. Measuring equipment for LED and Essilor Crizal® Prevencia™ filter is on Figure 2. On figure 3 is measuring equipment for LED and laser safety glasses LSG 09.

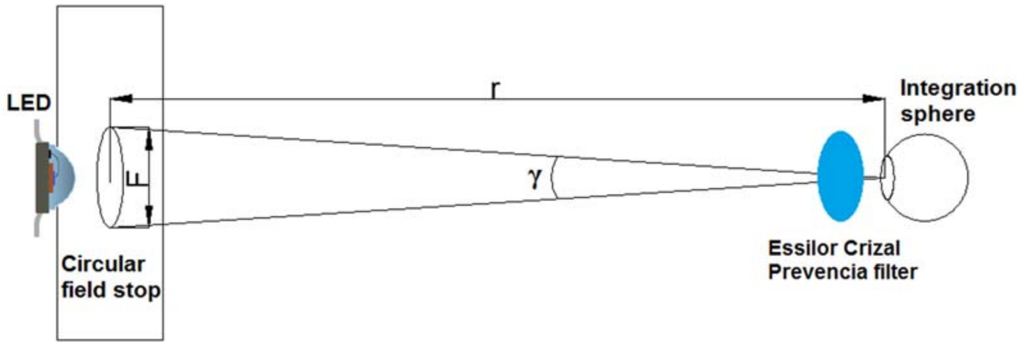

Figure 2. Measuring equipment for LED and Essilor filter

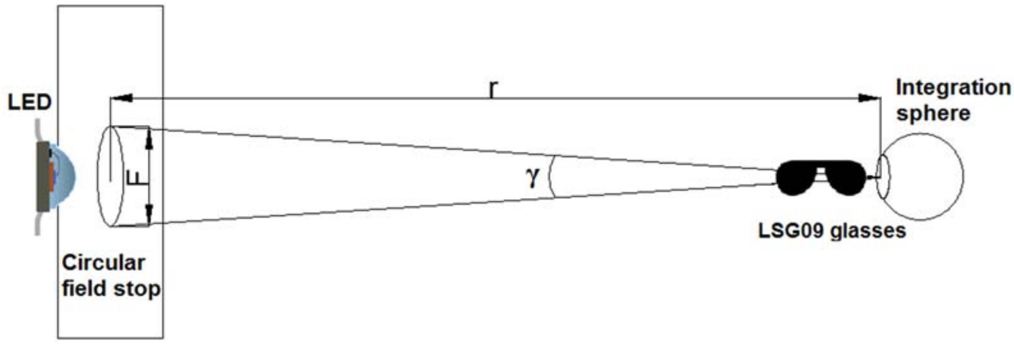

Figure 3. Measuring equipment for LED and LSG 09 laser safety glasses

Essilor Crizal® Prevencia™ filter is special glasses filter which is used for partly blocking violet and blue light from LED, sun and screens. Thanks to partly blocking violet and blue light eye should be less tired during using computer or working outside [4]. LSG09 are special glasses which are used for prevent eye injuries from laser radiation or light radiation. These special glasses protect eyes against UV radiation and blue light in the range of wavelengths from 190 nm to 450 nm and it protects against infrared radiation in the range of wavelengths from 740 to 1100 nm. In the first range it has optical density (OD) about 5 and in the second range of wavelengths it has optical density about 3 [5]. Optical density is value which show how much some material damps go through radiation. The higher value is the optical density value, the lower value is the transmittance. For example value of optical density 3 corresponds value of transmittance 0,1 % or value of optical density 5 corresponds value of transmittance 0,001 %. When using these two filters, the blue light hazard should be reduced.

RESULTS

There are results of calculated and measured data in Table II and in Table III. The first column in these tables is measurement distance r_m in metres. The second column is diameter of LED or lightning field of the bulb F in metres. The third column is measured illuminance E in lx. The fourth column is calculated blue light hazard irradiance E_b in W.m^{-2} for measured situation. The fifth column is distance $r_{500\ lx}$ in metres in which source creates comparison illuminance 500 lx. The sixth column is visual angle of source $\alpha_{500\ lx}$ in rad for illuminance 500 lx. The seventh column is solid angle of source calculated from visual angle $\Omega_{500\ lx}$ in sr for illuminance 500 lx. The eight column is calculated blue light hazard irradiance $E_{b\ 500\ lx}$ in W.m^{-2} for illuminance 500 lx. Penultimate column is blue light hazard radiance L_b in W.m^{-2}.sr^{-1}. Last column is value, how many percent the risk was decreased, while using Essilor filter or laser safety glasses. In the Figure 4 and 5 it is shown measured spectrum of classical bulb and LED while using Essilor filter or laser safety glasses.

TABLE II. MEASURED AND CALCULATED VALUES FOR CLASSICAL BULB TUNGSRAM 500 W

	r_m	F	E	E_b	r 500 lx	α 500 lx	Ω 500 lx	$E_{b\ 500\ lx}$	L_b	Δ
	[m]	[m]	[lx]	[W.m^{-2}]	[m]	[rad]	[sr]	[W.m^{-2}]	[W.m^{-2}.sr^{-1}]	[%]
Classical bulb	0,364	0,007	18227	6,20	2,20	0,0032	7,96E-06	0,170	21351	-
Essilor filter	0,364	0,007	16838	4,64	2,11	0,0033	8,62E-06	0,138	15998	25,07
Laser safety glasses	0,364	0,007	5213	0,38	1,18	0,0060	2,78E-05	0,037	1323	93,80

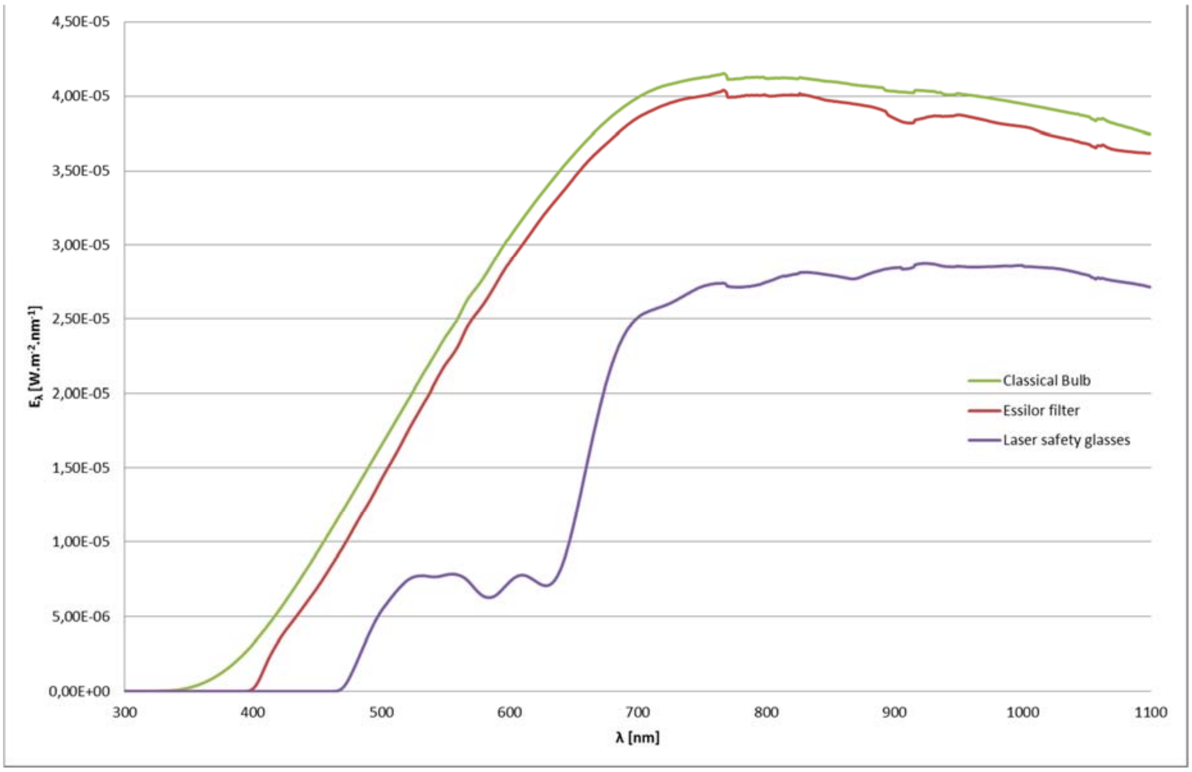

Figure 4. Measured spectrum for classical bulb with Essilor filter and with lasety safety glasses

TABLE III. MEASURED AND CALCULATED VALUES FOR WHITE LED 40 W

	r_m	F	E	E_b	$r_{500\,lx}$	$\alpha_{500\,lx}$	$\Omega_{500\,lx}$	$E_{b\,500\,lx}$	L_b	Δ
	[m]	[m]	[lx]	[W.m^{-2}]	[m]	[rad]	[sr]	[W.m^{-2}]	[W.m^{-2}.sr^{-1}]	[%]
LED	0,2	0,0166	13708	8,339	1,047	0,016	0,00020	0,304	1542	-
Essilor filter	0,2	0,0166	13209	6,577	1,028	0,016	0,00020	0,249	1216	21,13
Laser safety glasses	0,2	0,0166	3831	0,239	0,554	0,030	0,00071	0,031	44,1	97,13

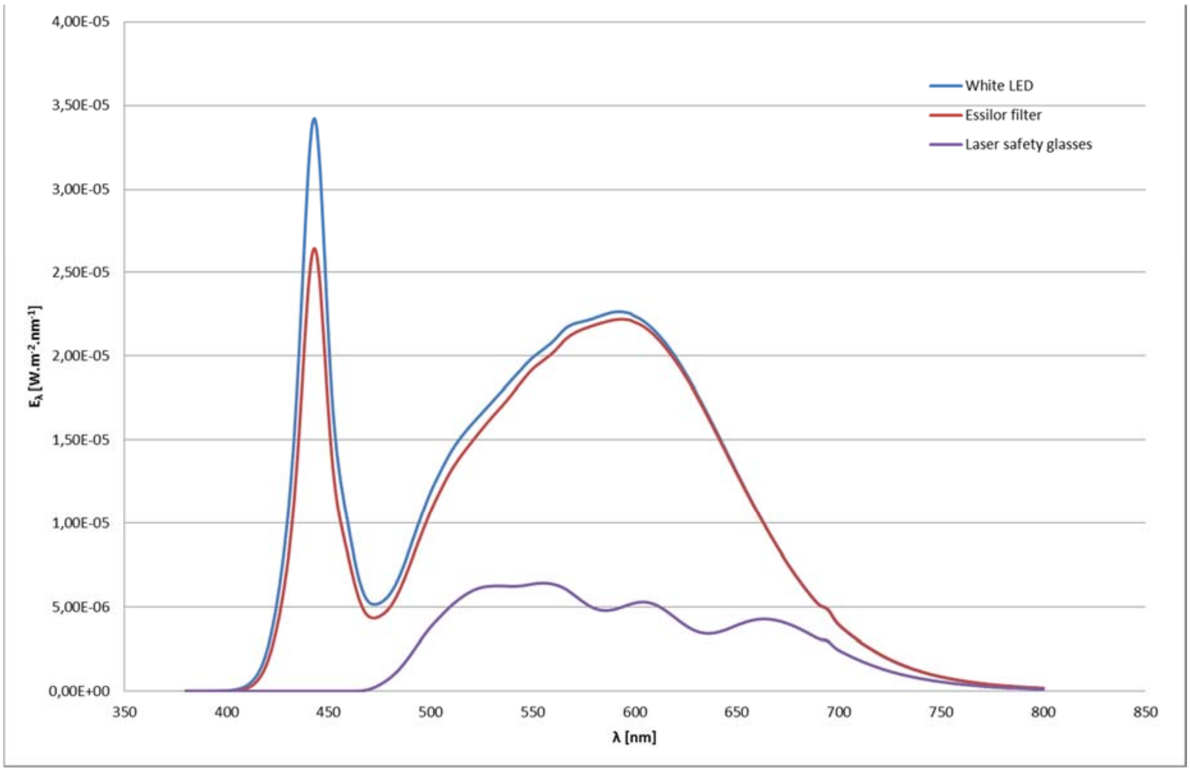

Figure 5. Measured spectrum for White LED 40 W with Essilor filter and with lasety safety glasses

CONCLUSION

The aim of article was to find out, how to reduce the blue light hazard by using blue light blocking filters. As blue light blocking filters they were used Essilor Crizal® Prevencia™ filter and laser safety glasses. They were used two sources for measurement – classical bulb and white LED. For both sources it was calculated blue light hazard according IEC EN 62471. From the calculated values for the classical bulb it is evident, that blue light hazard was reduced by 25 % for Essilor filter and 94 % by laser safety glasses. For the LED it is evident from the calculated values, that blue light hazard was reduced by 21 % for Essilor filter and 97 % by laser safety glasses. In the Figures 4 and five there are measured spectrums and from these figures it is seen how was change spectral distribution by using filters for each sources. The results show that glasses filters like Essilor Crizal® Prevencia™ could be used like prevention of observes for common use in household, shopping centers or office work. Laser safety glasses are more appropriate for work with light sources in labs or in factories, which produces light sources.

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Digital Light: Perception of Projected Visual Signal from Different Perspectives

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***Abstract*—High resolution "pixel light" modules enable new light functions like the projection of signs onto the pavement in order transmit information to the driver. It has to be proven that the driver can perceive the signal, and that no other traffic participant is confused or endangered by glare also in adverse weather situations. Therefore, we developed tools for the virtual development in order to evaluate the performance and the glare potential of a headlamp system. In this contribution, a certain projection headlamp system is analysed in a special traffic situation on a wet and a dry pavement.**

***Index Terms*—digital light, headlamp, perception, visual communication**

INTRODUCTION

Due to the invention of high resolution "pixel" light modules, the functionality and complexity of head lamp systems increases. Thus, numerous concepts for new light functions were presented in the recent years. An example is the marking light for illuminating the road edge, or the projection of signs directly onto the road, in order to transmit information to the driver or other traffic participants.

Although the intention of these concepts is great it has to be validated that the road safety is not impaired, and in case of visual communication that the receiver can perceive the information.

Especially on a wet pavement light reflexions cause glare in similar magnitude like a direct gaze in a head lamp [1]. Roughly, the reason for this is that the reflexion properties of the pavement changes from predominant scattering behaviour when the road is dry to strong forward reflexion when the road is wet. An example: the headlamp projects a sign onto the road in front of the car in order to give a signal to the driver. While this system is feasible on a dry road, on a wet road the specular reflexion can cause that the contrast of the projected sign becomes too low to be perceived by the driver, but at the same time the forward reflected light will glare other traffic participants, disadvantageously.

We have developed a couple of tools and methods in order to validate that the headlamp system is feasible and does not cause unfavourable effects. This is done virtually on basis of CAD data before prototypes are built-up, or on basis of measurements on the car or the headlamp. Our tool "CAGE" – computer aided glare evaluation – was designed for virtual glare evaluation which also considers adverse weather situations [2]. It helps to optimize the headlamp systems early in the development process and to avoid inconvenient experiences in strict assessments like that of IIHS [3]. The method of geometrical reduction that we invented enables to measure the full spatial light distribution e.g. that of a low beam luminance camera-based in a reference light hall. From this measurement, the luminance distributions seen from driver's view on specific kind of pavements in wet and dry state are calculated. Additionally, contrast isolines to a reference vision targets are determined in order to deduct statements on recognisability on the respective pavement and weather situation.

As an example, we examine in the following a headlamp system which projects a sign directly on the road in front of the driver in order to warn him. In order to do so, we imagine a simple but usual traffic situation in different weather conditions and consider the recognisability and glare potential from the perspective of different traffic participants.

SET-UP

We consider a 32x32 pixel light module that is integrated in the bumper of vehicle A in a height of 0.65m (see Fig. 1). Such a light module was chosen in order to follow up modules recently developed and presented to the community [5]. This pixel light module projects a sign onto the road in a region between 4m and 6.5m in front of the car with a homogeneous illuminance of 1000lx. The projected sign will be observed from a couple of traffic participants on a dry and on a wet concrete. Therefore, the BRDF of a dry and a wet concrete was modelled on basis of data from own research [amongst others 1] and from literature [6]. The simulations are processed by the same routines which we developed for the work presented in [2]. Next, the following situations are analysed:

A. A traffic situation at a crossroad

The vehicles A, B, and C approach a crossroad at the same moment (Fig. 1). When reaching the crossroad, A is located 15m in front of B, and C is located 3m right to B. The driver assistance systems of vehicle A judges this situation to be dangerous and in consequence warns the driver by projecting a sign onto the road. All three traffic participants observe this sign. The height of the eyes of all drivers is presumed as 1.2m.

B.Contrast consideration

Here we modify the scenario and apply additional a constant illuminance of 30lx as background to the warning symbol. We chose such a background illuminance thinking of the typical magnitude of illuminance of a low beam in that region close to the car. We simulate again the luminances seen by the drivers in A and B and analyse the contrasts

$$C = (L_O - L_U)/(L_U - L_V) \tag{1}$$

(L_O luminance of object, L_U luminance of background, L_V veiling luminance) because perception depends on contrast.

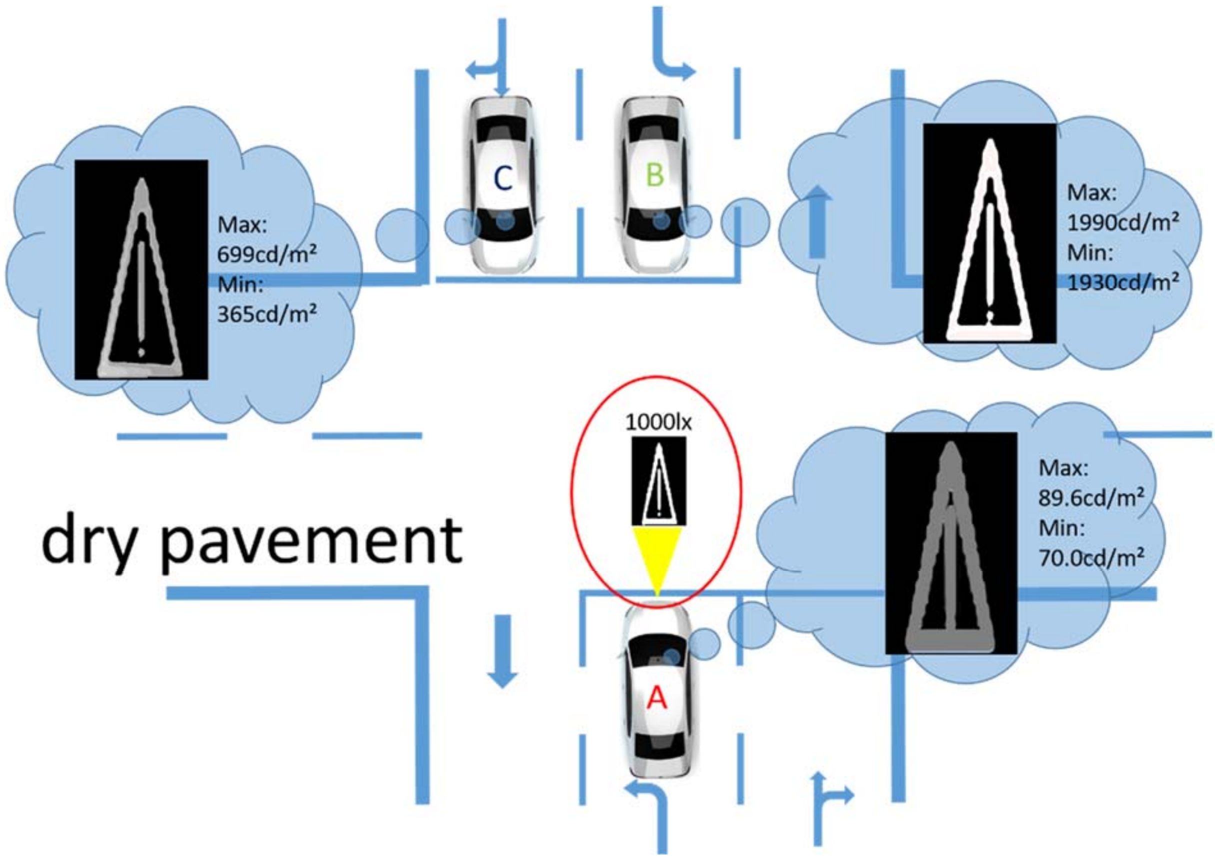

Figure 1. Vehicles A, B, and C meet on a crossroad. A warning signal is projected onto the dry concrete from vehicle A and its luminance is observed by the drivers in A, B, and C. Please compare with the results on the wet pavement in Fig. 2.

RESULTS

A.A traffic situation at a crossroad

1. Dry road, driver A: Driver A is the recipient of the message transmitted via the projection and he perceives the signs with luminances between 70.0 and 89.6cd/m².
2. Dry road, drivers B and C: Because of forward-scattering, the drivers B and C detect the sign in much larger luminances than driver A does up to 1990cd/m². Thus, B and C will clearly perceive the sign as a secondary light source. Although the resulting glare illuminances of this secondary light source is not distinctive, it has to be ensured that the projection will not attract the attention of other traffic participants which could affect the traffic safety. This has to be considered during the design of the system and the communication strategy.
3. Wet road, driver A: From the perspective of driver, the luminance is significantly reduced to 38.9cd/m². This is because the reflection properties are changed to strong specular forward reflection when the pavement is wet.
4. Wet road, driver B: For the same reason, i.e. the drastic change to specular reflection, driver B detects very high luminances up to 99940cd/m² which is leading to a contribution of some tenth of lx to the total glare illuminance. The impact on driver B of this additional glare stress is not discussed since we made no presumptions on the surrounding luminance, the other light functions, and on the adaptation of driver B's eyes.

5. Wet road, driver C: A positive consequence of the strong specular reflection of the wet pavement is that driver C is not able to detect the sign.

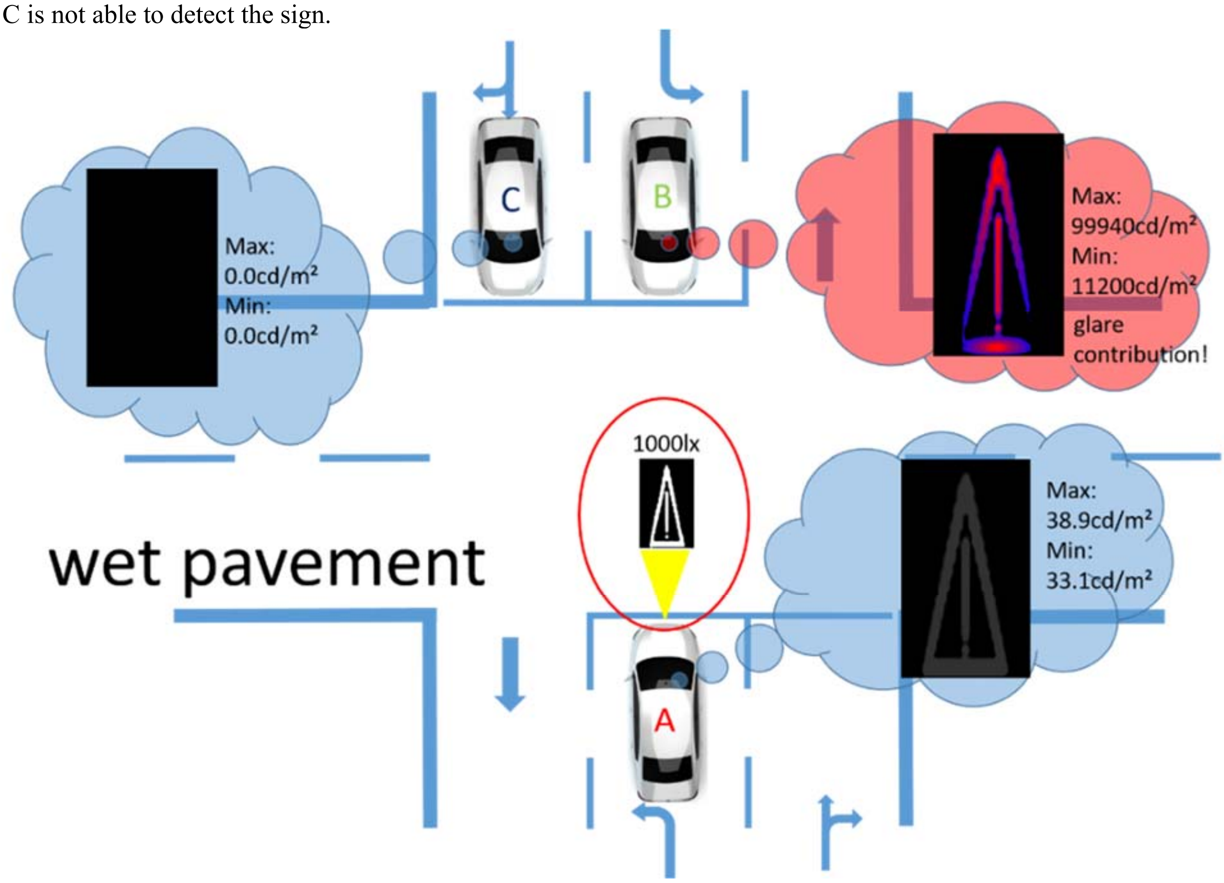

Figure 2. Vehicles A, B, and C meet on a crossroad. A warning signal is projected onto the wet concrete from vehicle A and its luminance is observed by the drivers in A, B, and C. Please compare with the results on the dry pavement in Fig. 1.

B.Contrast consideration

1. Dry road, Vehicle A: The recipient of the message perceives an average contrast of *C=34.3*.
2. Dry road, Vehicle B: The driver B who's attention could be diverted from the traffic by the projected sign sees an average contrast of *C=33.6*.
3. Wet road, Vehicle A: The luminance for A is distinctively reduced on a wet pavement compared to a dry pavement, as we found out above. But as the background luminance is reduced too, and the eyes adapt, the question is if the perceptibility is affected. The answer is that the contrast is only slightly reduced affected and *C=32.6*. Thus, it is to assume that without any further glaring light sources the perceptibility for the recipient will not be reduced on a wet road. But if A is glared by a further light source, e.g. the headlamps of B, the resulting veiling luminance would contribute to the denominator in Eq. (1). This veiling luminance will arise on a wet road and will reduce the contrast and the perceptibility, additionally. A possibility for an optimization is to network this light module with the environmental sensors in order to detect such scenario and to address the driver on an alternatively channel [1]. A compensation of the reduced contrast by increasing the light output of the module could be not appropriate because the glare load on B would be increased, as we will see below.
4. Wet road, Vehicle B: For B, the contrast will be distinctively increased on the wet pavement to *C=51.8* which could increase discomfort glare.

SUMMARY AND OUTLOOK

New lighting technologies like pixel light modules or laser scanner give the opportunity for defining new light functions which have the potential to increase traffic safety and to raise driving comfort. However, it has to be checked that no endangerment of any traffic participants occurs, e.g. by glare, and that the performance of the system is appropriate. As an example, we imagined a simple but very common situation and examined under which conditions glare or confusion on traffic participants can occur.

From the view of an industrial designer, such examinations have to be done very early in the development process before any prototypes are set-up. Otherwise, the development of the vehicle is too advanced to make changes with reasonable efforts. In order to maximize traffic safety, and to minimize efforts in the development process, we are developing virtual tools, and gave an example for an application in this contribution.

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Realization of a Test Setup for a Smart Light Guiding System with Assistance Functions for Elderly People

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***Abstract*— One common wish of elderly people is to live in their own apartment as long as possible. Often they have to move to retirement homes because they do not receive the appropriate assistance they need. A future assistance system could support elderly people to live self-determined in their own apartments. One conceivable assistance system is a light guiding system. Within a study at the research program "ITES" (Intelligente Technische EnergieSysteme, Smart Technical Energy Systems) a test setup for a light guiding system was built in the light laboratory of the University of Applied Sciences in Bielefeld. With the test setup four assistance functions are realized which should support especially elderly people to live safely in their own apartments. A conducted study shows that the presence dependent activation of the assistance functions has to be revised.**

***Index Terms*— age-appropriate housing, assistance system, smart home, smart light guiding system, test setup**

Concept of the Study

A. Introduction

The average age of the German population is increasing due to the demographic change and the growing life expectancy [1]. Consequently the number of elderly people will increase in the next decades. Thus not only the demand for age-appropriate living space is rising, there is also a demand for assistance systems which support elderly people in their residential environment. The assistance systems should support elderly people to live self-determined and safely in their own apartment as long as possible. One conceivable assistance system is a floor integrated light guiding system. In contrast to conventional lighting it is possible to illuminate certain routes (e.g. between bedroom and bathroom) purposefully with the light guiding system. Currently light guiding systems are used in public spaces and not for the described field of application.

B.Objectives

Goal of this study is the development of a floor-integrated light guiding system as a prototype and its validation. The activation of the assistance functions takes place depending on the presence of a person in bed. In addition the whole system should be integrable invisibly in the residential environment.

C.Approach

The test setup is built in the light laboratory of the University of Applied Sciences in Bielefeld. The assistance functions are implemented as a PLC-project (Programmable Logic Controller) on an industrial PC. In the first instance four assistance functions are realized: basic lighting, path lighting, evacuation lighting and manual activatable lighting. These assistance functions are based on the use cases defined in the master thesis of Kristin Gabel [2]. Purpose of the basic lighting is to allow users to orient themselves by the identification of the surroundings. The path lighting should support users to find their way at night e.g. from the bedroom to the bathroom or to the kitchen without searching for a light switch. Moreover the evacuation lighting helps the user to find a secure way out of the apartment in case of a fire alarm. Finally the manually activatable lighting offers the opportunity to use the illumination by the light bands regardless of the assistance functions described above.

As light source a LED-based light band is used. For the presence-dependent activation of the assistance functions a tape switch and an ultrasonic diffuse reflection sensor (UDRS) are used. The tape switch detects the presence of a person in bed of the test setup. In contrast to that the UDRS detects whether a person lays down or whether a person gets out of bed. The two mentioned devices are decisive for the correct functional principle of the test setup for the light guiding system. Thus a study with 22 test persons is conducted to validate the general suitability and the installation position of the tape switch and the UDRS. Finally research is done to examine the framework conditions for building integration of the light guiding system.

STUDY

A. Construction and Operating Principle

Goal of the construction is the realization of the four assistance functions listed above. The test setup (Fig. 1) covers 12 m² and is built modularly to enable an uncomplicated further development. It was necessary to build a "second floor" of OSB (Oriented Strand Board) to integrate three light bands evenly into the floor. Each light band can be driven separately. A fourth light band is integrated into the imitation of a door frame. Besides the light band a fire detector and a light sensor are mounted at the imitation of a door frame. The devices which are essential for the correct function of the light guiding system are installed in the bed of the test setup. The tape switch is fixed between the slatted frame and the mattress in the area where the center of the body of a potential user is positioned. In contrast to the tape switch, the UDRS and the push button are mounted at the head of the bed. All electrical devices are connected to corresponding terminals of the industrial PC which is placed next to the test setup (Fig. 1). The whole operating principle of the test setup is realized by the programming of the industrial PC as a PLC with the software TwinCAT 3. Furthermore a visualization is designed to monitor the different system parameters of the test setup.

Figure 1: Test Setup for the Smart Light Guiding System
[Source: Own Illustration]

For the activation of the four assistance functions different switch-on conditions have to be fulfilled. The assistance function "basic lighting" is activated basically if the bed is used the first time during night's rest (adjustable period) and the current value of the illuminance is below an adjustable threshold value at the same time. For the detection of the bed occupancy, the tape switch is used. If the basic lighting (Fig. 2) is activated, all floor integrated light bands are switched on for the rest of the night or until the current illuminance is above the threshold value. Furthermore the user of the light guiding system has the opportunity to disable the assistance functions separately via switch button. In this case the light guiding system registers all actions at the test setup without switching on the light bands. The assistance function remains disabled until it is enabled manually by the user via push button.

Figure 2: Assistance Function "Basic Lighting"
[Source: Own Illustration]

In case of a lying person who stands up, the person is first detected by the UDRS and then by the tape switch. Because of the order of detections and other factors, the control of the light guiding system realizes that a person is standing up and consequently activates the "path lighting". Additionally the current value of illuminance has to be below the threshold value of the illuminance, the current time has to be inside the time span of the night's rest and the path lighting must not be disabled by the user before the path lighting can be activated. If the assistance function "path lighting" is activated, the floor integrated light bands along the way e.g. to the bathroom are switched on as well as the light band in the imitation of a door frame (Fig. 3). Unlike the floor integrated light bands which should primary illuminate the way to a special room the purpose of the door frame integrated light band is to enable a better orientation.

Figure 3: Assistance Function “Path Lighting”
[Source: Own Illustration]

The assistance function “evacuation lighting” is automatically activated via fire detector and cannot be overruled by any user action for security reasons. It is only possible to end the evacuation lighting by a reset of the fire detector. For the evacuation lighting two scenarios are taken into consideration: optical release and optical blocking. In case of optical release the door frame is illuminated with green light in order to show that it is safe to pass the door (Fig. 4). Additionally the floor integrated light bands indicate the safe escape route with a “running light” in both scenarios of the assistance function “Evacuation Lighting”. The motion is illustrated by the arrows in Fig. 4 and Fig. 5. In the scenario of the optical blocking the door frame is illuminated with red light to emphasize that it is dangerous to pass the door (Fig. 5). Compared to the scenario “optical release” the running light in the scenario “optical blocking” guides the user in the opposite direction (direction is illustrated by the arrows, Fig. 4, Fig. 5).

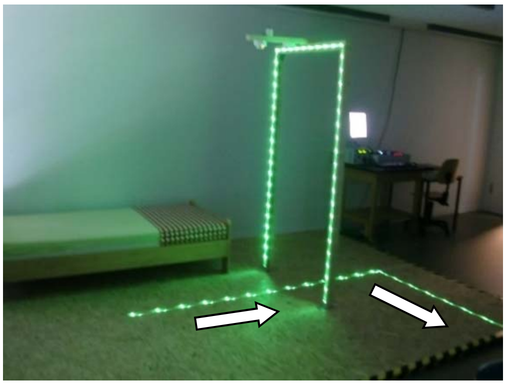

Figure 4: Assistance Function “Evacuation Lighting”, Scenario: “Optical Release”
[Source: Own Illustration]

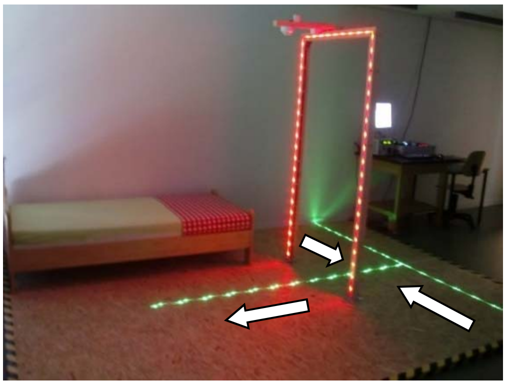

Figure 5: Assistance Function “Evacuation Lighting”, Scenario: “Optical Blocking”
[Source: Own Illustration]

The fourth assistance function “manual activatable lighting” gives the user the opportunity to switch on all floor integrated light bands for an adjustable period regardless of the predefined assistance functions (Fig. 6). Compared to the other assistance functions, the luminous flux is doubled in this assistance function because of the potential use during twilight.

Figure 6: Assistance Function “Manual Activatable Lighting”
[Source: Own Illustration]

B. Validation of the Operating Principle

The management of the assisting functions essentially depends on the detections of the tape switch and the UDRS. Erroneous detections cause erroneous functions of the light guiding system. Therefore a study is conducted to validate the general suitability of the tape switch and the UDRS. Additionally three installation positions per component are evaluated to finally determine the most suitable installation position. The preselection of the installation positions is carried out basing on the body measurements of the German population defined in DIN 33402-2 [3]. Tape switch and UDRS work independent from each other. Therefore it is possible to examine one installation position of the tape switch and one of the UDRS simultaneously. Overall the study comprises three test series (Tab. I).

TABLE I. STRUCTURE OF THE CONDUCTED STUDY [SOURCE: OWN ILLUSTRATION]

Structure of the Conducted Study	**Installation Position (cm)**	
	Tape Switch (distance to the head of the bed)	***UDRS (distance to the surface of the mattress)***
Test Series 1	92	53
Test Series 2	99	58
Test Series 3	107	63

For the study 22 test persons are recruited from the surrounding area of the University of Applied Sciences in Bielefeld. The participation in this study is voluntary and not rewarded monetary. In the first instance the age of the test persons is not decisive. The main objective is to validate the light guiding system with test persons of different physique. Each test person passes all three test series.

The task of all test persons is to lie down in the bed of the test setup and to get out of the bed ten times per test series. These motion sequences can be aggregated into ten cycles per test series. The test persons should act in a natural way e.g. they should take the lying position in bed they normally take at home. It is allowed to vary the lying position throughout the different cycles. The investigator notes the sum of detections for both considered components, each cycle and each test person in a trial protocol. A successful detection is displayed by the visualization of the light guiding system.

The raw data from the trial protocol is grouped in three categories for the analysis: erroneous detection, correct detection and multiple detection. A correct detection exists if per considered component, cycle and action (laying down or standing up) of the test person there is only one single detection. Consequently an erroneous detection exists if there is no detection and a multiple detection exists if there is more than one detection under the described circumstances.

C.Findings

The test setup of the light guiding system enables the presence dependent demonstration of the four assistance functions: basic lighting, path lighting, evacuation lighting and manual activatable lighting. Furthermore the test setup offers the opportunity to evaluate different devices (e.g. different light bands) which could be suitable for a commercial light guiding system in the residential environment.

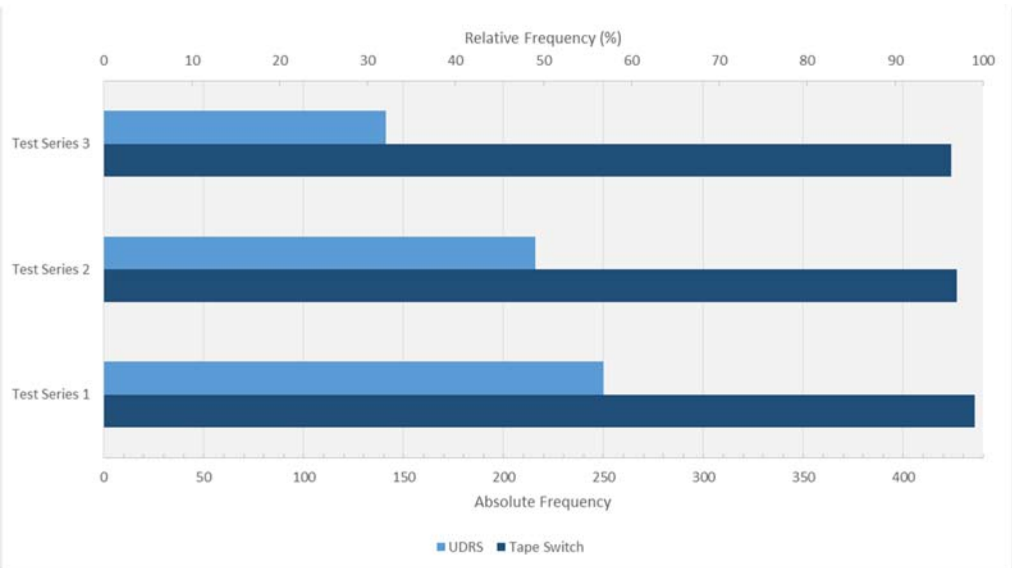

Figure 7: Results of the Conducted Study, Correct Detections (extract) [Source: Own Illustration]

Fig. 7 shows that the amount of correct detections of the tape switch is considerable higher than the amount of correct detections of the UDRS regardless of the test series. Overall there is no erroneous detection by the tape switch, all not correct detections are multiple detections. The highest amount of correct detection is achieved in test series 1 regardless of the considered component. For the tape switch the amount of correct detections is 99.1 % and for the UDRS only 56.8 %. The lowest amount of correct detections is achieved in test series 3 regardless of the component. In test series 3 the maximum installation positions are evaluated (Tab. I). The UDRS is in the highest evaluated installation position and the tape switch is in the installation position which is farthermost from the head of the bed. It was observed that in test series 3 especially small test persons do not trigger the UDRS because they do not manipulate the sound beam. In case of the tape switch it was observed that the centers of the bodies of shorter test persons are not exactly above the tape switch so that there are multiple detections more often. Overall tall test persons can be detected more reliable with this test setup nevertheless the motion sequences of the test persons also have a great influence. Persons who lie down in bed fast and flat can be detected hardly.

The analysis of the conducted study shows that the tape switch is a suitable device for the detection of a person in bed. The ideal installation position is 92 cm away from the head of the bed between slatted frame and mattress. Unlike the tape switch, the UDRS is not suitable for its field of application within the smart light guiding system because of a small proportion of correct detections in the conducted study. An ideal installation position cannot be named. Because of the low amount of correct detections by the UDRS, a reliable operation of the whole test setup of the light guiding system cannot be ensured at the moment.

C.Framework Conditions for Building Integration

For the realization of the four described assistance functions it is necessary to integrate the light bands into the floor. Depending on the construction size of the light bands it can be necessary to slice the screed for the installation of the light bands. This entails a significant interference in the building stock and additionally there is the risk to weaken the structure of the screed or to damage the pipes of an underfloor heating. Therefore the light bands should be preferably small so that it is possible to integrate the light bands into the flooring. For a simple integration of the light bands into the flooring especially prefabricated floorings like click laminate, parquet, linoleum or cork are interesting however it is necessary to construct a mounting rail for an even integration of the light bands into the floor. The research of the installation height of different floorings on the German market has shown that a light band should not be thicker than 5 mm to harness most of the floorings.

Furthermore the light bands have to be insensitive to mechanical influences and chemical detergents to enable a long lifetime. A floor is often wiped wet because of this a protection class of IP 65 or more is necessary. Finally an ideal light band should consist of RGB-LEDs to allow potential user to customize the light color.

D.Prospect

Prospectively the presence dependent management of the assistance functions needs to be developed so that a reliable operation of the test setup of the light guiding system can be ensured. Moreover a user interface for the light guiding system needs to be designed to enable adjustments by the user. A usability test with the test setup and potential users is only useful if the presence dependent management works properly. Regardless of the usability test, the illuminance during the different assistance function will be measured photometrically. Furthermore smaller light bands with RGB-LEDs can be tested in connection with the integration in different types of flooring. All these evaluations will be carried out in laboratory environment.

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Experimental LED Luminaire for Investigation of Non-visual Effect of Light to Human Circadian System

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Abstract - ***R*elationship among light and human health, disease, and wellness is one of the most researched areas in lighting technology of the decade. The progressing scientific findings in the fields of chronobiology, photobiology, and scotobiology are necessary for composing of entire image how artificial light directly impacts the human circadian system. It is known that non-visual photoreceptors - intrinsically photosensitive Retinal Ganglion Cells - ipRGCs, which are co-responsible for synchronization of circadian rhythm, require blue spectral components in the light with a maximum spectral sensitivity around 460 – 480 nm, but also receive input from visual photoreceptors. Researchers have identified intensity, spectrum, duration/pattern, and timing of light exposure as important variables that control the responsiveness of the non-visual system. We therefore developed modular LED luminaire, which is able to control all of these variables and allowing dynamic change of the spectral power distribution of luminous flux with possibility of colour temperature changing in the range 2400 K - 10 000 K (Ra >90, Δuv < 0.0005) and also possibility to set any hue in the colour gamut given by fixture construction. Circadian system response was verified by mathematical model developed by Rea et al. Circadian stimulus (CS%) was calculated for range of CCT: 2400 K - 10 000K and compared to commercial artificial light sources commonly used in residential lighting as well as standard CIE illuminants together with two types of sky ("Clear" and "Cloudy").**

Index Terms-- **Circadian stimulus, correlated colour temperature (CCT), human circadian system, light emitting diode (LED), spectral power distribution (SPD).**

INTRODUCTION

Our biological clock is controlled by sun light and can be synchronized also by bright light within a day hours, darkness at night and precisely timed cycle of changing wavelength dominance during the day. New findings in the fields of chronobiology, photobiology, and scotobiology provide necessary information how light directly impacts the human body and brain [1]. Discovery of specialized non-visual ocular cells - intrinsically photosensitive Retinal Ganglion Cells - ipRGCs helped comprehend the transmission of light signals to the brain for synchronization of the biological clock [2]. Humans are exposed to a substantial amount of electric lighting as well as natural light, all of which has some effect on our physiology regardless of the type of source. New researches related to light and health leads to the questions - how we should illuminate architectural spaces. It is estimated that people spend 90% of their time indoors with limited exposure to natural light, while artificial illumination from general lighting, including mobile devices, computers and TVs, dominates. New technologies allow to improve efficiency and productivity, but it is necessary to do many research yet for correct understanding of impact light to humans, because some works shows that light is necessary for vision as well as non-visual effects of light is needed for overall health and well-being [3]- [5].

Artificial lighting passed diametrical change during its evolution. Fire from chips of wood and gas lamps was replaced by electrical ligth from tungsten bulbs, discharge lamps, fluorescent tubes and light emitted diods - LED, which is commonly used in these days. Different light sources have different spectral power distribution of luminous flux, therefore research of effects of dynamic lighting to the human beings in terms of visual and non-visual response is very important for correct projection of modern illuminating systems. Future concepts of artificial lighting in offices, hospitals, educational institutes and residential objects should cover results of current and future researches, therefore luminaires used in lighting systems today should adapt them. According to standards illumination levels and homogeneity of illumination is basic requirement for the most task areas, but designers of illumination systems should also consider appropriate correlated colour temperature (CCT) when developing appropriate illumination throughout the space. While studies suggest 6000 K – 8000 K LEDs with a spectral composition leaning toward a blue spectral focus may have the best biological impact, this is likely undesirable to occupants. 5300 K or higher lights, closer to daylight white, may also be good for alerting affects, but proper selection must balance individual comfort and focus requirements. 3500 K – 5500 K were found through studies to be the most visually pleasing, however conclusions revealed there was not a single preferred spectrum. [6].

Appropriate luminaires is needed for meeting requirements of modern lighting designs, therefore it was developed experimental luminaire, which try to cover the most of lighting designers' needs.

MATERIALS AND METHODS

A. Construction of experimental LED luminaire

Construction of experimental luminaire was divided into several steps according to opto-mechanical disciplines. At first it was necessary to chose appropriate LEDs in terms of type, dominant wavelength and amount. Oslon SSL 150 and Osram Ostar LEDs (Osram, Germany) was chosen for colour mixing cluster. Amount of LEDs was under intensive development and number of calculations was done to establish four package cluster as a sufficient for adequate CCT range and high CRI. One of the main goal during development was CRI > 90 in whole range of CCT. Four different LEDs colours - Red, Green, Blue, White - with spectral half band width in range 20 - 100 nm was used to reach the aim. Colour mixing cluster contains RED LED (λ_{max} = 617 nm), GREEN LED (λ_{max} = 617 nm) BLUE LED (λ_{max} = 465 nm) and WHITE LED (2700K). Optimum amounts of LEDs for whole luminaire was calculated, so that luminous flux of luminaire reaches approx. 2500 lm. It was described above that variable CCT is very useful for many lighting designs. Young people will prefer different CCT for learning or for working on PC, seniors may prefer different lighting scheme during day in terms of CCT and intensity as well. Experimental luminaire was calibrated in range 2400 K - 10 000 K (Δuv < 0.0005), because lower CCT is useful to use at evening time while higher CCT is more efficient for melatonin suppression during day. The luminaire is designed to hold CCT and CRI stable during dimming up to approx. 5% of max intensity. This part of development is not trivial, because natural behaviour of LEDs is colour shifting during dimming, therefore it is necessary algorithmically compensate colour shifts during LED driving. It is possible also to set any hue and saturation level in the colour gamut given by LEDs combination [Fig.1]. This is useful for composition of lighting scene aimed to decoration or ambient lighting as well.

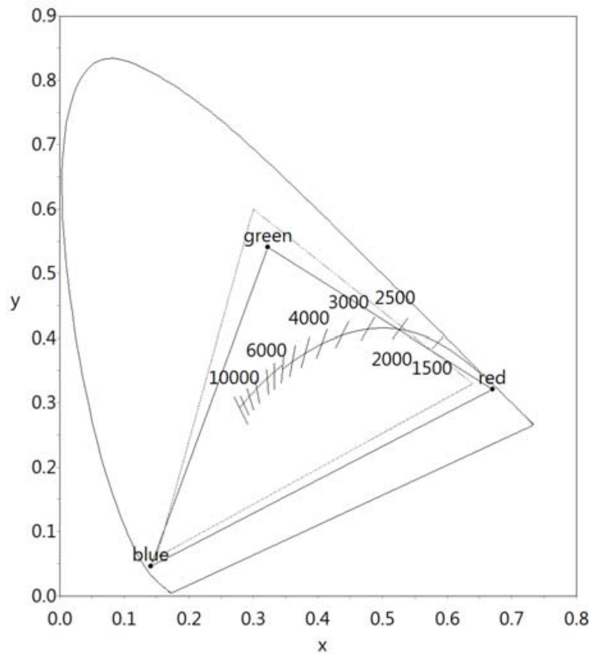

Figure 1. *Comparison od colour gamuts plotted in CIE 1931, dotted line - sRGB, solid line - experimental luminaire.*

B. Mechanical design

Aluminium metal plate (thickness = 4 mm) was used as a flat heat sink for adequate passive cooling and as a base of whole luminaire. Aluminium profiles mounted on the base create skeleton of luminaire shape. For inner surface of luminare sides was used white reflector film (FusionOptics, USA) with high surface reflectance (97%) across all wavelength of visible light spectrum, therefore inner surface is not spectral dependent, due to quality colour mixing of four different LEDs colours. Diffusive PMMA sheet (Plexiglas, Germany) was used for homogenous brightness across luminous area. It was chosen standard FR4 material For LED PCB. Layout of single LED across PCB was optimized, so that quality of colour mixing stay same especially in places where PCBs touch each other. Thermal management of heat transfer from LEDs to flat heatsink was verified by thermal camera 870-1 (Testo, Germany) [Fig.2].

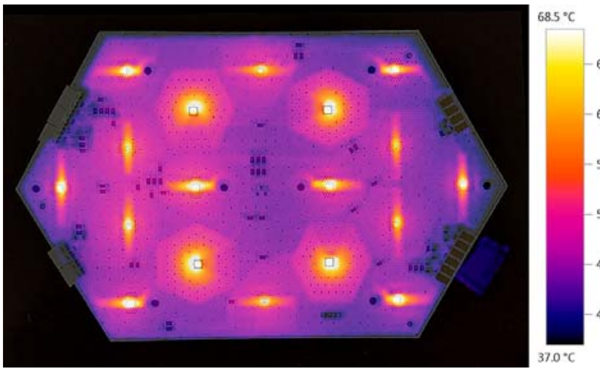

Figure 2. *Thermogram of LEDs PCB.*

Luminaire has trefoil design so that it could be possible to combine more than one fixtures into various lighting patterns. **[Fig. 3]**.

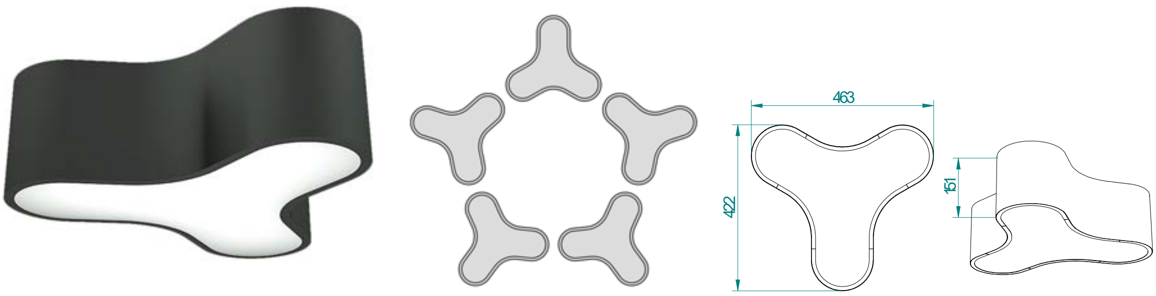

Figure 3. *Trefoil design of luminaire, lighting pattern, mechanical dimensions*

C. Control

It was developed application for mobile phones for easy control of luminaire properties. Application has two modes: *manual* and *automatic*. In manual mode it can be set CCT, dimming, hue and saturation of light output. Automatic mode change CCT in defined range. Changing time correspond to sunrise and sunset time in given location.

D. Figure of merit for circadian performance and light quality

Complexity of phototransduction of human circadian system requests new model of spectral sensitivity, because established photometric light measures that use the V_{λ} spectral weighting function, such as photopic lux, are inadequate for quantifying light intended to regulate non-visual physiology and behavior. Some models have been established already, MS. Rea et al. (2005, 2010, 2012), Ámundadóttir et al. (2013) , M. Andersen et al. (2012), DIN (2009) **[7]-[9]**. As previously reported **[10]** non-linear model of MS. Rea et al. has been chosen for comparison and verification of spectral power distribution (SPD) of various light sources and light output of experimental luminair respectively. This model describes circadian system response to light by circadian light- CL_A and circadian stimulus - CS. Circadian stimulus characterizes the relative effectiveness of the source as a stimulus to the circadian system. This value can be easily calculated by free calculator **[11]**. Spectral power distribution (SPD) was taken by spectrometer Spectromaster C-7000 (Sekonic, Japan).

RESULTS AND DISCUSSIONS

All living organisms including humans are adapted to natural light during its evolution, therefore artificial light inside buildings should mimic dynamic changes of daylight. For comparison it was chosen SPD of commercial artificial light sources commonly used in residential lighting as well as standard CIE illuminants together with two types of sky ("Clear" and "Cloudy"). Next additional SPDs was randomly taken (June 2017, 13:35 CET, clear sky) outside in common environment (buildings with green areas around) within one minute for demonstration of variability SPD and their quick dynamic change from eye's point of view. Measuring sensor was held in eye level parallel to direction of view in front of eye. Each SPD was normalized to 555 nm, then it was calculated from each SPD Correlated Colour Temperature (CCT), Colour Rendering Index (CRI) and Circadian Stimulus (CS) - photopic illuminance of the stimulus = 300 lx. As can be seen from Fig. 4 for circadian impact evaluation it is necessary to cover not only incident light to the surface, but also the reflected light from the various colour surfaces.

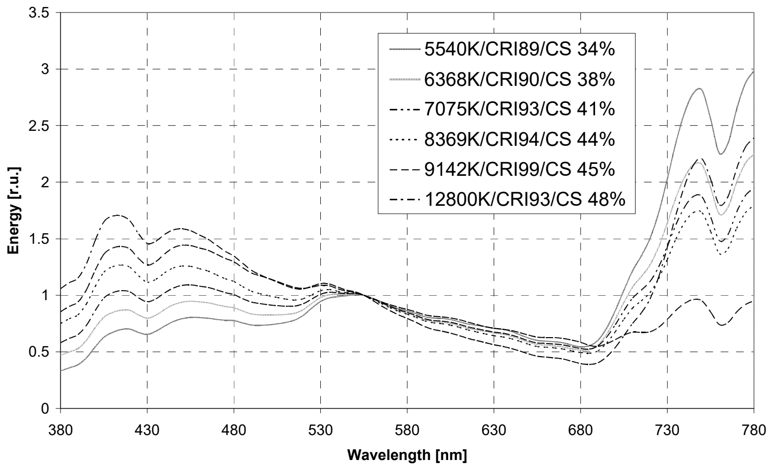

Figure 4. *Normalized spectral sensitivity of reflected light randomly measured in common environment (buildings with green areas around) within one minute with calculated values of CCT, CRI and CS - circadian stimulus (Rea, 2012).*

Calibrated experimental luminaire was warmed up and step by step set CCT via control software from range 2400 - 10 000K. For calculation of circadian impact each CCT was measured by spectrometer. The results of calculations is stated in Table 1.

TABLE II. THE FIGURES OF MERITS OF SPDS USED IN ANALYSIS. DATA WAS ASCENDING ORDERED BY CIRCADIAN STIMULUS - CS

LIGHT SOURCE	CCT	CRI	CS [%]
LED 4000K	4000	85	26
Incandescent Bulb	2450	95	26
Cloudy Sky	4300	99	29
LED 2700K 80CRI	2700	80	29
LED 5700K	5700	60	30
LED 2700K 90CRI	2700	90	31
A	2850	100	32
D50	5000	99	33
D55	5500	100	36
LED 7500K	7500	70	40
D65	6500	100	40
Clear Sky	7000	99	41
D75	7500	100	43

LIGHT SOURCE	CCT	CRI	CS [%]
Exp. luminaire	4200	98	27
	2398	85	29
	2699	92	30
	3199	96	34
	5612	97	36
	6494	96	40
	7998	94	43
	9974	93	46

In Table 1 can be nicely seen that circadian stimulus calculated from experimental luminaire's SPD increases with higher CCT and CS value very nice correlate to CS calculated from common light source. One big advantage of RGBW system of colour mixing concept for experimental luminaires is variability of output spectra and their dynamic change, which can be control automatically [Fig. 5], second advantage is possibility to set polychromatic light as well as monochromatic light output for these types of experiments **[12],[13]**. It means that developed luminare can be used for control of circadian rhythm experiments, which help complete necessary information about phototransduction of human circadian system.

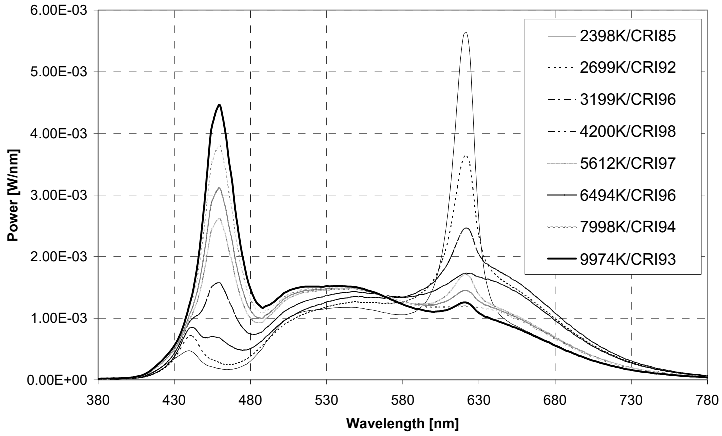

Figure 5. Example of spectral power distribution, which can be controlled automatically.

Calculation model has relatively high uncertainty in predicting the effectiveness of practical polychromatic light sources, as indicates Table 1, therefore it will be important to directly compare model predictions for white light sources below and above about 4000 K.

CONCLUSIONS

Lighting change rapidly in these days due to still new findings regarding connection between light and human. Irregular light - dark pattern or light exposures at the wrong circadian time can lead to circadian disruption and disease risks. Future of lighting is at start of development, but one key point which needs to be considered is that personal light exposures should be measured using calibrated devices that measure light as it affects the circadian system rather than the visual system (photopic light) **[14]**. Producers of luminaires is still looking for the right communication protocol for smart lighting system, new LEDs are developed each six month with better efficacy and new materials for better cooling of LEDs systems is optimized as well as optic systems, but main goal stays still same - natural and healthy lighting system. Research of non-visual response of light is not finished yet, so we can look forward for new findings which can be lead lighting development to various directions.

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Study of LED Modulation Effect on the Photometric Quantities and Beam Homogeneity of Public Lighting

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***Abstract*— This paper discusses the implementation of a light emitting diode based visible light communication system for Visible Light Communications (VLC) in road safety applications. Visible Light Communication (VLC) represents a progressively developing communications technology. This technology uses optical radiation in the visible range in order to illuminate a given area also for the communication purposes (download). One of the conditions of using the technology is the construction of a VLC modulator. The use of the technology Bias-T proves to be a highly efficient concept of the VLC modulator. The article deals with the design of a high power broadband Bias-T allowing the use of the VLC technology The designed Bias-T was created and its functionality verified using a network analyser and the software-defined radio. Other problem is correct design of modulation circuits so that final public lightning using optical communication meets standard requirements on Photometric Quantities and Beam Homogeneity. Authors of this article performed research on visible light communication possibilities of public lightning in terms of modulation circuits (M-PSK, M-QAM, OFDM) implementation into the lamp concepts and final fulfilment of mandatory standards on Photometric Quantities and Beam Homogeneity.**

***Index Terms*-- Public Lightning, Smart City, LED technology, VLC, Broadband over Visible Light.**

INTRODUCTION

A very important characteristic of the LED is a simple adjustability of the luminous flux. The LED can be regulated in the entire range (0-100%) without loss of luminous efficacy and without reducing their median lifetime. This feature is primarily concerned with the energy balance of lighting systems, although the secondary may not concern only energy savings but also the luminous flux adapting to its surroundings, density and speed of traffic and drivers adaptation, [9].

Another very important feature of the LED, which can be used with advantage in the public lighting, is their switching speed. While conventional light sources used in public lighting (e.g. high pressure sodium lamps) are started up to the nominal luminous flux after a few minutes and their re-inflammation is also possible after its cooling (also a few minutes), the LEDs do not have this problem. The LEDs react to a nominal luminous flux immediately and if we consider only the white LED provided with luminophore slowing down their response to changes into electrical parameters so the width of the band is in the order of MHz values (typically 3.5 MHz), [8]. By using a suitable modulation format of the luminous flux, ideally in combination with an OFDM transmission technology (Orthogonal Frequency Division Multiplexing) the parallel light can be achieved and the simultaneous data transmission in the luminous flux without causing the variation of the resulting luminous flux from the perspective of an observer so that it can reach transmission speed up to 1Gbps. In August 2013, the consortium Li-Fi presented a VLC transmission system allowing communication at a transmission speed of 1.6 Gbps. The same result was achieved in 2015 by a team around Xingxing Huang using a pre-equalization technique [1]. At the end of 2015, the team achieved a transmission speed of 2.0 Gbps using implementation of adaptive bit allocation [2]. According to the current statements, the consortium Li-Fi is working on a VLC system with a transmission speed of 10 Gbps.

Broadband over Visible Light (BVL) is a new research direction based essentially on VLC technology. Again, it is intended to utilize the visible spectrum of optical radiation as a communication direction to the end user (download) and to utilize the infra-red spectrum of optical radiation (940 nm or 850 nm) in the reverse communication direction (upload). Moreover, compared to the VLC concept, in the case of BVL, it is intended to use the chipset of the Broadband over Power Line (BPL) technology, which, inter alia, allows the use of the OFDM MQAM modulation format at the number of 1,536 sub-carriers in the frequency range from 2 MHz to 34 MHz (for transmission speed 100 Mbps, physic layer

RM ISO/OSI), or frequency range from 2 MHz to 86 MHz (for transmission speed 1200 Mbps, physic layer RM ISO/OSI, HomePlug AV2 transceiver QCA7500 from Qualcomm Atheros).

HIGH POWER WIDEBAND BIAS-T

For the proper interconnection of the BPL and VLC technologies in the form of the resulting BVL technology, it is necessary, inter alia, to choose a suitable concept of the modulator. A concept based on Bias-T is the current trend in the technological solutions of the VLC modulator [3]. The first changes to the Bias-T design for the BVL technology must be based on the required frequency band of the BPL technology chipset based on standard HomePlug AV/AV2, which corresponds to 90 % of the current solutions. This standard defines the lower frequency f_{min} = 2 MHz. The reason is a frequency reserve for the possibility of simultaneous usage Fig. 1. Design of high power wideband Bias-T for Broadband over Visible Light of the narrowband technology Power Line Communication (PLC), [4]. At present, the available solutions to performance Bias-T's are defined by the lower frequency f_{min}, which ranges around the values of 10 MHz.

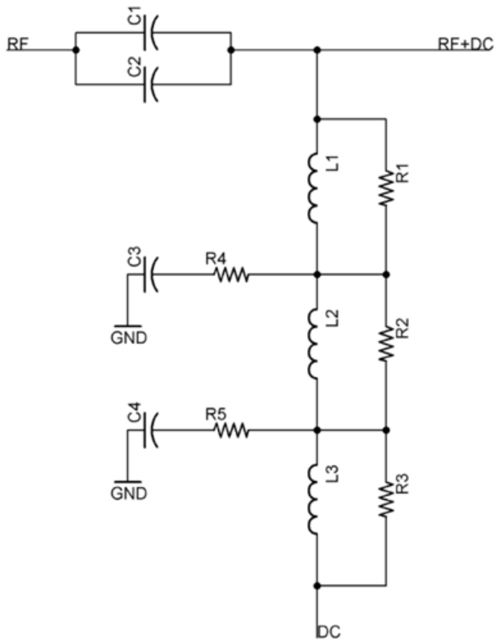

Figure 1. Design of high power wideband Bias-T for Broadband over Visible Light.

Other changes, when designing Bias-T for the BVL technology, must reflect the changes in the lighting technology. The recent trend in the lighting technology is to reduce the current value of the operating point IDC while increasing the value of the operating point voltage UDC. For example, conventional light intended for public lighting having the performance of 80 W (Thor) defines its driver operating point in the form of IDC = 700 mA and UDC = 112 V. It is not possible to construct a Bias-T for such high values of IDCmax only on the basis of one coil in terms of requirements for a high inductance value. Current load distribution into multiple branches at the expense of deterioration of S-parameters is a more appropriate method, which is not critical in the case of a BVL concept. In the case of this article, Bias-T with the parameters of IDCmax = 1 A and UDCmax = 150 V at the minimum frequency bandwidth Bmin of 100 MHz was considered.

Measurement of S-parameters of the final Bias-T prototype according to Fig. 1 was conducted using a Network analyser Rhode-Schwarz ZVB4 [7]. Based on the comparison of the simulation results and the final measured values, we can say that real results approximate to the results of the simulations. Parameter S21 that indicates signal transmission loss from the RF input to the RF + DC output. According to the measurements, there is a decrease in level 3 dB to the frequency 100 MHz, Fig. 2.

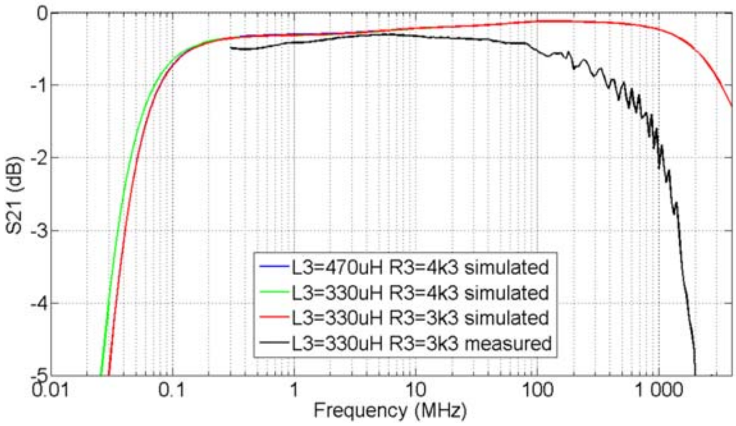

Figure 2. Result of simulation and measurement S21 of the final Bias-T prototype.

VERIFICATION OF ABILITY TO MODULATE ON THE BASE OF SDR

Figure 3 shows a scheme of realized experiments. The measured distance was 350 cm from the middle. The middle means the start of measurement; the photodetector was placed direct under the light. The distance between light and the photodetector was 3 m. This distance is similar to the distance of street lighting (staying person).

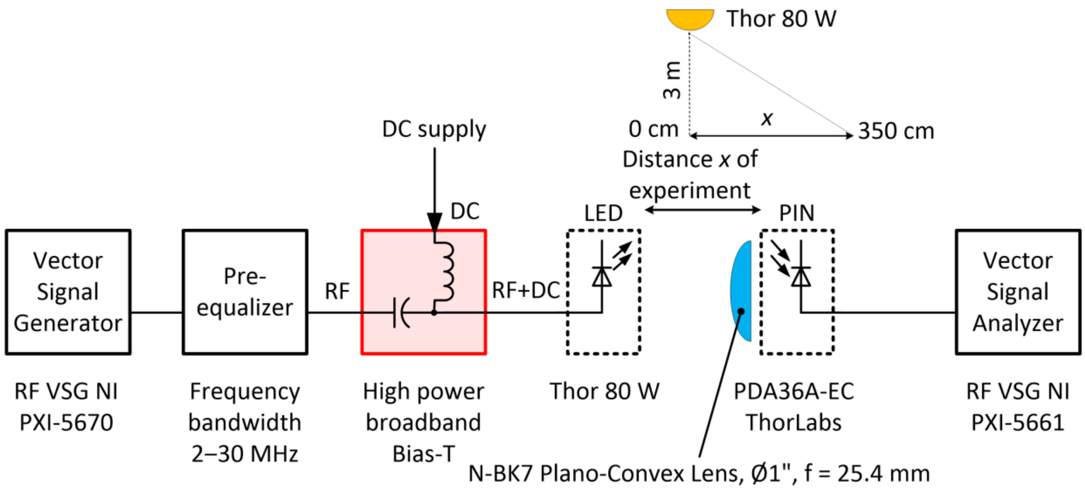

Figure 3. Block diagram.

The setting of measured system for ceiling light: carrier frequency 3 MHz, bandwidth 1-4 MHz, M-QAM modulation, gain Tx, Rx 0 dB, message symbols 10 000, Tx filter *Root raised cos*, sample width 16-bit, distance photodetector - ceiling light: 350 cm, measured distance range 0-350 cm, measured parameters Eb/N0, BER a EVM, [5].

The frequency attenuation characteristics of communication chain were measured by the vector network analyzer (VNA) before the measurement, which are shown in Fig. 4. This figure shows that the attenuation increases with increased distance. In the middle of measurement (detector direct under the light) the attenuation increased 47 dB in comparison the reference. In the distance 3 m, the attenuation increased 68 dB which negatively influences the communication. The carrier frequency 3 MHz was chosen for purpose the increasing of bandwidth. Increasing frequency causes increasing attenuation against reference, with larger bandwidth increases attenuation value of difference between the highest and lowest frequency of transmitted signal. This causes failure of some modulations or total break-up of communication for all modulations. In choice BW = 4 MHz means that there are 2 MHz from the carrier frequency on each side (+/- 2 MHz).

Figure 5 shows the comparison of BER parameters for different bandwidths and modulation M-QAM. There are displayed maximal reached distances for separated modulations for different bandwidths for which the BER values were recorded. Moreover, the FEC limit were marked. It could be said generally that the measurable bit error rate was in longer distances between photodetector and the light, [6]. They were usually 2 and 3 last distances when the bit error rate considerably increased [7].

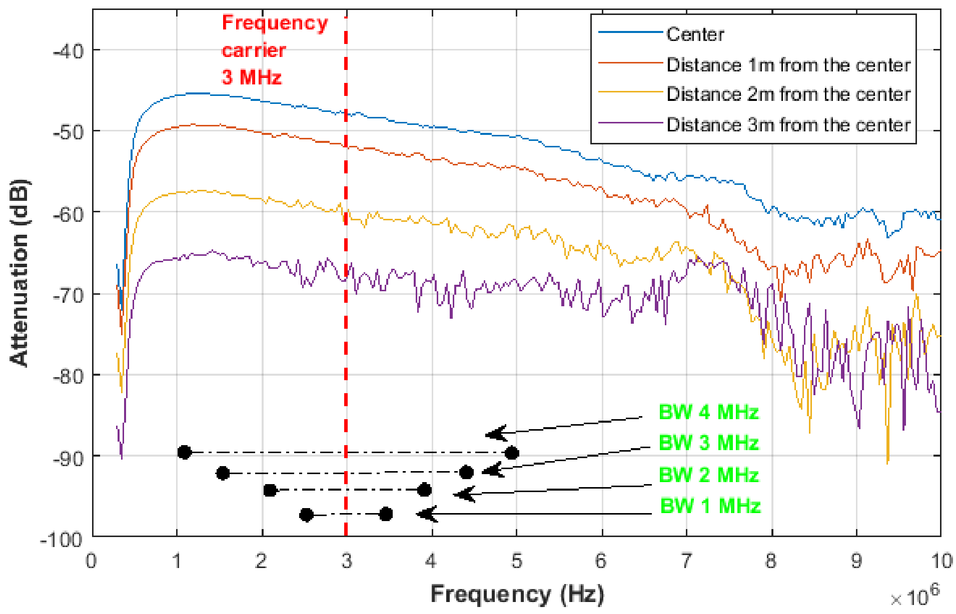

Figure 4. Frequency attenuation characteristics of the communication chain.

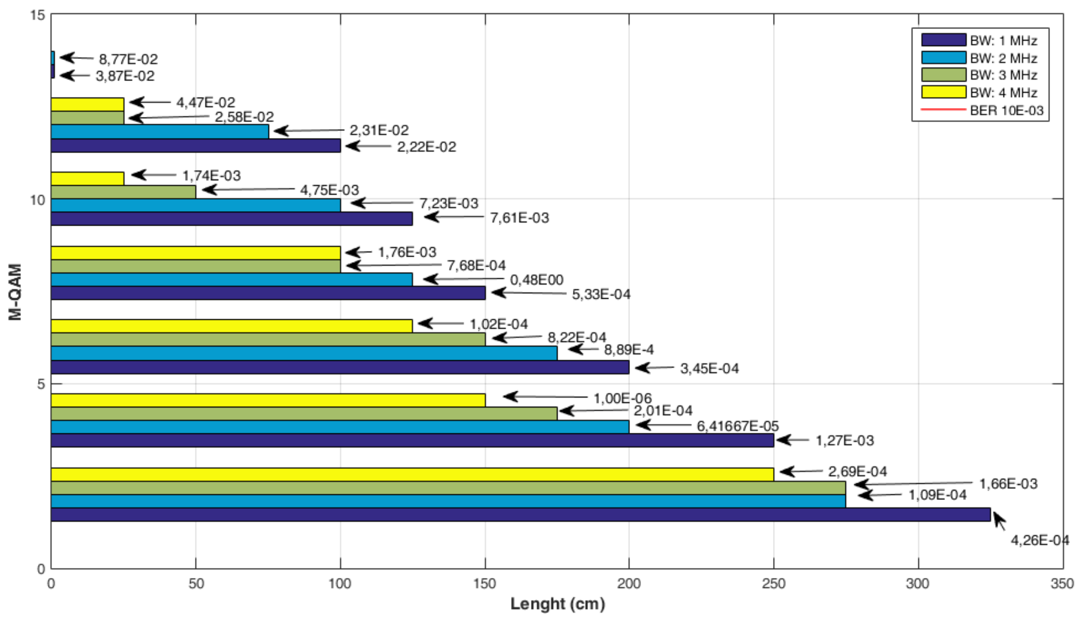

Figure 5. Dependence of bit error rate on distance from middle x from different types of M-QAM modulations with different bandwidths.

Following Fig. 5 and Fig. 6 show comparison of two bandwidth 1 MHz and 4 MHz, the lowest and greatest measured. These graphs show that the Eb/NO value decreases and EVM value increases with increasing distance. Further the available distance from the middle decreases with increasing bandwidth. Generally, the bit rate increases with wider bandwidths but the available distance decreases. Fig. 4 also shows that the signal to noise ratio values are lower for bandwidth 1 MHz than for bandwidth 4 MHz. The higher bandwidths are more predisposed to disturbances. The same deals for EVM parameter with the difference that the values increase with the distance.

Results

The basic advantage of topology interconnection of the public lighting with modern communication systems can be seen in the fact that it de-facto provides data connectivity on all roads in the territorial areas of towns and villages. It is important to realize that the public lighting network have two major advantages from this point of view. The first advantage is the strategic position of public lighting networks. They cover almost completely the surface of all the towns and villages. The second advantage is the ownership of the public lighting networks. The dominant owners are the municipalities themselves. It means that the public lighting network can be used as a skeleton (bearer) to transfer and retrieval the information from whole area of the municipalities.

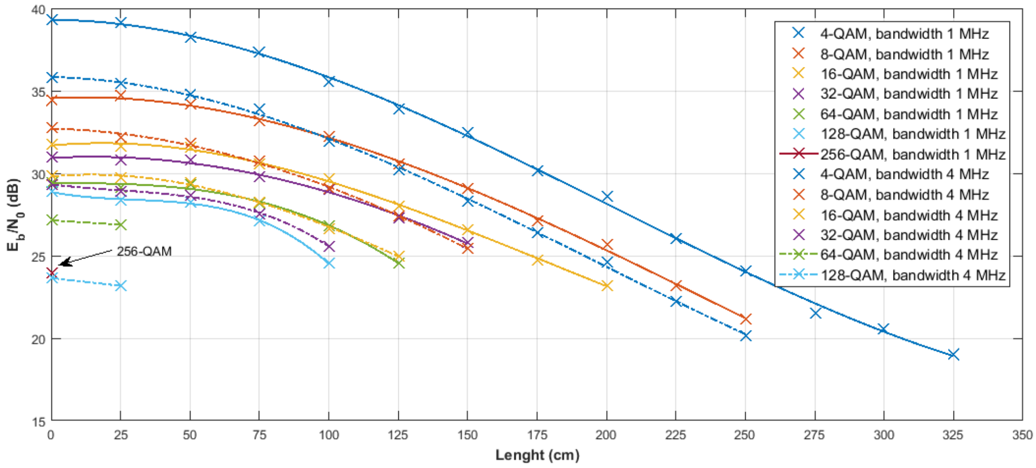

Figure 6. Dependence of Eb/N0 on distance from the middle of light for different types of M-QAM modulations with bandwidths 1 and 4 MHz.

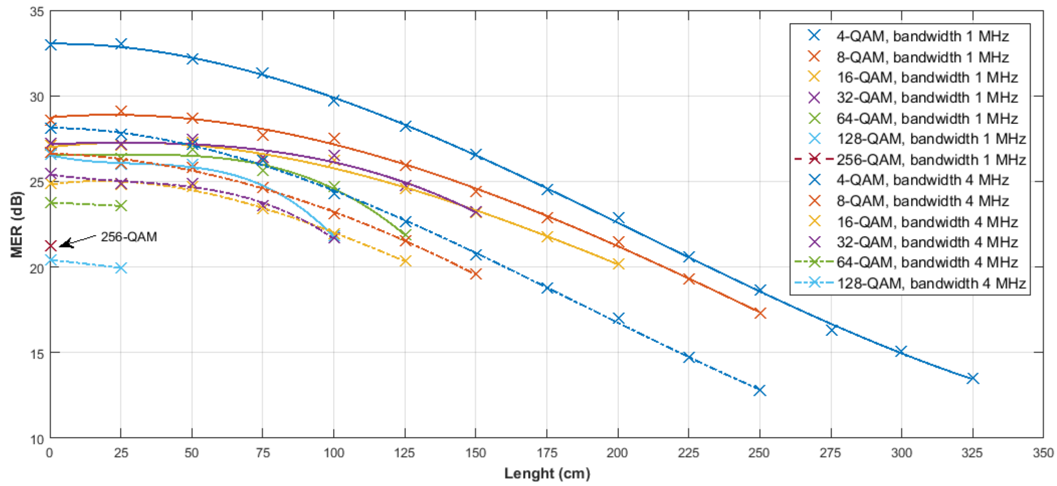

Figure 7. Dependence of EVM on distance from the middle of light for different types of M-QAM modulations with bandwidths 1 and 4 MHz.

Conclusions

The lamps with radiation characteristics like Street lamps were tested. In this article the measurements only on short illumination distances (laboratory conditions) were done. Based on measured characteristics, they could be approximated for illumination distances of street lighting with input power 60 W. Currently we also work on measurement and modelling of data transmission by classical types of communications. In order to provide plural data connectivity it is necessary to think about moving the switches of the public lighting from distribution board to individual luminaires during preparation for restoration and maintenance of the public lighting. This step ensures that the network of the public lighting will be powered during the whole day and not only during the absence of daylight. Although permanent voltage presence primarily does not provide the required connectivity, it will supply any technological device that needs a permanent supply. Data connectivity of the public lighting network can be provided by using three basic technologies. This is the signal transmission through the network of the public lighting, an installation of fibre optic cables in the implementation of new linear structures within the public lighting and the utilization of existing mobile providers (LTE, prospectively the technology 5G). Each of these options has certain advantages as well as shortcomings in the installation itself or in its own operation.

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Possibility of Bandwidth-Widening with Luminescent Layer in LED Structures

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***Abstract*— LEDs are the most innovative light sources in lighting technics as well as industrial application. LEDs compared to incandescent bulbs have lots of advantages, but important disadvantage of their application are temperature sensitivity and relative narrow spectrum.**

To widening bandwidth there are several known solutions, e.g. application of phosphor, but these structures have many disadvantages, e.g. different ageing, loosing of good focusability, etc. One of the possible solutions is application of multiple layers of different composition, and realizes several radiation peaks with luminescence.

The method we use for wavelength broadening is growing luminescent layer. It means application of multiple layers of different composition, where the light originated from active layer exits the LED unchanged only partially, meanwhile remainder radiation excites additional layer(s), and realizes several radiation peaks with luminescence.

Wavelength converter achievable with two luminescent layer also, results three wavelength photon emission.

***Index Terms*—GaInAsP; LED; luminescence; multi-wavelength.**

INTRODUCTION

The white light emitting LED light source has become dominant in the advanced lighting technology in recent years. Despite the fact that LEDs replace varied light sources with very different properties, most of these LEDs have blue light – yellow phosphor structure.

Because of LED has narrow bandwidth, the broadening is necessary in lighting applications, and there are several well-known methods exist. One of the possible ways is multi-color LED, mostly red-green-blue (RGB) LED which means three chips in one package or three independent LED structure grown on common substrate. The wide spread solution is the blue LED completed with yellow phosphor. Other ways are the blue LED with yellow + red phosphor or yellow + green phosphor. Solutions of combination of two above well-known also, e.g. blue and red LEDs in common package completed with yellow phosphor.

The phosphor and the substrate of phosphor cause considerable losses. The point wise of LED decreases several orders of magnitude, (though most lighting applications still point-like). The phosphor has thermal contact with the LED and higher temperature affects ageing phosphor also.

The RGB LED operates with additive mixing of three basic color light, which is causing a sense of white. It has much worse color rendering than LEDs with phosphor, because the radiation ranges of individual diodes are very narrow and these covers very small parts of the wide visible range (380-780 nm).

Operation of the three diode problematic because of working points should be adjusted individually and must be continuously corrected as different ageing happened.

These problems have incurred in visible range, are even greater in the case of LEDs for measurement purposes. The following InP-based GaInAsP LEDs operating in the near infrared range, and these are can be light sources of spectrophotometric measures in handheld instruments. The energy source of handheld devices is limited, so tempering is not possible. The LED suitable for measurement in handheld devices has to be almost temperature independent operating ranges without tempering as well. The only-one LED is not a sufficient for spectrophotometric measurements because radiated narrow range. The customized widening of radiation bandwidth is necessary for specific wavelengths or wavelength ranges Meanwhile it is important to keep LED point wise, remember, we have to make 3-5 orders of magnitude smaller point-like light source than usual in lighting applications.

It can be seen that requirements above are strict, neither phosphor solution nor multichip solution can satisfied. Different solutions exist for bandwidth widening also, e.g. tandem-LED, quantum-LED. In our experiment we performed luminescent layer for band widening. The results, if partially, will hopefully be useful for researches in visible range as well.

EXPERIMENTAL

E. Requirements of LEDs in NIR hand-held spectroscopy

Near infrared (NIR) spectroscopy is suitable to detect -OH, -NH, -CH functional groups in organic materials, with absorbing resonant wavelength of stretching vibrations typical of these bonds. The presence of organic materials and their concentration can be inferred from the detection of material-specific functional groups. The bond vibration wavelengths are λ=3-4μm in these functional groups, however, in practice, in orders of magnitude smaller signals can be effectively measured in the range of 1st-3rd harmonics (λ=1000-1800 nm) due to better signal to noise ratio of shorter wavelength detectors. Another advantage is that the short wavelength radiation penetrates deeper into the material, this way the volume composition of samples can be measured.

The incandescent lamp was the typical traditional light source of NIR spectroscopy earlier. The maximum radiation of incandescent lamps is in this range 1000-1200 nm (depending on temperature of filament), but the wavelength range necessary for the measurement is narrow within the wide range of radiation. The useful radiation power compared to the power consumption of incandescent lamp is very small, the efficiency is poor. The LED as radiation source of NIR spectroscopy compared with the incandescent lamp has a lot of advantages [1]. The LED wavelength range is narrow and can be planned. The advantages of LEDs are their short response time (x*10-9 s), good focusability, high efficiency, low power consumption, and multiple expected lifetime compared to incandescent lamps [2]. The latter features of LED make it especially suitable for use in hand-held devices, allowing faster and less expensive measurement than before.

Typical application areas are for example biological samples, human health diagnostics, measurements of agricultural crops, measurements in oil industry, environmental and plastics industry measurements.

The disadvantage of LEDs comes from one of their advantageous features: the narrow range of radiation allows a specific wavelength measurement only. To detect or determine the concentration of a specific organic material measurements have to be taken at several (at least two) wavelengths, because they should be distinguished from other present substances in the environment (this usually means water or other organic materials). To achieve this, the operation of several (typically three) different wavelength LEDs is mostly common in current practice. The drawback of the solution is that the radiation source is not entirely focusable, and the temperature dependence and aging parameters of various wavelength emitting LEDs are different. The ideal source of radiation is a single semiconductor structure that emits a wide band range while it has minimum temperature dependence.

F. Selection of suitable materials

The wavelength range of compound semiconductor LED has to be tunable by changing the composition of the active layer, and it should be in λ=1000-1800 nm range. As it shown in Fig. 1., the GaInAsP compound semiconductor is suitable as an efficient NIR radiation source.

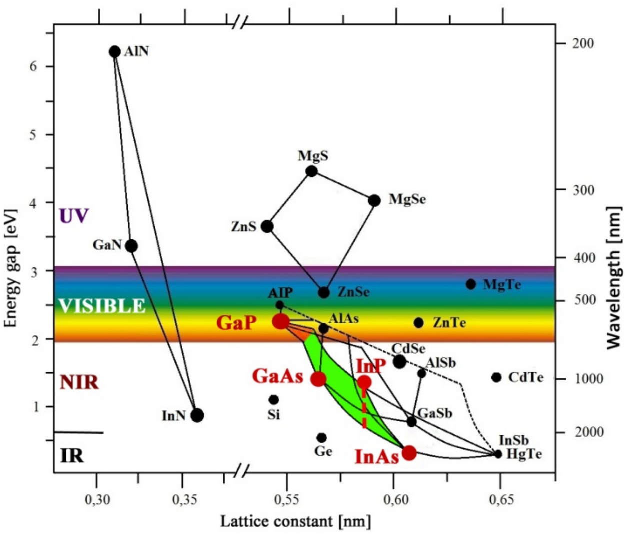

Fig. 1. Lattice constant – band gap relationship in some important semiconductor materials [5]. Along the vertical dashed line tunable wavelength NIR semiconductors lattice-matched to InP are made possible. [3]

In order to tune the wavelength of the radiation the composition of the active layer has to be changed, however, the lattice constant usually changes along with it. The errors caused by lattice-mismatch reduce the efficiency of the LED. The wavelength is tunable in the GaInAsP/InP material system meanwhile the lattice-constant remains unchanged. GaInAsP lattice-matched to InP LED structure can be prepared in the 960-1670 nm wavelength range where the substrate absorption is negligible [3, 4]. The dashed line through InP shows the actual compounds lattice-matched to InP in Fig. 1.

Liquid phase epitaxy (LPE) is an ideal method for growing thin layers, where thicknesses and composition must be tuned up accurately, and because it is relatively cheap and easy.

G. Broadening with luminescent layer

The measurement range in handheld spectroscopy of organic materials are generally wider than the bandwidth of a single LED therefore a wider wavelength range of operation is preferred.

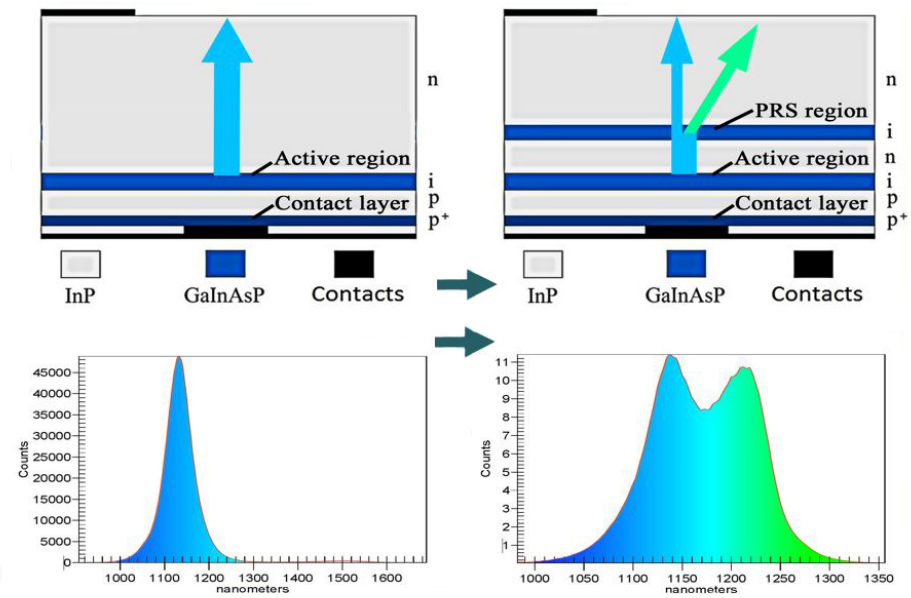

Fig. 2. Ordinary layer stucture and spectra of InGaAsP/InP LED (left) and layer structure including a luminescent layer with widened spectra (right).

The method we use for wavelength broadening is growing luminescent layer. We were grown LEDs by liquid phase epitaxy (LPE) because it is an ideal method for growing thin layers, where thicknesses and composition must be tuned up accurately. On the other hand it is relatively cheap and easy, material-saving, relatively quick and typically fit to research purpose production.

To grow luminescent layer means application of multiple layers of different composition, where the light originated from active layer exits the LED unchanged only partially, meanwhile remainder radiation excites additional layer(s), and realizes several radiation peaks with luminescence [6, 7]. Fig. 2. shows usual layer structure compared with luminescent structure.

A single chip luminescent LEDs are capable of emitting light in wide wavelength range, so they can find application as light sources for modern detector diode array spectrometers. To grow efficiency of LEDs and to make more sophisticated spectra we deigned a new structure.

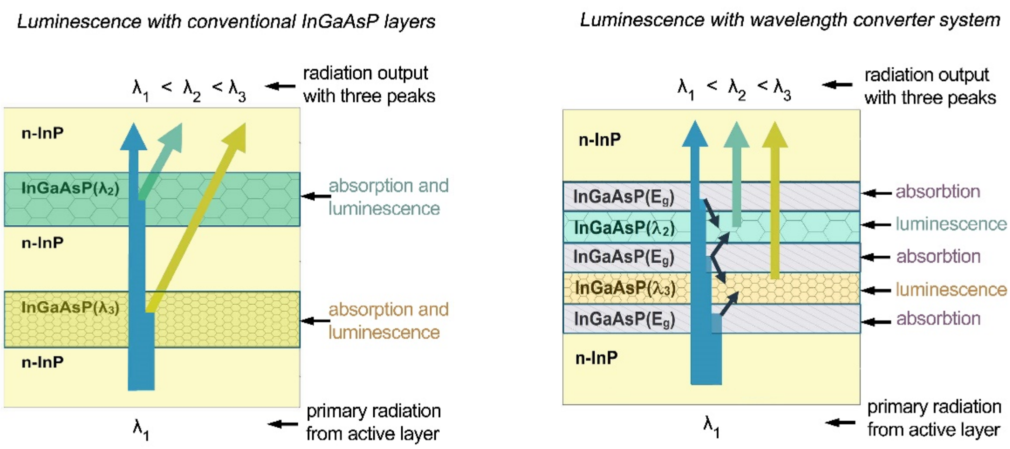

Fig. 3. Schematic luminescent layer structures of GaInAsP/InP NIR LED for radiating three wavelength peaks: luminescence with conventional InGaAsP layers (left), luminescence with wavelength converter system (right).

Fig. 3. shows a completely new structure we built on the right side opposite the earlier on the left side. The difference compared to the previous structure is the separation absorption and emission, into separate layers. The emission layers are embedded in absorption layer. The built in narrow band gap GaInAsP layers serve as potential well enhancing the direct recombination of the optically excited charge carriers. The emission layers have lower band gap than the active layer and the first absorption layer. The free charge carriers diffuse to neighboring (lower band gap) emission layer, within free path distance and radiating at higher wavelengths. The λ3 radiation passes through the λ2 luminescent layer unchanged, because its highest wavelength, as well as absorption layers are transparent for λ2 and λ3 luminescent radiations also. Light emitting layers are close to each other.

RESULTS

The intensity of LED emission at different part of the spectrum may vary in opposite direction due to changing the operation temperature. This could result in measurement errors which is difficult to correct. [8, 9] The shift of the emission spectrum of multi wavelength LEDs is a sum the change of the emission spectra of its components. Temperature dependence of the spectrum can be design in two ways. Important sections for a given measurement points can have the same temperature coefficients, or can have near zero between the two adjacent peeks of the LED. Owing to this, another possible area of use is application to meet the needs of small temperature-dependent use, especially in handheld instrumental measurements, where complex circuit correction cannot be realized because of simplicity, or temperature correction because of low power consumption.

We were grown various LEDs, and measured LED characteristics as a function of driving current and temperature. As temperature increases, the peak of the emission spectrum shifts towards higher wavelengths, while the efficiency is decreasing. The peak wavelength shows a slight blue shift at high current, but this does not compensate the heat-induced red shift, only reduces it at real operating conditions [5]. Therefore, the measured temperature dependence is important in practice. Radiation peaks of active layer and luminescent layer can be near and far. In both cases, nearly temperature independent sections are formed. 1120-1230 nm LED has relatively near peak points. Based on measurements in accordance with the theoretical calculations nearly temperature-independent linear section formed between two radiation peaks (Fig. 4.). Changes in the relative intensity in 1150-1200 nm range are within 1%

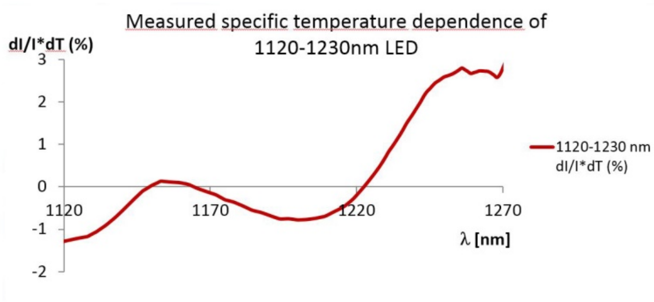

Fig. 4. The luminescent LED with near peak points has nearly temperature independent section between two peak points

In other case with far peak points, temperature dependence of 1200-1400 nm LED were measured. It can be corrected linearly at peak wavelengths. Temperature independent sections are created above peak wavelengths of 20-50 nm (Fig. 5.). These sections are particularly suitable for measuring if there is proper amplitude and detector sensitivity. To do so, the wavelengths of LED should be tuned so that these wavelength values will set to be on sections of measurement.

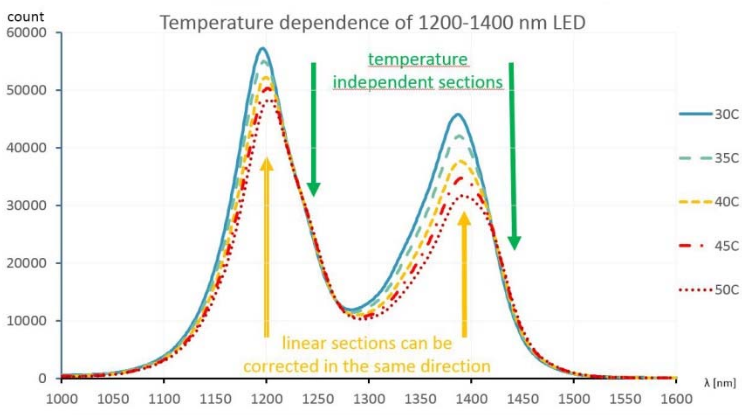

Fig. 5. The luminescent LED with far peak points has temperature independent sections above peak pionts

Fig. 6. compares temperature dependences of a luminescent LED and a common LED with active layer only. The grey line show reference values at 25°C for both LEDs. Continuous colour lines show changing radiation intensity of

luminescent LED at different temperatures, scattered lines show the same in case of LED without luminescent layer. Radiation intensities decrease below peak wavelengths by increasing temperature, in both cases. Intensities increase by increasing temperature above peak wavelengths and setting to nearly constant values. Maximum intensities shift to longer wavelengths. Low temperature dependence section formed between two peak wavelengths of luminescent LED thanks to the opposite effects.

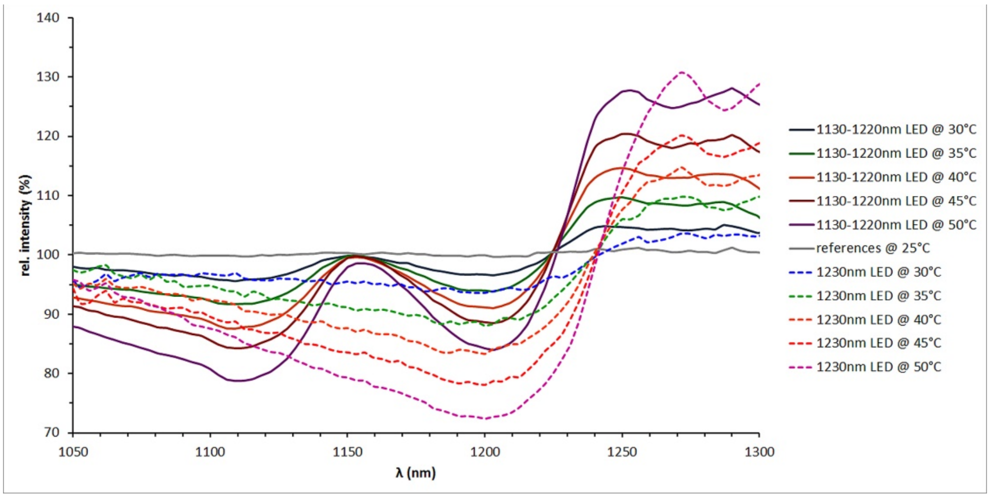

Fig. 6. Temperature dependences of a LED with luminescent layer 1130-1220nm peaks and without it 1230nm peak radiation

Our new layer structure shown on Fig. 3. has further advantages. The efficiency of this layer structure is more than ninety percent. Intensities can be adjusted by the thicknesses of each layer, similarly, as the above-mentioned structure, but considering the absorption of the intermediate layers as well is developing a complex system of layers, wherein the interaction between layers is very important. We made it by Liquid Phase Epitaxy and absorption layers serve as anti meltback layers also, therefore it performs two function at the same time. This type of structure works similarly than phosphor conversion white LED structure, but it is more compact and stable, because all layers are lattice matched to the substrate.

CONCLUSION

GaInAsP/InP LEDs with spatially and spectrally stabile broad emission spectrum can be prepared in a single semiconductor structure. The LED structure contains an electrically pumped active layer at p-n junction as a primary light source, and a wavelength converter region required for broadening the spectrum of the device by luminescence. The wavelength of the active and luminescent layer(s) and their intensity is tunable with material composition, and the layer thicknesses. This allows to grow LEDs which are efficient, precisely tuned to the desired wavelength in wide range, narrow beam and almost independent of temperature. Two-wavelength LED in several wavelength range was developed and characterized. The device structure has closely spaced emitting layers and small emitting area. The emission of the LEDs broadened in a new way keeps the focusability, it is almost independent of temperature, can be accurately tuned to a desired wavelength range and the spectral intensity is adjustable. The LED is suitable for the specified purpose as a light source of NIR handheld spectrometer, it has high efficiency and almost temperature independent.

Our results can be used in the visible range, but still need to improve a lot. The operating principle can be used in other material systems as well as in visible range, but only partial results can be expected with 2-3 luminescent layer because wider visible range and larger lattice constant differences. The EU had set a goal for 2020 that the luminous efficiency of commercial white LED reach 242 lm/W. We do not know how to increase the efficiency of LEDs over it, but it is a possible way to the future.

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Distortion Electrical Power in the Measurement of Electrical Parameters of Luminaires

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***Abstract*—The measurement of electrical parameters of luminaires are very important for assessment electrical power consuption in comparison of luminous output of the luminaire. The difficulties have started when electronics has been implemented into luminaires e.g. balasts and at present drivers for LED luminaires. The connection between electrical parameters and photometric parameters is undoubtedly an essential part of the measurement process of luminaires which in the practice can be separated. Based on the result of the measurement of electrical and photometric parameters customer quite often decides if it is product appropriate or not for purposes make decision if product will buy or not. The parameter representing ratio of consumpted electric power in connection with luminous flux of luminaire is so-called luminous efficacy lm/W. The modern luminaires are powered via power supplies as it was mentioned above e.g. electronic ballast, LED driver, etc. With using of this new technologies have started problems in the electrical measurement of luminaires due to appear distorted currents and impact deformation performance. Besides real and reactive power into the calculation of the apparent power input another parameter and this is parameter called as distortion power. Total power of the luminaire is therefore vector sum active, reactive and distortion power. The paper deals with the measurement of electrical parameters of different types of luminaires.**

***Index Terms*—Current distortion, Luminous efficacy, Distortion power, Supply voltage, harmonic**

INTRODUCTION

Presently described problems in the measurement of electrical parameters of luminaires emerge especially for LED products were this topic is quite often discussed. At the present the efficiency of luminaires and lighting systems are still hot topic in the lighting engineering. Efficiency expressed in lm/W of the luminaire is the most important parameter for the user when decides to use particular luminaire. Unfortunately it is not sufficient only to consider this parameter, because expression of the efficiency of the luminaire not account into all power which is flowing through the luminaire. The measurements of electrical parameters are usually carried out in testing laboratories to assess luminous efficacy. However discrepancies in the results of measurement were revealed by inter-laboratory comparison were big deviations between participants occured. After that some proposals were raised against treatment of electric power measurement by testing laboratories what has started discussion about measurement of electric power of LED product especially. Based on the results it can open the question of the new quantification other significant parameters influencing efficacy of luminaires represented by lm/W and impact of these parameters for the practice. [1]

In the paper it shows the influence of the distortion power as component of appear electricity power. Furthermore results of measurements reveal influence supply voltage on particular components of input power of luminaire and they show non-linearity between the increasing distortion of supply voltage and the distortion of the current in the electricity curcuit of ballast or driver in the luminaire. Due to this can be shown that allowed deviations in the supply voltage may cause significant deviations in the measurement of electricity power of the luminaire at the nominal values. Especially in the case of LED luminaires with drivers installed in the luminaire has significant difficulties with distortion of the electrical power (deformed power). Input power of the luminaire is the sum of the vectors of the all partial powers in the luminaire.

If testing laboratories want to compare their electrical measurements they should not treat only about active power what is inappropriate and often misleading.

The problems with reactive power were solved for luminaires with inductive ballasts by means of compensation capacitors. The new approach in the construction of the luminaires with switching power supplies generate deformed power more significantly. Some of the producers of luminaires install into the luminaires electrical elements for elimination of this effect. Therefore customer should consider also this when is looking for luminaire without described problems.

INPUT POWER OF LUMINAIRES

Input power is mathematically described complex variable. At the present is often considered only with active power what as it was mentioned above this approach is wrong. In real conditions is voltage distorted and it is not possible to determine electrical power in the simple way.

H. Input power undistorted waves

Calculation of undistorted input power is possible only in network with luminaires with harmonic filter.

$$\overline{S} = \overline{U}_{f1}.\overline{I}^{*}_{f1} + \overline{U}_{f2}.\overline{I}^{*}_{f2} + \overline{U}_{f3}.\overline{I}^{*}_{f3} \quad [VA] \tag{1}$$

$$P = \mathrm{Re}\{\overline{S}\} = U_{f1}.I_{f1}.\cos(\varphi_1) + U_{f2}.I_{f2}.\cos(\varphi_2) + U_{f3}.I_{f3}.\cos(\varphi_3) = P_1 + P_2 + P_3 \quad [W] \tag{2}$$

$$Q = \mathrm{Im}\{\overline{S}\} = U_{f1}.I_{f1}.\sin(\varphi_1) + U_{f2}.I_{f2}.\sin(\varphi_2) + U_{f3}.I_{f3}.\sin(\varphi_3) = Q_1 + Q_2 + Q_3 \quad [VAr] \tag{3}$$

$$S = \left|\overline{S}\right| = \sqrt{P^2 + Q^2} \qquad [VA] \tag{4}$$

where: U_{f1}, U_{f2}, U_{f3} - phase voltage,

$\varphi_1, \varphi_2, \varphi_3$ - phase of voltage,

P - active power,

Q - reactive power,

S - apparent power.

Using of this mathematical approach according to described relations is purely theoretical. In real conditions each voltage appears distorted. For small deformations but this effect is so small i.e. it can be neglected.

I. Input power distorted waves

The described method of calculating the power lights in the network can be used in network with the lamp connected between phase and neutral but also if the lamps are connected interphase. If the lights have a special power supply with harmonic filter, for example, variable switching power supply, so they are always fed with a distorted voltage. The power supply voltage appears deformed in the calculation of the deformation performance.

$$P_1 = U_{0_{f1}}.I_{0_{f1}} + \sum_{h=1}^{n} U_{h_{f1}}.I_{h_{f1}}.\cos(\varphi_{h_{f1}}) \quad [W] \tag{5}$$

$$P_2 = U_{0_{f2}}.I_{0_{f2}} + \sum_{h=1}^{n} U_{h_{f2}}.I_{h_{f2}}.\cos(\varphi_{h_{f2}}) \quad [W] \tag{6}$$

$$P_3 = U_{0_{f3}}.I_{0_{f3}} + \sum_{h=1}^{n} U_{h_{f3}}.I_{h_{f3}}.\cos(\varphi_{h_{f3}}) \quad [W] \tag{7}$$

where: P_1, P_2, P_3 - input power,

$U_{0_{f1}}, U_{0_{f2}}, U_{0_{f3}}$ - DC voltage,

$I_{0_{f1}}, I_{0_{f2}}, I_{0_{f3}}$ - DC current,

$U_{h_{f1}}, U_{h_{f2}}, U_{h_{f3}}$ - harmonics of voltage,

$I_{h_{f1}}, I_{h_{f2}}, I_{h_{f3}}$ - harmonics of current.

The total active power is calculated as follows:

$$P = \sum_{f=1}^{3}\left(U_{0_f}.I_{0_f} + \sum_{h=1}^{n} U_{h_f}.I_{h_f}.\cos(\varphi_{h_f}) \right) \qquad [W] \tag{8}$$

The total reactive power is calculated:

$$Q = \sum_{f=1}^{3} \sum_{h=1}^{n} U_{h_f}.I_{h_f}.\sin(\varphi_{h_f}) \qquad [VAr] \tag{9}$$

The total deformed power is calculated as the sum of the deformed powers in the individual phases. Taking the deformation performance of the vector difference between apparent power and the amount of active and reactive power:

$$D = \sum_{f=1}^{3} \sqrt{\sum_{j=0}^{n} \sum_{k=0}^{n} \left[U_{j_f}^2 . I_{k_f}^2 - U_{j_f} . I_{j_f} . U_{k_f} . I_{k_f} . \cos(\varphi_{j_f} - \varphi_{k_f}) \right]} \quad [va] \tag{10}$$

where U_{j_f}, U_{k_f} - voltage harmonics, where j a k describe harmonics and f describes phase,

U_{k_f} - harmonics of voltage, where k describe harmonics and f describes phase,

I_{j_f} - harmonics of current, where k describe harmonics and f describes phase.

Apparent power of deformed wave:

$$S = \sqrt{P^2 + Q^2 + D^2} \qquad [VA] \tag{11}$$

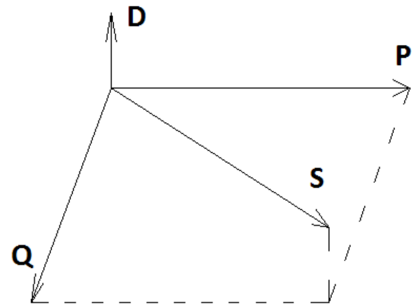

Figure 8. Vector diagram of power

THE RESULTS OF MEASURING ELECTRICAL PARAMETERS IN A LABORATORY

Luminaires with magnetic ballasts with electronic ballasts and LED drivers in the nowadays represent the majority of lighting systems. For all of these types it is characterised by non-linear VA characteristic and currents containing harmonics. Although such luminaires with ballasts and driver file should contain harmonics filter, this is not always the rule and not always the function of properly dimensioned filters. Waveforms showed in the Figure 2 characterise electrical parameter distortion of selected luminaires. That is in the case of the other luminaires are operating at normally conditions the nominal current varies only. It can be seen that waveform is approximately the same. With this description, it can be conceived courses of streams and the effects on the power supply. [2]

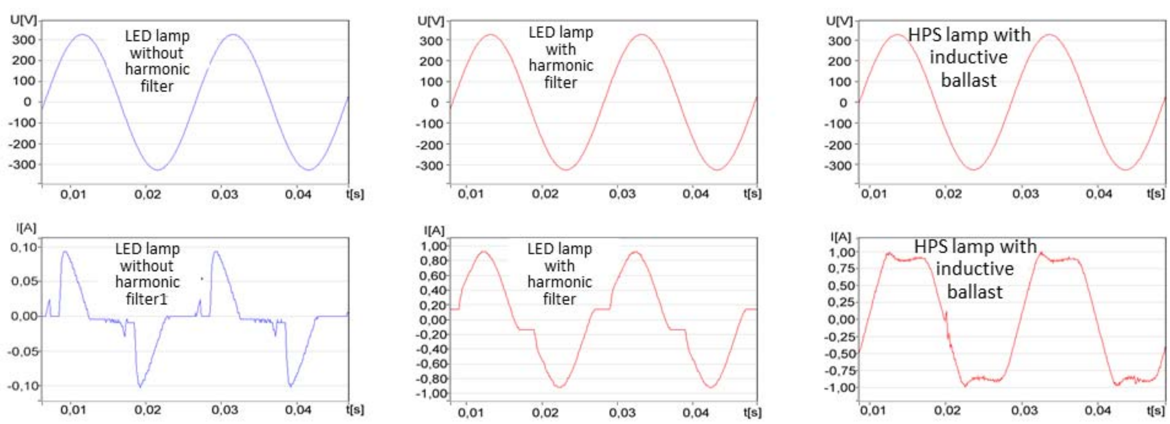

Figure 9. Behaviour of the luminaires with sinusoidal power supply voltage

Currently in the public lighting networks luminaires with inductive ballast are used. These luminaires have a nonlinear VA characteristic and non-harmonic currents cause flows. Size of the current distortion increases in that way the size of voltage distortion increase as well. Undistorted power supply voltage does not occur.

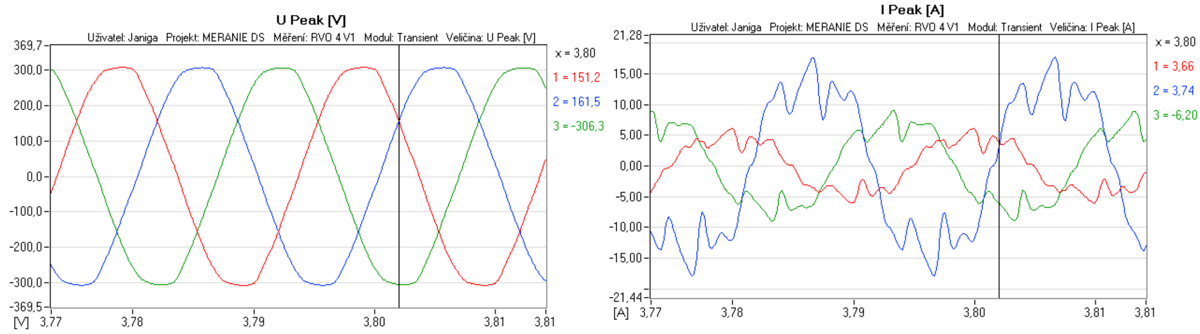

Figure 10. Voltage and current in public lighting network

Distorted currents cause issue distortion power which is necessary to take into account when calculating the power consumption. Finally distorted currents cause increased losses, voltage distortion and greater stress of network elements. Deformed currents flows are eliminated in lamps with electronic ballasts. Harmonic generation in the LED luminaires is depending on the power supply. If the power supply to the LED does not harmonics filter then generate this lamp strong distorted currents. [3]

CONCLUSIONS

In the paper the problematic about measurement of the electrical power of the luminaires was presented. From the text it can be shown that often assumption of undistorted electrical parameters flow through luminaires is misleading. Therefore distortions and reactive power should be considered in electrical measurements. Even more new parameter of deformed power was presented what should be investigated in more detail. At the end was shown problem about measurement of electrical parameters what is possible scratch of discrepancies between results what was proved in the comparison between testing laboratories measured electrical power of LED products. In the future this problematic should be investigated to a larger sample of LED luminaires.

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Automated System for Measurement of Luminous Intensity Distributions with Imaging Photometer

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***Abstract*—This paper describes method for obtaining total luminous intensity distributions with imaging luminance measurement device, goniometer and transmission screen. The problem of using transmission screen with non-Lambertian scattering distribution function of transmitted light via the screen and influence of diffused light in photometric room were discussed. Obtained results were compared with goniophotometer measurements.**

***Index Terms*—bidirectional transmittance distribution function, goniophotometer, imaging luminance measurement device (ILMD), luminous intensity distribution,**

INTRODUCTION

Luminous intensity distributions are the most important properties of lighting devices. They are the basis for calculating required illuminance values by engineers for indoor rooms and outdoor areas. Most common method for getting luminous intensity distributions is measurement that uses the system of goniometer and photometer's head. There are many types of goniophotometers [1],[2]: moving detector, moving mirror, two-axis goniophotometers and other. Due to the fact that intensity measurements are performed point-by-point on specified grid, data acquisition time may last up to several hours to get light intensity distributions in high angular resolution. For this reason, alternative methods to shorten measurement time and increase angular resolution are sought. For instance, goniophotometers carrying out "on the fly" measurements (registration of light intensity with simultaneously rotation of goniometer's table in one axis) are increasingly used.

MEASUREMENT USING IMAGING PHOTOMETER

J. *Luminance to light intensity calculations*

Measurement of luminous intensity distribution using two-dimensional luminance meter is relatively recent method, although first attempts to acquire photometric data from luminance distributions recorded on special photographic films were dated back to early 60s [3]. Nowadays, imaging photometers similar in design to digital cameras are currently used. Photometric tests with the ILMD are carried out using transmission or reflection screen [4],[5]. Lighting device is directed to the centre of the measurement screen whose luminance distributions are acquired by imaging photometer. The obtained luminance map is converted to intensities distribution using formula below [6],[7]:

$$I(H,V) = \frac{\pi \times L(x_i, y_j) \times r(x_i, y_j)^2}{\tau} \times \frac{1}{\frac{f(\alpha)}{f(0)}} \tag{1}$$

where: $r(x_i,y_j)$ – distance between lighting device photometric centre and elementary surface element dS_{ij} of the screen with (x_i,y_j) coordinate that has optical projection in (i,j) pixel of matrix luminance meter, $L(x_i,y_j)$ – measured luminance of dS_{ij} element, $f(\alpha)$ – bidirectional transmittance distribution function (BTDF) dependent on observation angle of the screen – figure 1, τ – transmission coefficient of the screen.

Angles (H,V) or (C,γ) are calculated from appropriate angular system projection on the screen surface using pixel coordinates (i,j), their optical image on the plane and geometrical parameters of the measurement system.

The projection screen should scatter transmitted light according to Lambert's Law (Fig. 1):

$$f(\alpha) = I_0 \cos(\alpha) \tag{2}$$

where: I_0 – light intensity in reference axis.

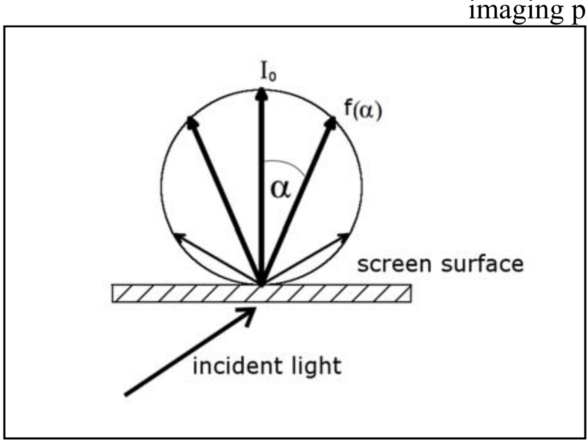

Figure 11. Lamberian transmittance

Property above is satisfied only in narrow angular range by special diffusive screens with small dimensions. Mostly such screens cannot be produced larger than 50 cm×50 cm and are impractical for large luminaires measurements of luminous intensity distribution. However, non-Lambertian diffusive screen can be used for light intensity distribution measurements, but bidirectional transmittance distribution function must be known.

The τ factor in equation 1 is calculated from the formula [8]:

$$\tau = \frac{\int_0^\infty S(\lambda)\times\tau(\lambda)\times V(\lambda)d\lambda}{\int_0^\infty S(\lambda)\times V(\lambda)d\lambda} \quad (3)$$

where: *S(λ)* – relative spectral distribution of light source, *V(λ)* – spectral sensitivity of the human eye, *τ(λ)* – monochromatic transmission coefficient of the screen.

If monochromatic transmission coefficient is constant as a function of wavelength, then total transmission coefficient is the same for all light sources regardless the lighting device spectrum. In fact, each projection screen has more or less variable monochromatic *τ(λ)* coefficient. Hence, correction due to transmission coefficient should be done.

K. Measurement system using ILMD

The main advantage of the usage of imaging photometer for light intensity distributions measurement is short measurement time which is like a shot with digital camera. However, it is difficult to obtain light distributions in the whole half-space of lighting sources performing one luminance-map measurement. Exception is small family of lamps with tiny dimensions and narrow beam angles (e.g. some LED sources). For instance, measurement screen with dimensions 1070 mm width and 800 mm height gives possibility to get light intensity distribution in angular range not wider than 30° in horizontal plane (when lighting device is placed 1.9 m from the screen). Measurement angles can be widened by using larger flat screens, spherical screens or complicated optical systems [9]. However it has to be noted that larger measurement surfaces recorded by device with the same matrix resolution result in worse luminance map resolution This issue can be avoided adopting goniometer for lighting device positioning (figure 2).

Measurement is performed by arranging lamp with goniometer and getting individual luminance map for a given angle. Angular mesh for the geometry adopted for goniometer and luminance map is numerically calculated. Before luminance map measurements, spectral distribution of transmitted light S(λ)×τ(λ) is measured using spectroradiometer. Using τ(λ) distribution from independent spectral measurements of the screen, spectral distribution of source S(λ) and then total transmission coefficient τ can be calculated. Luminance map measurements are carried out twice for all coordinates on angular grid. The second measurement takes into account light diffused in photometric room. This measurement is made placing shutter on the optical axis to shield projection screen from direct light. Values of luminance measured with shutter are subtracted from the first measurement. In the last part luminance maps are converted to light intensity grids and then connected witch each other.

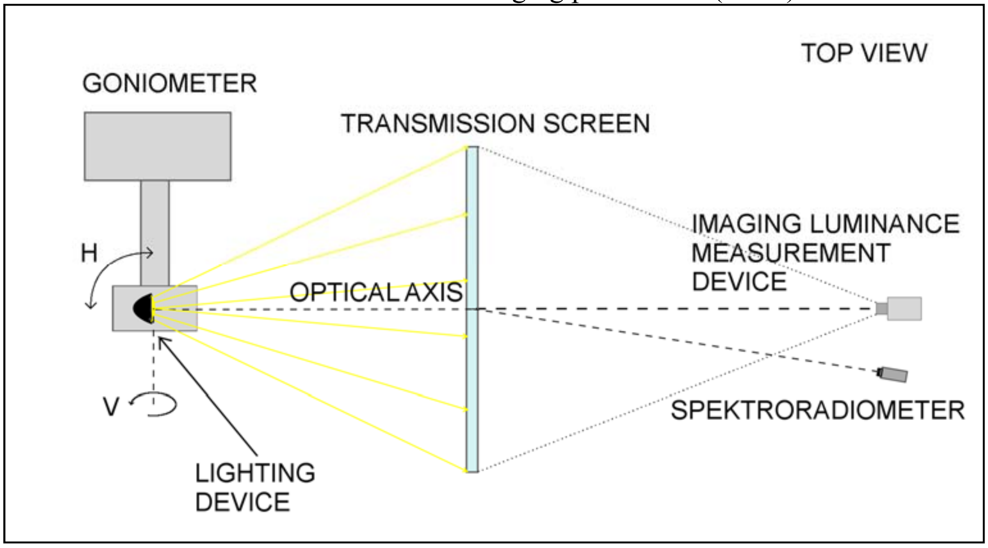

Figure 12. Measurement of light intensity distribution using imaging luminance measurement device, goniometer and projections screen

BIDIRECTIONAL TRANSMITTANCE DISTRIBUTION FUNCTION DETERMINATION

Real scattering distribution function of transmission screen isn't given by Lambert's law. In most cases $f(\alpha)$ in equation 1 is unknown, but it can be determined experimentally comparing two intensity matrices of identical angular grid obtained using goniophotometer and imaging luminance measurement device. Formula 1 with $f(\alpha)=1$ is used for calculations of approximated luminous intensities from luminance map of the screen measured by two dimensional matrix luminance meter. Then bidirectional transmittance distribution function $f(H,V)$ is given by

$$f(H,V) = I_0 \frac{I_{ILMD}(H,V)}{I_{GP}(H,V)} \tag{1}$$

where: $I_{ILMD}(H,V)$ – luminous intensity calculated from luminance measured by imaging photometer for horizontal H angle in vertical V plane of the (i,j) pixel imaged on the projection screen; $I_{GP}(H,V)$ – luminous intensity from goniophotometer measurements, I_0 – luminous intensity of elementary part of screen surface in reference axis.

The above method was used to measure $f(H,V)$ characteristics for angular range observed by imaging luminance measurement device. Luminous intensity I_{GP} of H-V coordinate of each pixel imaged on the measurement screen was approximated from intensity values measured using goniophotometer on H-V angular grid with 0.1° resolution. Characteristics $f(H,V)$ in horizontal and vertical plane was presented in figure 3.

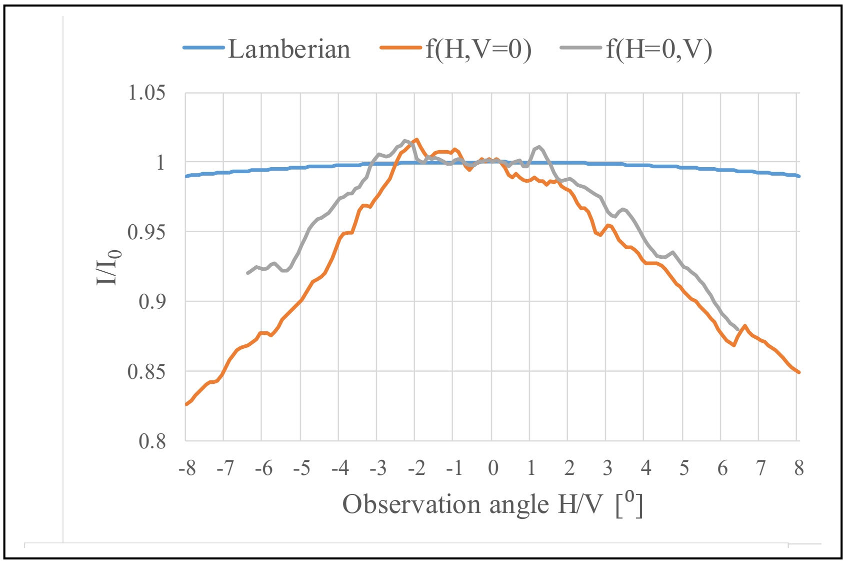

Figure 13. Partial bidirectional transmittance distribution function

TESTS OF LIGHTING DEVICES

Different types of lamps (table 1) have been measured in two ways to validate developed method. Transmission coefficients had been obtained using formula 3 and spectroradiometric measurements.

TABLE III. TESTED OBJECTS PARAMETERS

Lamp identification	**Lamp parameters**		
	Maximum length of lighting surface	***Light source (colour)***	***Calculated transmission coefficient***
1	40 cm	LED (warm white)	55.0
2	50 cm	LED (red)	62.6

First measurement was made using matrix luminance meter, transmission screen and goniometer. Measurements parameter were as follows:

- imaging photometer LumiCam 1300 Advanced with matrix resolution 1370×1020 (horizontal × vertical) was used,
- distance between device lighting centre and the projection screen (photometric distance): 5.1 m;
- distance between luminance meter and screen: 5.1 m;
- lens with focal length 28 mm (of ILMD);
- dimension of effective measurement surface observed by ILMD: 1540×1150 mm (length × height) .

Second measurement of the same lighting device was performed on goniophotometer on distance 10.1 m with angular step equal to 1^0. The test results in horizontal plane have been compared – figures 4 and 5.

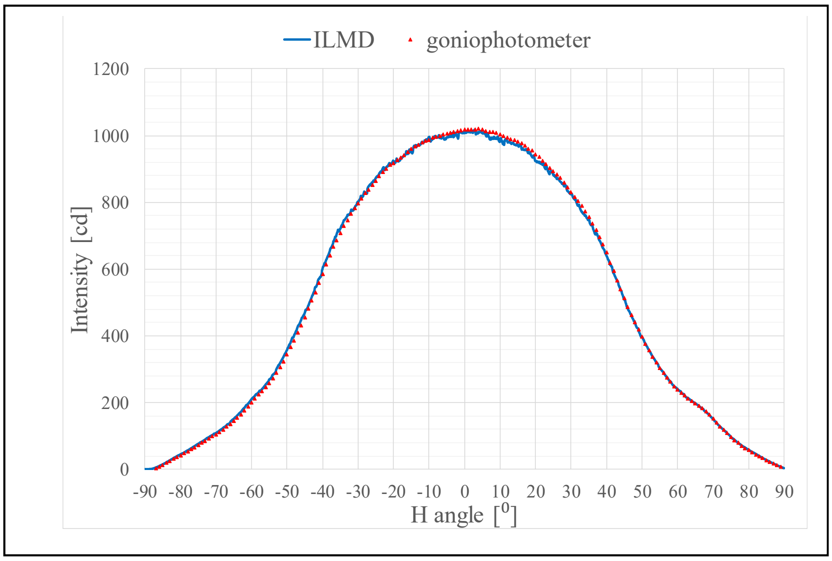

Figure 14. Comparison of light intensity distribution measurements by two methods– lamp 1

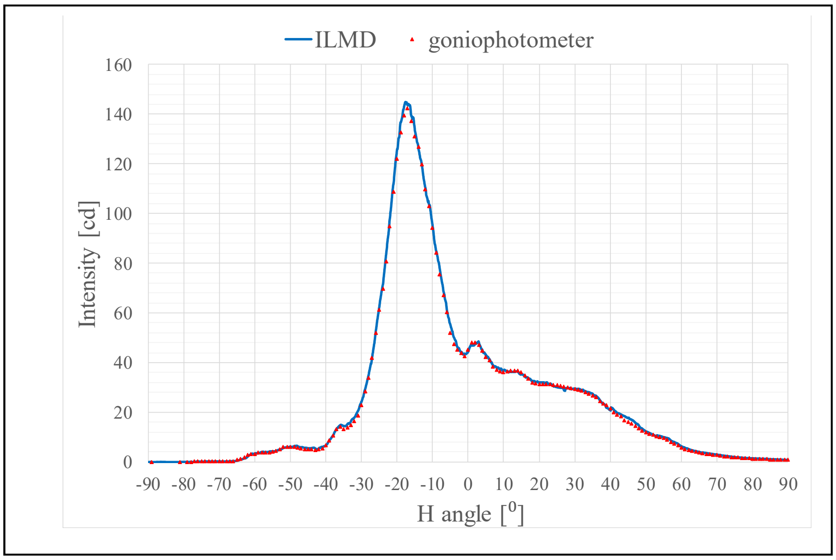

Figure 15. Comparison of light intensity distribution measurements by two methods – lamp 2 (car stop light)

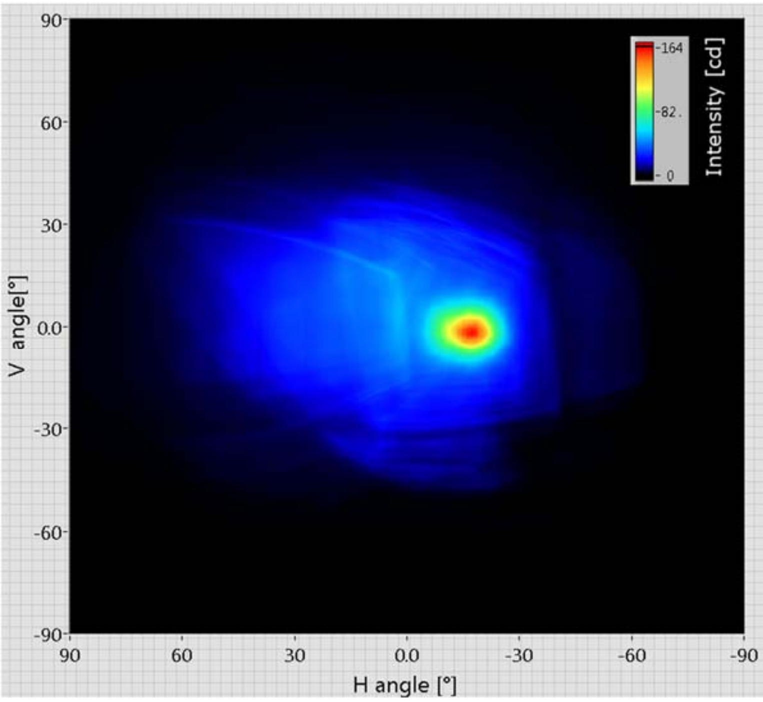

Figure 16. Intensity graph – lamp 2 (car stop light)

From measured luminance by each pixel luminous intensity was calculated and then averaging with resolution of 0.1° in each direction on *H-V* angular grid have been done.

Extended uncertainties with k=2 and p=0.95 for Gaussian distribution: 5.2% for system using ILMD and 4.2% for goniophotometer measurements.

CONCLUSIONS

After taking into account real transmittance distribution function of the screen, transmission coefficient for light emitted by device and light diffused in photometric room during measurement, we have obtained reliable and consistent results. Single total light intensity distribution with very high angular resolution was collected in less than 2 hours which is almost impossible when using classic goniophotometer. This method can be ground-breaking in its application but further researches of different lighting devices are needed to validate and improve method.

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The Comparison of Different Types of Spectroradiometers in Terms of Uncertainty of Measurement

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***Abstract*—This article describes and compares different types of spectroradiometers in terms of uncertainty of measurement of spectral power distribution. Measurement of spectral power distribution is important for evaluation of main photometric quantities. In order to compare different types of spectroradiometers, it is used scanning spectroradiometer with single detector and double monochromator as reference. Although uncertainty of the measurement of spectroradiometer is known, there are complications with measuring narrow spectral peaks. With small bandwidth it is possible to measure narrow peaks correctly. However with wider bandwidth the measured peaks are more widespread. Thus compact array spectroradiometers can be used for measuring light sources with wide spectrum without peaks. However for measuring discharge lamps and LED with narrow spectrum with acceptable uncertainty of measurement it is necessary to use single or double slit monochromator. Next task is focused on testing spectral accuracy of different spectroradiometers. Spectral shift can influence calculated photometric quantities.**

***Index Terms*-Uncertainty of measurement, spectroradiometer, double monochromator, bandwidth, spectral accuracy, spectral resolution, spectral power distribution.**

INTRODUCTION

The measurement of spectral power distribution (SPD) of light sources is one of the main tasks in photometry. Photometric quantities such as color rendering index or correlated color temperature are calculated directly from relative SPD. There are many types of spectroradiometers or spectrophotometers on the market. However, it is necessary to choose right spectroradiometer for specific use. For field measurement suffices compact spectroradiometers with multi-array detector. For laboratory purposes it is necessary to have single or double monochromator with proper aperture, slits and filter in order to measure narrow peaks in spectrum. In terms of uncertainty of the measurement, we can divide uncertainty of absolute and relative spectral power measurement. This article mainly focuses on the uncertainty of relative spectral distribution, meaning accuracy of finding specific spectra peaks.

SPECTRORADIOMETRY IN THEORY

A spectroradiometer is a device measuring spectral power distribution of UV, VIS, NIR or IR region of spectrum. In general they are referred as spectrometers. Every spectroradiometer generally consists of entrance aperture, entrance slit, collimator mirror, dispersive part, such as gratings or prism, focusing optical parts and detector. There are two types of spectrometers. First group have fixed grating and multi-array detector based on CCD/CMOS or photodiode chip. The second group has rotating grating and single detector. They have single or even double monochromator and high spectral accuracy of measurement. However, their measuring speed is low and they are heavy and very expensive [1].

L. Multi-array spectroradiometer

Multi-array spectroradiometers are very compact fast measuring devices. They are best suited for fast measurement and mobility. These compact spectrometer have even size of hand and can measure hundreds values with one charge. The spectroradiometer consists of entrance aperture, such as optical connector for fibres or cosine diffuser, entrance slit, mode stripers, collimating mirror, grating, focusing mirror, filters and detector. This system is called symmetrical Czerny-Turner design. Light enters entrance slit and is collimated by a spherical mirror. After light impacts on grating, it is diffracted on second spherical mirrors and focused on one-dimensional linear detector array. However, all these components have many configurations and it necessary to choose the right configuration for specific measurement. Thus it is necessary to select entry parameters such as wavelength range, which is often limited by grating density (lines/mm). These are main grating densities: 300 - A type, 600 – B type, 1200 – C type, 1800 – D type, 2400 – E type, 3600 – F type [2]. For photometry best suited gratings are 600/1200 lines/mm. Detector choice is also very important. For high speed measurements is very good detector based on 2048 pixel silicon based CCD. However, it has low signal to noise ratio. CMOS based detectors have better signal to noise ratio, but they are more expensive.

The size of slit for photometric measurement should be as followed: 10, 25 or 50 µm. In case of wider slits, signal on detector is better, however at cost of spectral resolution. Although symmetrical Czerny-Turner design limits stray light very efficiently, there is a phenomenon called order overlap. When 400 nm light is scattered on grating, it scattered also its 2nd order – 800 nm. Thus it is necessary to integrate NIR and UV filter when measuring VIS. These filters are usually changed automatically. This may cause typically 0.04 % stray light [2].

M. Single detector monochromator

In comparison with multi-array spectrometers the monochromator has rotating grating and single detector. For better spectral resolution there are double monochromator systems. Technically it is the system of two monochromators in series, where every one of them has its entrance and exit slit. Thus it is even more important to choose right slits. Wider slits cause distorted spectrum and too thin slits cause weak signal on the detector. Light comes first into entrance aperture or integrating sphere, which diffuses and collimate light into entrance slit of the first monochromator. Then light comes through the chopper and entrance filters to collimating mirror and then on grating. Grating tower often consists of three gratings plates. Each grating plate is for different spectrum measurement (UV, VIS or NIR region). Then diffracted monochromatic lights come to focusing mirror and exit slit. In case of double monochromator this whole process repeats in the second monochromator in order to reach higher spectral purity.
All moving parts are very precise and it is recommended to install monochromator on anti-vibration laboratory table. The main disadvantages of this system are slow measurement speed and necessarily for steady laboratory conditions. Moreover regular calibrations have to be carried out on the very specific place at laboratory. VIS and NIR region of spectra is in the most cases calibrated with FEL Halogen Lamp 1000 W, for UV region it is used deuterium lamp [1].

SPECTRAL COMPARISON OF SPECTRORADIOMETERS

In order to compare spectroradiometers in terms of spectral accuracy, it is necessary to have precise spectral measuring device, which can be used for comparison with other spectrometers. In this case it is double monochromator Gooch & Housego OL 750 in the following configuration. There is the entrance integrating sphere G&H GH-OL IS 670-LED with two inputs. There are free slits, first as the entrance slit has 0.25 mm, the second as the exit slit of the first monochromator has 2.5 mm and the third exit slit from the second monochromator has 0.25 mm. This configuration gives spectral resolution of 1 nm. In the following Table 1 there are measured peak wavelengths of mercury lamp in order to test spectral accuracy of this measuring system.

TABLE I. MEASURING MERCURY SPECTRAL LINES WITH G&H OL 750 DOUBLE MONOCHROMATOR

Mercury lamp measurement [nm]		
Spectrum lines	Measured	Deviation
365.4	365.2	0.2
404.7	405.0	-0.3
435.8	436.0	-0.2
546.1	546.1	0.0
577.0	577.0	0.0
579.1	579.0	0.1

In comparison test there are seven tested spectroradiometers including double monochromator. For measurement of spectral peaks in wide VIS region with equal distances it is used programmable light source Gooch & Housego OL-490-PS system, which includes xenon lamp as a light source. In the software it is able to simulate any spectrum in VIS region. In this test it is used generated spectrum with peaks from 380 to 780 nm with distance of 30 nm. Double monochromator G&H OL-750 is connected with programmable light source with optical fibre directly to entrance of integrating sphere. Every measurement was carried out 20 times and all showed spectrums are mean values. The tested spectrometers are followed.

Avantes AvaSpec - 2048 is a compact spectrometer with multi-array 2048 pixel CCD detector and fibre-optic cable FC-UV200-2 with entrance cosine diffuser. Thus it can only measure irradiance. It uses symmetrical Czerny-Turner 75 mm focal length system. According to Avantes specification with present configuration of grating with 600 lines/mm and 50 µm slit it has spectral resolution 1.2 nm. Uncertainty of measurement of absolute spectral power is estimated $U_{95\%} = 3.02\ \%$ [3]-[5]. In following Figure 3 there is measured spectrum with Avantes spectrometer and G&H double monochromator. The measured spectrum by Avantes is shifted by -0.95 nm against the double monochromator G&H OL-750. In region of low signals Avantes has significant noise in measured data.

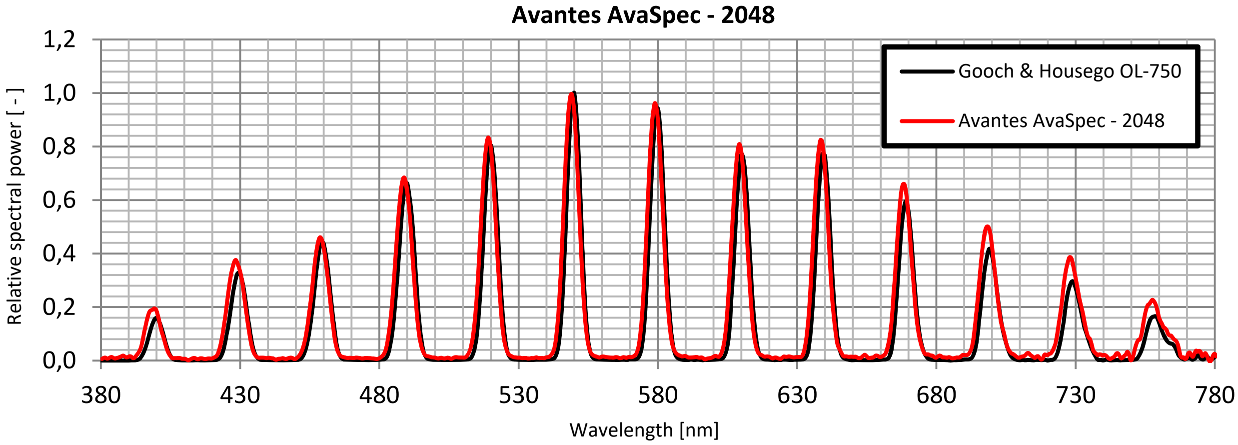

Figure 3. Measured spectrum with Avantes AvaSpec - 2048

JeTi SCB 1211 UV is a compact spectroradiometer with multi-array 2048 pixels CCD detector and entrance optics with optional cosine diffuser. Thus it can work in radiance or irradiance mode. Spectrometer has 4.5 nm optical bandwidth and 1 nm wavelengths resolution and 0.5 nm wavelength accuracy. It measures spectrum from 230 to 1000 nm with illuminance range from 2 to 20 000 lx. Uncertainty of measurement of illuminance/irradiance is $U_{95\%} =$ 3.17 % [3]-[5]. Spectral shift is -0.90 nm against the double monochromator G&H. In Figure 4 is shown measured spectrum with JeTi spectroradiometer and double monochromator G&H OL-750.

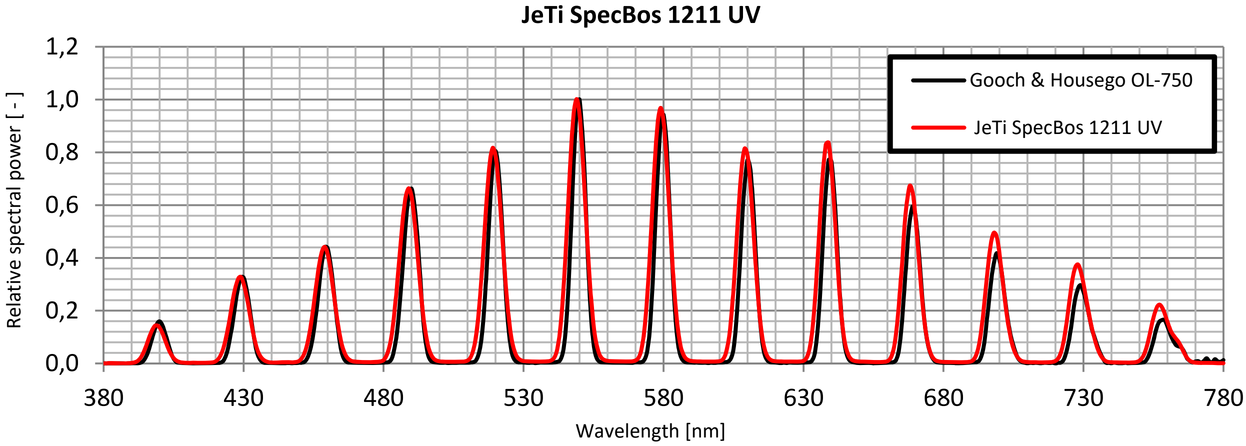

Figure 4. Measured spectrum with JeTi SCB 1211 UV

Spectroradiometer Konica Minolta CS-1000A is primarily focused on measurement of radiance/luminance and spectral power distribution. It measures spectrum from 380 – 780 nm with spectral bandwidth 5 nm and spectral accuracy of 0.3 nm. Measuring range is from 1 to 8000 cd/m^2. Uncertainty of measurement of luminance is estimated to $U_{95\%} =$ 2.22 %. In case of measurement of spectra, there is spectral shift (mean value) of -0.32 nm. In Figure 5 there is measured spectrum with Konica Minolta CS-1000A spectroradiometer and double monochromator G&H OL-750.

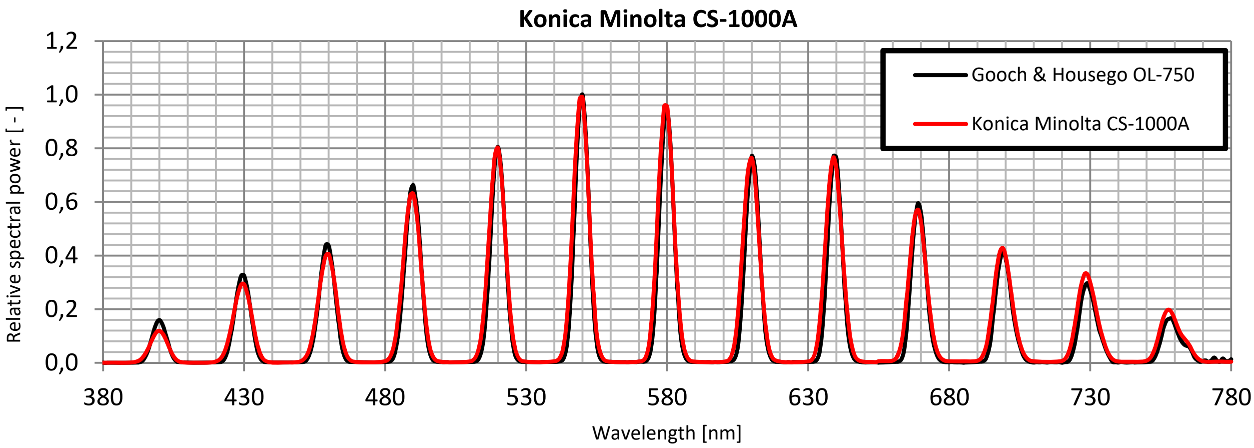

Figure 5. Measured spectrum with Konica Minolta CS-1000A

Spectroradiometer Sekonic C700 is a very mobile device focused on spectrum and illuminance measurement. However, its mobility influences its photometric qualities. It has 128 pixels CMOS detector and illuminance range from 1 to 200 000 lx. Uncertainty of measurement of illuminance is $U_{95\%} = 5.14$ %. The measured spectrum is shown in Figure 6. From figure it is obvious, that spectrometers bandwidth is bigger than at previous spectroradiometers. It causes effect of measurement of wider peaks in comparison with double monochromator G&H OL-750. The mean value of spectral shift against the monochromator is -0.8 nm.

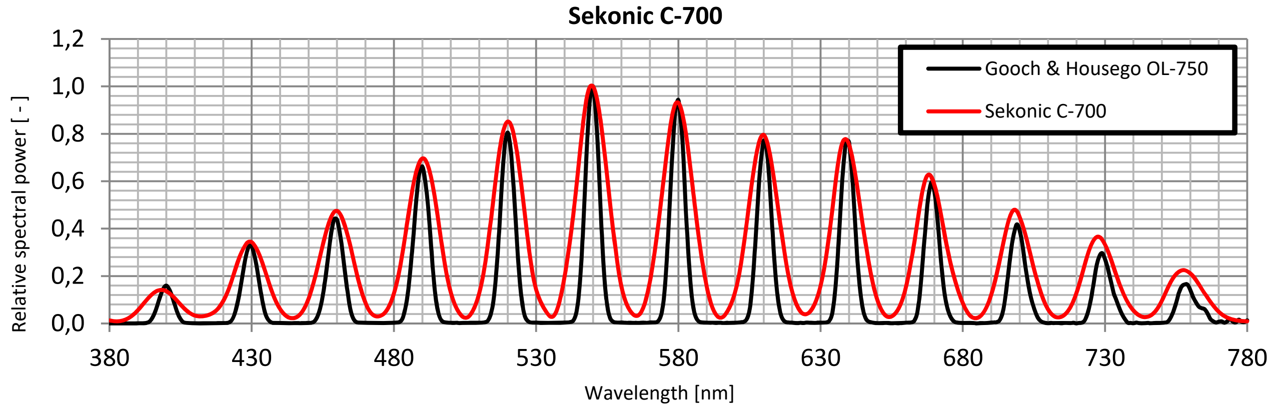

Figure 6. Measured spectrum with Sekonic C-700

Spectroradiometer Uprtek MK350S is a mobile device measuring spectrum and irradiance/illuminance with range from 20 to 70 000 lx. It has spectral bandwidth 12 nm. Spectral accuracy is 1.0 nm. Uncertainty of measurement of illuminance is calculated to $U_{95\%} = 5.04$ %. In the Figure 7 there is shown measured spectrum with Sekonic C-700. Measured spectrum is shifted by -1.4 nm.

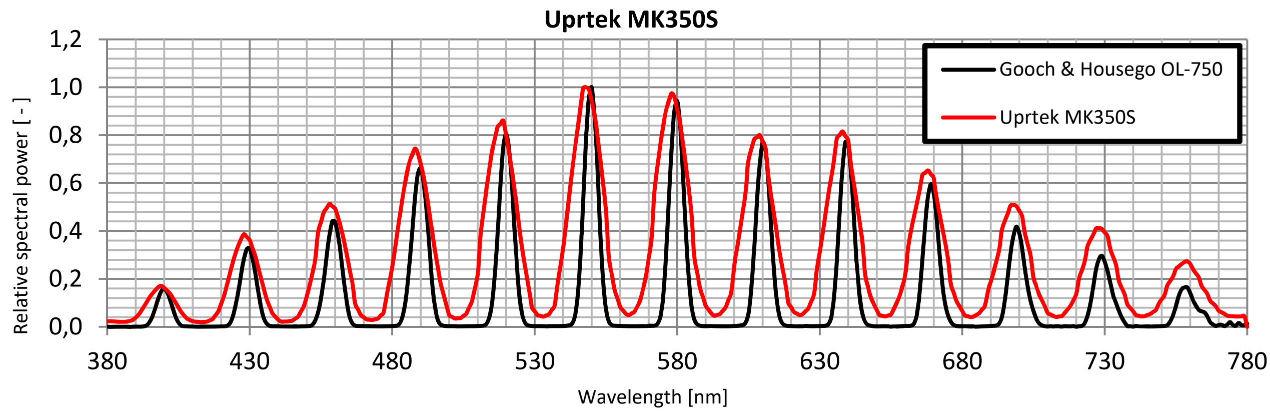

Figure 7. Measured spectrum with Uprtek MK350 S

Gossen Mavospec Base is a mobile spectroradiometer, which is the smallest from the comparison test. It is built on 256 pixels CMOS sensor and measures spectrum from 380 to 780 nm. Illuminance range is from 10 to 100 000 lx. Spectral bandwidth is less than 15 nm and wavelength accuracy is 0.5 nm. Uncertainty of measurement of illuminance is estimated to $U_{95\%} = 3.22$ %. The spectral shift against the double monochromator is 4.14 nm. The measured spectrum is shown is Figure 8.

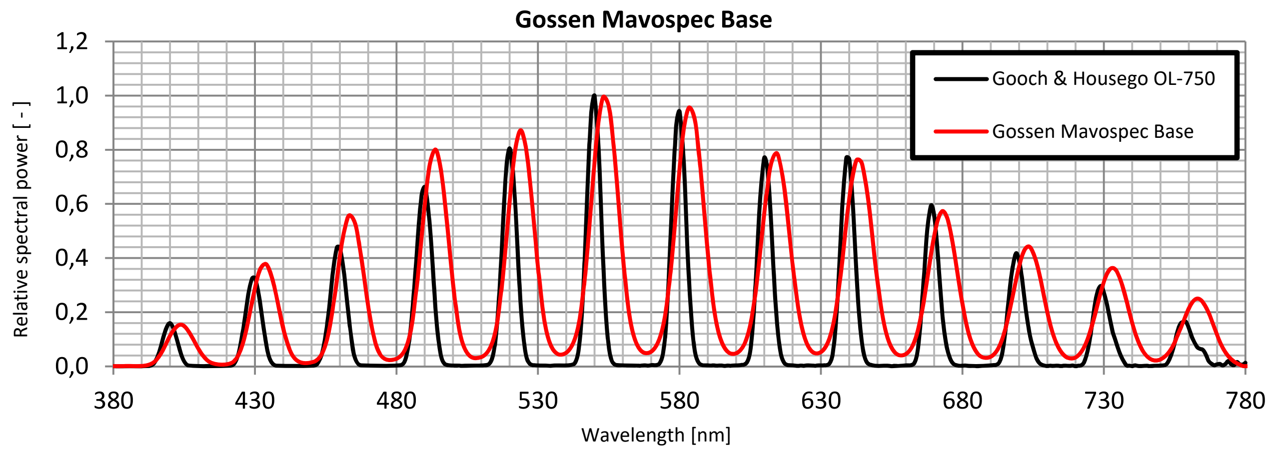

Figure 8 Measured spectrum with Gossen Mavopec Base

ABSOLUTE COMPARISON OF SPECTRORADIOMETERS

In order to compare spectroradiometers in terms of measurement of spectral power it is used light normal Osram Wi 41/G with luminous intensity $I = (280{,}4\ \pm 2\ \%)\ cd$ [5]. The measurement is carried out on the photometric bench with 1 mm positioning ruler. Light normal is powered with programmable current source Gooch & Housego OL 83A. Laboratory is black coated and photometric bench is surrounded with black curtains. Moreover there are two baffles on photometric bench to limit stray light. In the following Table 2 there is illuminance measurement comparison.

TABLE 2 ILLUMINANCE MEASUREMENTS COMPARISON

Name	Gossen Mavospec Base	JeTi SCB 1211 UV	Sekonic C-700	Uprtek MK350S
E_V [lx]	278.21	278.16	273.54	281.32
Dev. [%]	0.781	0.798	3.352	-0.327
$U_{95\%}$ [%]	3.22	3.17	5.14	5.04

EVALUATION OF RESULTS

The comparison test proved expectations. Spectral bandwidth is the key parameter for measurement narrow spectral peaks. Thus it depends on thickness of used slits. However, it is necessary to select right slit according to specific use. In case of high illuminance on the input, we can select smaller slits. However, for low luminance measurement it is better to have wider slits in order to have good signal to noise ratio. Spectroradiometers Avantes AvaSpec 2048 has good spectral resolution and measured spectrum corresponds with spectrum measured with double monochromator G&H OL-750. However, it has significant noise at low signal regions. Jeti SpecBox 1211 UV measures spectrum similarly as Avantes, however with slightly better noise. Konica Minolta CS-1000A measures tested spectrum the most correspondingly to double monochromator without almost any spectral shifts.

The measuring capabilities of tested spectroradiometers fully correspond to their photometric parameters. Mobile multi-array spectroradiometers have usually bigger entrance slit and bandwidth. Thus they are not intended for narrow spectral peaks measurement. However, they offer fast preliminary spectrum measurement at acceptable price range. In case of spectral accuracy tested mobile spectroradiometers has significant spectral shift, which contributes to uncertainty of measurement of photometric quantities. In our test Uprtek MK350S and Gossen Mavospec Base were out of date for next calibration and their spectral shifts are significantly higher. Thus it is necessary to have spectroradiometers regularly calibrated. In terms of uncertainty of measurement of illuminance all spectroradiometers capable of irradiance measurement passed the test. All deviations lied within their uncertainty of measurements interval.

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Uncertaint of Near Field Photometry

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***Abstract*—The paper describes calculation of uncertainty of measurement of luminous intensity distribution of large luminaires at goniophotometer of type 2 with short photometric distance (near field photometry). The short photometric distance causes non-perpendicular incidence of the light coming from the edges of the luminaire onto the photocell of the goniophotometer and thus the measured luminous intensity values could be smaller, than values measured with goniophotometer with adequate photometric distance. The paper should highlight such measurement complication and enlighten operators of goniophotometer of type 2 how to correct measured values of luminous intensity and calculated values of luminous flux of the luminaire.**

***Index Terms*--goniophotometer, luminous intensity distribution measurement, photometric distance, uncertainty.**

LUMINOUS INTENSITY DISTRIBUTION MEASUREMENTS

One of the basic procedure often carried out by photometric laboratories is measurement of luminous intensity distribution of luminaires at goniophotometer. There are three basic types of goniophotometer used in photometric laboratories and described in 0. Most photometric laboratories are using goniophotometer type 3 – goniophotometer based on light source Z rotation around a vertical axis and a mirror Z1 and Z2 arrangement around a horizontal axis. The photometer head F is fixed (see **Napaka! Vira sklicevanja ni bilo mogoče najti.**). The advantage of goniophotometer of type 3 is the possibility of long photometric distance (in the horizontal axis). The disadvantage is instability of reflection factor of used mirrors. The second often-used goniophotometer type is type 2 with the light source Z rotating around a vertical axis o and the photometer head F on the arm R movable around the luminaire. The advantage of goniophotometer of type 2 is the direct illumination of photocell (without mirrors). The disadvantage is the need of very high laboratories to achieve adequate photometric distance.

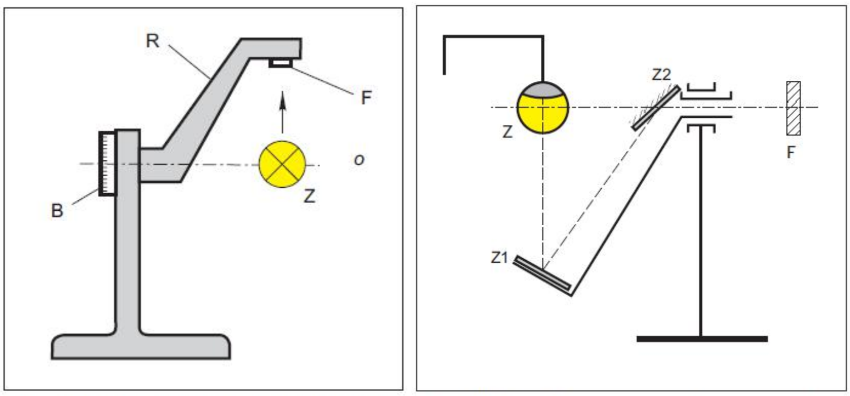

Figure 1. Two mostly used types of goniophotometer: Type 2 (on the left) and type 3 (on the right) 0**Napaka! Vira sklicevanja ni bilo mogoče najti.**.

This paper is focused on goniophotometer of type 2, which is used at Czech Technical University in Prague, FEE. As mentioned above, the main disadvantage of goniophotometer of type 2 is the dependence of its photometric distance on the height of the laboratory. Therefore, the goniophotometer used at Czech Technical University is constructed with photometric distance 2 meters only. The photometric distance limits the size of luminaires, which could be measured at such goniophotometer. The maximal size of luminaire is limited by the point light source definition, which says, that to be able to measure the luminous intensity with low level of uncertainty, the biggest dimension of the luminaire should be smaller than one fifth of photometric distance. If not, the uncertainty rises fast with decreasing proportion of the biggest dimension of luminaire to photometric distance of goniophotometer.

DETERMINATION OF LUMINOUS INTENSITY OF DIFFERENT TYPES OF LUMINAIRES

Luminous intensity is defined as spatial density of luminous flux. Therefore luminous intensity $I_{\gamma\zeta}$ is determined as luminous flux Φ of luminaire contained in unitary solid angle Ω – see equation (1).

$$I_{\gamma\zeta} = \frac{d\Phi}{d\Omega_{\gamma\zeta}}. \tag{1}$$

A solid angle of an object is equal to the area of the segment of a unit sphere, centred at the angle's vertex, which the object covers. Thus, luminous intensity is defined only for point light source (vertex). As a point light source could be considered a light source of its biggest dimension much smaller than the distance of the observer. Usually the biggest dimension of the luminaire should be at least five times smaller than the distance from the observer **Napaka! Vira sklicevanja ni bilo mogoče najti.**. Luminaires that does not meet such requirement should be considered as linear, planar or spatial. Than the determination of their luminous intensity is more complicated. Such luminaires must be imaginary divided to a few of partial pieces (i.e. of the dimension dx for linear luminaire), which meets the requirement of point light source (see above) and then the luminous intensity is determined as a sum (integral) of luminous intensities of all partial light sources (see Figure 2. – the determination of linear luminaire luminous intensity).

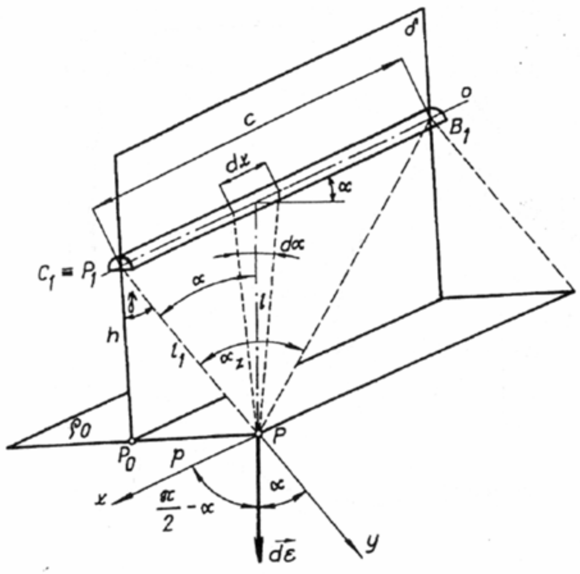

Figure 2. Determination of non-point (i.e. linear) luminaire by partial luminaires of dimension dx **Napaka! Vira sklicevanja ni bilo mogoče najti.**.

Conventional luxmeters are usually installed as the detector at goniophotometers. However, no conventional luxmeter can detect the size of measured luminaire, divide it to partial point light sources, measure the illuminance from each point light source separately (with different angle of light incidence α – see Figure 2.) and finally integrate it to resulting value applicable for correct luminous intensity result. Thus, luminous intensity measurement at conventional goniophotometers of type 2 with limited photometric distance is either limited by the size of luminaire (at least five times smaller than photometric distance), or its uncertainty rises with the size of the measured luminaire.

UNCERTAINTY OF LUMINOUS INTENSITY MEASUREMENTS OF LARGE LUMINAIRES

There are two types of standard uncertainties that should be considered for any measurement. The first one is standard uncertainty u_a of type A, which describes a statistically estimated standard deviation of measured values and could be evaluated only for several times repeated measurements of the same physical value at the same conditions. The second one is standard uncertainty u_b of type B, which is describes systematic errors of measurement caused by methodology, inaccuracy of measurement devices, etc. [3]. Type B evaluation of standard uncertainty is usually based on scientific judgment using all of the relevant information available, which may include:

- previous measurement data,
- experience with, or general knowledge of, the behaviour and property of relevant materials and instruments,
- manufacturer's specifications,
- data provided in calibration and other reports, and
- uncertainties assigned to reference data taken from handbooks.

Uncertainty type B is composed of many uncertainty components describing each of systematic measurements errors. Thus, final type B uncertainty is determined as the sum of all partial components. One of described components is uncertainty u_{bf} of the finite dimensions of devices used for luminous intensity measurements, especially [4]:

- photometric distance of goniophotometer r_0,
- a half of the characteristic dimension a of the luminaire,
- the diameter b of luxmeter photocell.

Standard uncertainty u_{bf} of the finite dimensions of devices used for luminous intensity measurements could then be calculated by the following formula [4]:

$$u_{bf} = \frac{\left| 1 - \left(\frac{r_0}{\sqrt{\left(r_0^{\ 2} + (a+b)^2 \right)}} \right)^3 \right|}{\sqrt{3}} . \qquad (2)$$

The following table (TABLE I.) shows the rise of the standard uncertainty u_{bf} of the finite dimensions of devices with decreasing ratio r_0/a of the photometric distance r_0 of goniophotometer and the half of the characteristic dimension of the luminaire a calculated using equation (2).

TABLE I. UNCERTAINTY OF THE FINITE DIMENSIONS OF DEVICES FOR DIFFERENT PHOTOMETRIC DISTANCE TO LUMINAIRE SIZE RATIOS [5]

r_0/a ratio	4,6	4,4	4,3	4,1	3,9	3,8	3,6	3,4	3,3	3,1	3,0	2,8	2,6	2,5
u_{bf} (%)	1,0	1,1	1,2	1,3	1,4	1,5	1,7	1,8	2,0	2,2	2,5	2,8	3,1	3,5
r_0/a ratio	2,3	2,1	2,0	1,8	1,6	1,5	1,3	1,1	1,0	0,8	0,7	0,5	0,3	0,2
u_{bf} (%)	4,0	4,6	5,3	6,2	7,4	8,9	10,9	13,5	17,2	22,2	29,1	38,2	48,5	56,1

EMPIRIC VERIFICATION OF CALCULATED UNCERTAINTIES

Luminous intensity of 60 cm long linear luminaire was measured at its optical axis at 3 m long photometric bench to verify the rise of the standard uncertainty u_{bf} with decreasing ratio r_0/a of the photometric distance r_0 and the half of the characteristic dimension a (length) of the linear luminaire.

Measured values of luminous intensity at luminaire optical axis for different distances from luminaire are shown in Figure 3. [5].

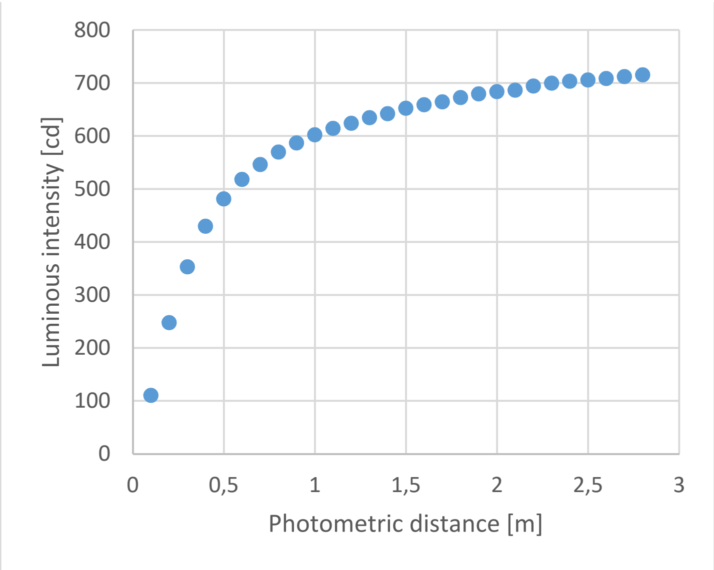

Figure 3. Measured values of luminous intensity at luminaire optical axis for different distances from 60 cm long linear luminaire [5].

Figure 3. confirms rising deviation of luminous intensity of luminaire at its optical axis from the regular value 718 cd with decreasing photometric distance from linear luminaire. Measurement of luminous intensity at luminaire optical axis is characterised by identical distance of the photocell from both edges of linear luminaire and rising angle of incidence of the light coming from both edges of luminaire with decreasing photometric distance.

The different situation occurs for measurement directions outside of optical axis of luminaire at goniophotometer. The distance of both edges of luminaire is different outside of optical axis and angles of light incidence could decrease with moving away from the optical axis of luminaire (with rising γ angle in C-γ photometric system). At near field, one edge of the luminaire could be several times farther from the photocell then other edge for directions far from optical axis.

Results of luminous intensity measurement of linear luminaire at 2 different photometric distances at 2 different photometric C planes (transversal C0-C180 and longitudinal C90-C270) at goniophotometer confirms above mentioned assumptions. Measured luminous intensity of the luminaire at insufficient photometric distance (r_0/a = 1,6) was lower than values at sufficient photometric distance for all γ angles for C0-C180 transversal photometric plane (see Figure 4.). Measured luminous intensity of the luminaire at insufficient photometric distance (r_0/a = 1,6) was lower than values at sufficient photometric distance for lower γ angles (near optical axis), but higher for higher γ angles far from optical axis for C90-C270 longitudinal photometric plane (see Figure 5.). Deviation of measured luminous intensity values in both figures corresponds with (is less then) uncertainty 7,4 % for r_0/a ratio 1,6, as shown in TABLE I.

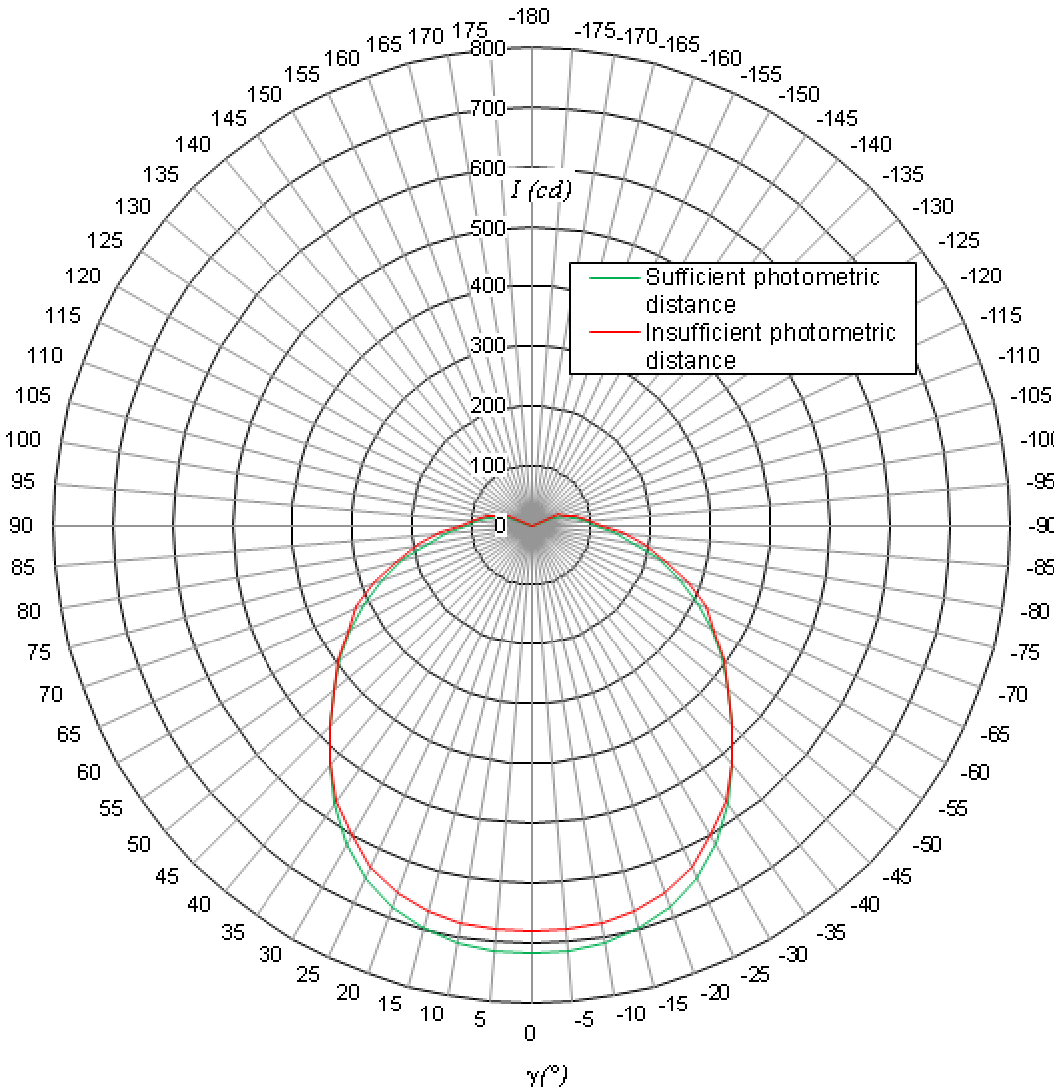

Figure 4. Luminous intensity of sample luminaire at C0-C180 photometric plane measured at sufficient and insufficient photometric distance.

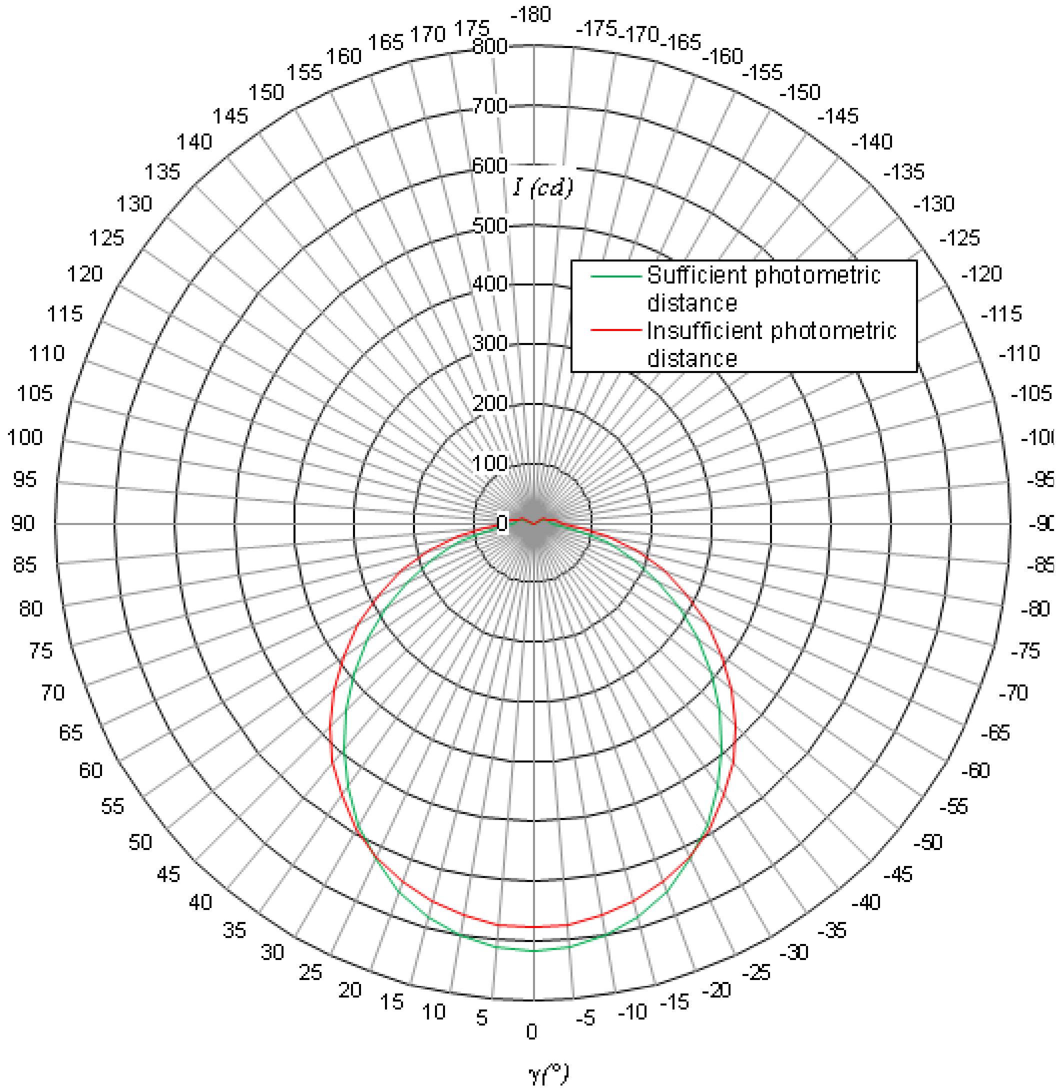

Figure 5. Luminous intensity of sample luminaire at C90-C270 photometric plane measured at sufficient and insufficient photometric distance.

CONCLUSION

The research described in this paper confirms the rising uncertainty of luminous intensity measurement of real (non-point) luminaires at goniophotometer type 2 with decreasing photometric distance. Particular results of luminous intensity such measurements at sufficient and insufficient (low) photometric distance at goniophotometer type 2 are compared in Figure 4. and in Figure 5. and described in the chapter above.

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Practical Assessment of Photobiological Safety of Light Sources Based on Requirements of Standard EN 62471

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***Abstract*—The article presents a method of evaluating irradiance, spectral irradiance and spectral radiance, for purposes of determining risk groups of light sources. Measurement methods have been developed on the basis of general requirements and diagrams incorporated in the standard EN 62471: 2008. The paper classifies risk groups of light sources and luminaires in terms of photobiological hazard and exposure limits when the skin is at the hazard of visible and infrared radiation. The construction of the stand for measuring parameters of optical radiation using the system of Bentham type IDR300-PSL based on double monochromator. That system has been specially designed to assess photobiological safety of light sources. Five LED light sources have been selected for examination. On these basis, a risk assessment of photobiological tested sources has been estimated and the appropriate risk group and time of safe exposure has been assigned for each of light source. Article has been finalized the conclusions on results of measurements.**

***Index Terms*--Blue light hazard, light emitting diode (LED), photobiological hazard, risk group.**

Introduction

The lighting market now provides many types of semiconductor light sources, i.e. light-emitting diodes (commonly referred to as LEDs). Considering their undoubted advantages such as energy efficiency and durability, LEDs are more and more often used to provide lighting at working stations and in rooms, but also homes. As conventional light bulbs over 7 W were withdrawn on 1 September 2016, it is possible to claim that LEDs will became the main replacement. It is an already observable tendency: next generation fluorescent lamps and halogen bulbs are at the margins of the lighting market. However, their method of optical radiation (white light) generation is different, compared to other types of light sources.

Where in case of ultraviolet or infrared emitting illuminators the users usually are less or more aware of the fact that the emitted radiation can be harmful to them [2], they appear not to have such a concern when it comes to light sources, especially new generation ones. This is mainly due the lack of general awareness of the fact that optical radiation emitted by the sources (except possible ocular and skin hazard due to ultraviolet radiation) may also pose a risk to the retina by visible radiation, especially within the range of the so-called blue light, and to the retina, cornea and lens by infrared radiation.

Usually, the user selects a replacement for the conventional light bulb based on the light emitting technology used, the price and/or parameters declared by the manufacturer, such as rated power, bulb equivalent output and light colour.

However, the question arises whether the use of new generation light sources (LEDs) is safe and – in particular – whether the emitted optical radiation poses no health risk. To make an attempt and answer this question, five selected LED light sources were tested to determine risk groups to be assigned to in terms of photobiological safety.

This paper is aimed at the presentation of risk groups, determined on the basis of tests, classified by photobiological safety of new generation GLS light sources and general conclusions resulting for the users.

Classification Of Light Sources By Photobiological Safety

The standard [4] provides criteria of photobiological safety of lamps that are defined as sources designed for generation of optical radiation [3]. There are four risk groups according to [4] as follows:

1) Exempt group
2) Risk Group 1 (Low-Risk)
3) Risk Group 2 (Moderate-Risk)
4) Risk Group 3 (High-Risk).

Exposure limit values for individual risk groups are defined based on existing criteria and maximum permissible exposure values used for the assessment of optical radiation hazard in the working environment. The difference is that separate assumptions on permissible safe exposure times for each of the five photobiological hazards in the same category were made to determine criteria for classification into individual risk groups.

Exposure limit values and safe exposure times assumed for individual risk groups (except Risk Group 3) as regards individual hazards are summarised in standard [4]. According to the applied classification, Risk Group 3 includes light sources that may pose a hazard even for momentary or brief exposure, and light sources whose parameter values (obtained by tests to determine hazards) exceed the limits for Risk Group 2. As a rule, the risk group assigned to the illuminator corresponds to the highest risk group indicated (resulting from all concerned photobiological hazards).

Scope Of Testing For Photobiological Safety Of Light Sources

For general lighting service sources, the following measurements shall be taken according to the standard [4]:

- irradiance in order to determine:
  – lens near-UV hazard over the wavelength range 315 to 400 nm, E_{UVA},
  – corneal and lens infrared hazard over the wavelength range 780 to 3 000 nm, E_{IR},
- spectral (effective) irradiance in order to determine the ocular and skin hazard due to UV radiation over the wavelength 200 to 400 nm, E_S,
- spectral (effective) radiance in order to determine:
  – retinal blue light hazard over the wavelength range 300 to 700 nm, L_B,
  – retinal thermal hazard over the wavelength 380 to 1 400 nm, L_R.

Method Of Light Source Testing To Determine Photobiological Safety

The measurement method relating to the parameters of optical radiation emitted by electric optical radiation sources to be classified into risk groups in terms of photobiological hazards due to optical radiation was developed in accordance with requirements of the standard [4] and Directive [5] regarding artificial optical radiation [1]. The method was based on the IDR300-PSL spectroradiometer system supplied by Bentham. The system was specially designed to evaluate photobiological safety of lamps.

As provided for in the standard [4], general lighting service sources, i.e. sources intended for lighting spaces (e.g. those used for lighting offices, schools, homes, factories, roadways or automobiles) shall be measured at a distance where the illuminance is 500 lx (typical value of general lighting service illuminance used in, for example, offices, schools, etc.).

Description Of The IDR 300-PSL Spectroradiometer System Supplied By Bentham

The main element of the entire spectroradiometer system is the IDR 300-PSL double monochromator that features one input aperture and three output apertures (one in the first monochromator and two in the other one) – see Fig. 1.

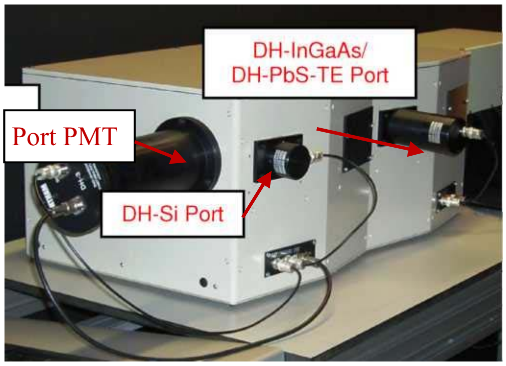


Figure 1. View of the monochromator with marked input circuits

The input circuits are used to connect the following detectors:

– DH-3 photomultiplier tube (port PMT) – UV-radiation precise measurement within the range 200 to 320 nm,
– DH-SI silicone detector (port DH-Si) – radiation measurement within the range 200 to 1100 nm,
– DH-InGaAs detector (port)– IR radiation measurement within the range 900 to 1 700 nm,
– DH-PbS-TE detector (port) – IR radiation measurement within the range 1000 to 3000 nm.

The photomultiplier is installed at the port opposite to the aperture, the SI detector – at the port near the photomultiplier, and the InGaAs or PbS detectors are interchangeably installed at the output aperture of the first monochromator.

The spectroradiometer system is equipped with two multiple fibre quartz lines that are interchangeably connected to the monochromator input aperture. The first optical fibre line together with the D7 optical component (equipped with a PTFE diffuser ensuring cosine corrections) is used to measure the relative spectral emission of radiation sources and determine absolute irradiance by irradiance measurements. The other optical fibre line connects the monochromator input to the TEL 309 telescope used to measure radiance (Fig. 2).

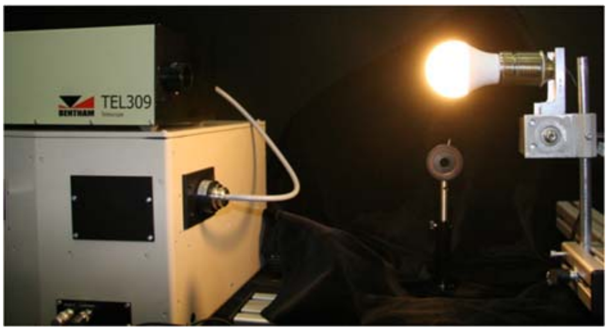


Figure 2. View of the TEL 309 telescope connected to the monochromator during radiance measurements

To ensure proper measurements, the spectroradiometer system requires calibration. For this purpose, there are three standard sources: CL 7 deuterium type, CL 6-H quartz-halogen type and SRS 12 quartz-halogen type – installed in a photometric sphere:

- The CL 7 deuterium standard source (Fig. 3) is used to calibrate the spectroradiometer system within the range 200 to 40 nm. It is equipped with the 706-type power supply (Fig. 3).

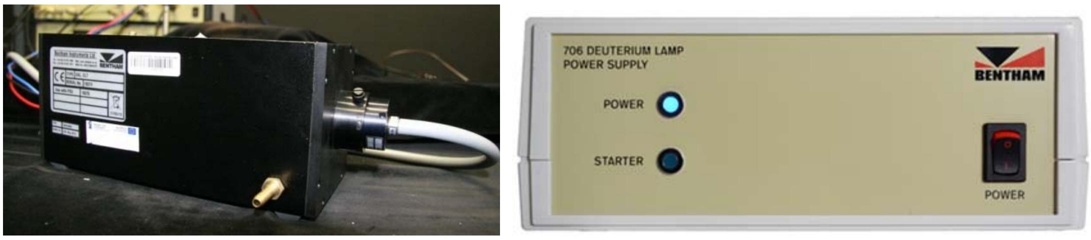


Figure 3. View of the CL 7 deuterium standard source and the 706-type power supply

- The CL 6-H quartz-halogen standard source (Fig. 4) is used to calibrate the spectroradiometer system within the range 300 to 1 100 nm. It is equipped with the 605-type DC power supply (current 6.3 A) – see Fig. 4.

Figure 4. View of the CL 6 quartz and halogen standard source and the 605-type DC power supply

- The SRS 12 (sphere) quartz-halogen standard source (Fig. 5) is used to calibrate the spectroradiometer system within the range 300 to 1 400 nm to measure radiance. It is equipped with the 605 type DC power supply (current 8.3 A).

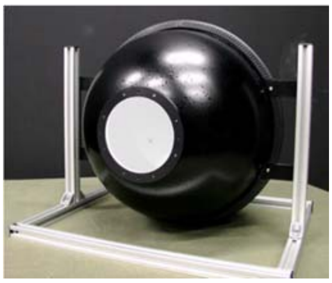


Figure 5. View of the SRS 12 quartz-halogen standard source (sphere) on the input side

For infrared radiation hazard measurements, a relay optical component with the 417-type power supply and the PbS_TE detector are used. The relay optical component comprises a set of lenses and a speed selector. The main element in the selector is a blade with five apertures to cover the optical sensor located on the selector base (Fig. 6). The selector base is attached to the relay cylinder of the optical component. Figure 6 shows the complete relay optical component installed at the monochromator input.

Figure 6. Complete relay optical component installed at the monochromator input and the 417-type power supply

MEASUREMENT CONDITIONS

N. Light Source Ageing

To maintain stable radiant flux emitted by the light source during the measurement process and provide reproducible results, new light sources shall be seasoned (the so-called ageing or seasoning) for at least 100 hours prior to optical radiation measurements. Prior to measurements, LED sources shall be kept switched on for at least 60 minutes. This time is required to stabilise the luminous flux emitted by the sources..

O. Test Environment

The measurements were taken in a dark room at the Optical Radiation Laboratory at the Central Institute for Labour Protection, at the optical radiation hazard test station. There are now windows in the room and the walls are coated with matt black paint. The photometric darkroom prevents the effect of optical radiation being directly emitted from other sources than the tested ones and the radiation being reflected from elements of the equipment, room walls and measuring instrumentation. In addition, the room is air-conditioned, and as such a stable ambient temperature can be obtained, which is essential to maintain stable operation of the light sources being tested and limit the measurement error during measurements of the radiation emitted by such sources.

P. Illuminance

Illuminance measurements were taken using the DH400-VL luxmeter head connected to the IDR300-PSL monochromator supplied by Bentham. The head features a relative sensitivity suitable for the relative sensitivity of the human eye V_λ. The measurement was taken on the vertical plane at the location of the measuring detector. By changing the distance of the source being tested, changing indications of the luxmeter display were observed. If the indication was 500 ± 1 lx, the distance was assumed as the measuring distance during the measurement of irradiance spectral distribution.

Q. Software Used To Aid The Procedure Of Light Source Testing – Kreator PSL Wizard

Kreator PSL Wizard serves as a guide that starts the test procedure by entering data relating to the source to be tested, through selection of hazards being assessed, to a report with results of individual test stages.

The optical radiant energy emitted by the source depends on the source visual angle that is associated with the applied field of view. Therefore, the energy should be measured at the properly determined distance. Apart from the determination of distance at which the tested source emits 500 lx, it is also essential to determine properly dimensions of the source and the distance from its apparent image because the data is used to find the source visual angle.

If the source has no optical system, the measurement distance to be assumed starts on the surface mapped into the eye. (This applies to sources with diffuse (iridescent) bulbs.) If the source is equipped with an optical system (e.g. a lens), the magnified apparent image is generated behind the system. Also, the image of the source with a clear bulb is visible behind the bulb. It is the apparent source for which the measurement distance must be selected because the source is mapped into the eye.

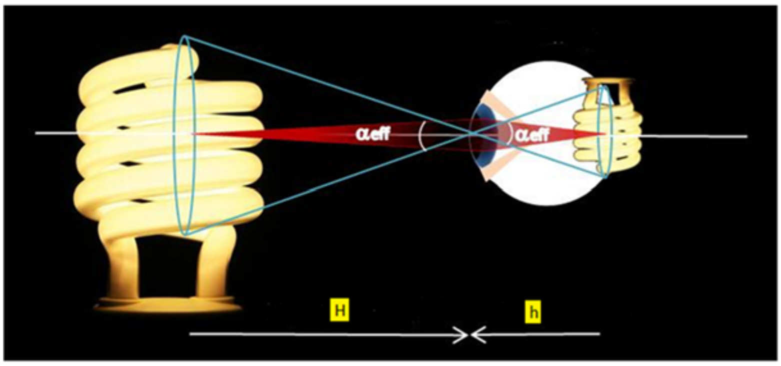


Figure 7. View angle of the source and the retinal image

The visual angle defines the area of the exposed retina. The source being observed is directly mapped onto the retina (Fig. 7) for momentary irradiance and the effective angular subtense (α_{eff}) at the distance h, which is the same as the source visual angle during the assessment performed at the distance H. The information about the retinal image size is necessary to evaluate the retinal hazard. The measurement at the minimum distance of 200 mm corresponds in practice to the highest retinal hazard.

The distance from the reference point on the source to the spot with the apparent source must be positioned using the PSL Profiler attachment (Fig. 8).

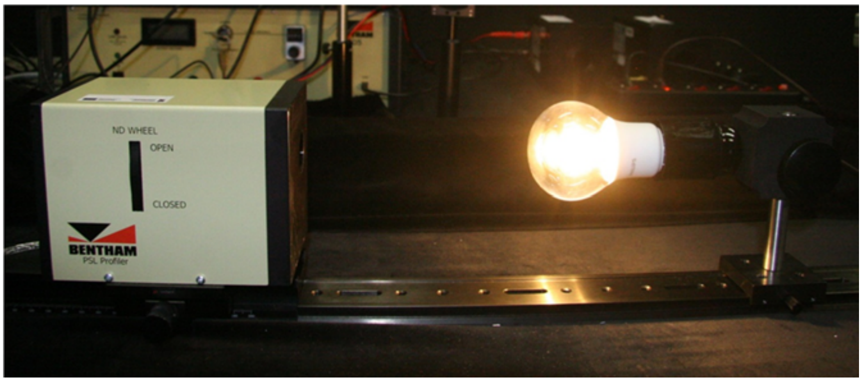


Figure 8. View of the PSL Profiler attachment during assessment of apparent source positioning

The maximum field of view for the PSL Profiler is approximately 120 mrad (to maintain sufficient resolution of the CMOS matrix for the smallest sources with the angular subtense of 1.7 mrad). As recommended in the standard [4], the minimum illuminating surface of the source during measurement shall be at least 50 % of the total emitting surface of the source.

For sources with diffuse-coating bulbs or sources with diffusers, it is required to check whether the emission area is uniform. As for sources with integrated reflectors, lenses and other optical systems, the emission area may be defined not only by the source, but also jointly with such systems.

For the tested LED sources, four of them featured diffuse bulbs, and therefore there was no problem with proper determination of the measuring distance. However, for the CorePro LED bulb supplied by PHILIPS, it was necessary to use the PSL Profiler attachment. The obtained source image behind the reference point is shown in Fig. 9.

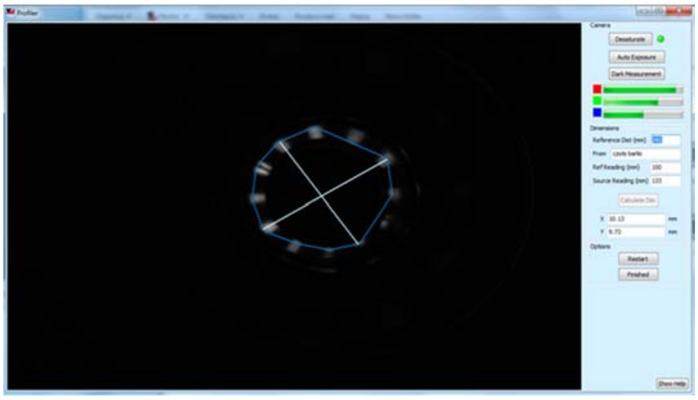


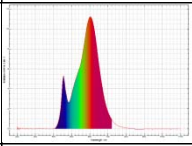
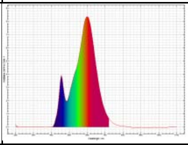
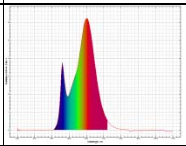
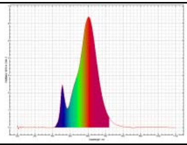
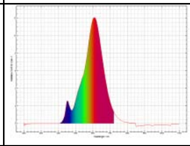
Figure 9. View of the source image behind the reference point in the PSL Profiler opening

Technical Description Of The Tested LED Sources

All tested LED sources are replacements for traditional A-series light bulbs, and therefore they come with the E 27 screw base. The tests concerned three LED sources supplied by: PHILIPS, GTV and BEMKO. Also, two LED sources available in supermarkets (Castorama – DIALL and Auchan - HFNE), the so-called no name. Four sources (GTV and BEMKO as well as DIALL and HFNE) are equipped with the A 60 type bulb that is diffuse (iridescent). As for the bulb in the LED source supplied by PHILIPS, it is clear and LEDs are eclipsed by a specially designed optical system. As declared by the manufacturers, the sources are interchangeable with bulbs whose output is 40 W (PHILIPS), 60 W (GTV, HFNE and DIALL) and 75 W (BEMKO).

Table I summarises basic parameters on light source packaging as provided by the manufacturer. Basic performance parameters of light sources that are interchangeable with conventional bulbs include: power, luminous flux, life of a lamp, colour temperature, colour rendering index, lamp dimensions (length and diameter).

TABLE II. DESCRIPTION OF THE TESTED LED SOURCES WITH THE E27 SCREW BASE – PARAMETERS PROVIDED BY THE MANUFACTURER

Source code	LED 1	LED 2	LED 3	LED 4	LED 5
Manufacturer / Distributor	GTV	BEMKO	AUCHAN	DIALL/Castorama	PHILIPS
Product name	LD-PC3A60-10W	E27-A60-120-3K	HFNE A60-P	LED*806 lm	CorePro LEDbulb
Power [W]	10	12	10	9	6.5
Luminous flux [lm]	840	1 055	806	806	470
Colour temperature [K]	3000	3 000	3 000	2 700	2 700
Colour rendering index [-]	≥ 80	≥ 80	bd	no data	no data
Luminous flux beam angle [°]	220	no data	no data	210	no data
Life of a lamp [h]	40 000	30 000	15 000	15 000	15 000
Type of bubble	A 60	A 60	A 60	A 60	no data
Spectrum of a radiation					
Photo of the light source					

TEST RESULTS

According to requirements in the standard [4] concerning the tested general lightning service LED sources, the evaluation of photobiological safety covered:

– ocular and skin actinic ultraviolet hazard (E_{IR}) over the wavelength 200 to 400 nm,
– ocular near ultraviolet hazard (E_{UVA}) over the wavelength 315 to 400 nm,
– retinal blue light hazard (L_B) over the wavelength range 300 to 700 nm,
– retinal thermal hazard (L_R) over the wavelength 380 to 1 400 nm,
– ocular infrared radiation thermal (L_R) over the wavelength 780 to 3 000 nm.

Therefore, irradiance and radiance measurements were taken correspondingly to the tested hazards and ranges. The results presenting the listed hazards, assigned risk groups and times of safe exposure are presented in Table II.

TABLE III. SUMMARISED ASSESSMENT RESULTS FOR PHOTOBIOLOGICAL HAZARD POSED BY A LED SOURCES

Type of photobio logical hazard	**Wave-lengths [nm]**	**Function of biological efficiency**	**Symbol**	**Denomi-nation**	**Source code**	**Exempt group**		**Safe exposure time [s]**
						Measurement result	*Emission limits*	
Actinic UV	200 ÷ 400	$S_{UV}(\lambda)$	E_s	W·m^{-2}	LED 1	$17.5\ 10^{-5}$	0.001	> 30 000
					LED 2	$14.3\ 10^{-5}$		
					LED 3	$6.79\ 10^{-5}$		
					LED 4	$7.25\ 10^{-5}$		
					LED 5	$1.13\ 10^{-5}$		
UV-A	315 ÷ 400	—	E_{UVA}	W·m^{-2}	LED 1	0.00021	10	> 10 000
					LED 2	0.00016		
					LED 3	$9\ 10^{-5}$		
					LED 4	$7\ 10^{-5}$		
					LED 5	$5.65\ 10^{-5}$		
Blue light	300 ÷ 700	B(λ)	L_B	W·m^{-2}·sr^{-1}	LED 1	13.912	100	> 100
					LED 2	17.419		
					LED 3	9.07		
					LED 4	9.569		
					LED 5	12.228		
Retina thermal hazard	380 ÷ 1 400	—	L_R	W·m^{-2}·sr^{-1}	LED 1	272.63	280 000	> 10
					LED 2	297.33		
					LED 3	$6.79\ 10^{-5}$		
					LED 4	258.48		
					LED 5	566.78		
Cornea and lens thermal hazard	780 ÷ 3 000	R(λ)	E_{IR}	W·m^{-2}	LED 1	0.00456	100	> 1 000
					LED 2	0.00568		
					LED 3	$9\ 10^{-5}$		
					LED 4	0.00412		
					LED 5	0.00648		

CONCLUSIONS

The presented results of individual hazards of the tested LED sources unambiguously conclude that the sources are safe and pose no photobiological hazard. Therefore, all tested LED sources are classified into the exempt group. Please note that the obtained results relate only to unitary items of LED sources, selected at random from among a wide and still-changing offer on the market.

For LED sources used for general lightning service, thermal hazards do not occur because the values obtained from measurements range from 0.005 % to 0.1 % of the exposure limit value. A similar conclusion is also drawn from the ocular near-ultraviolet (UV-A) hazard because the values obtained by measurements range from 0.0004 % to 0.0021 % of the exposure limit value for the hazard.

Practically speaking, potential hazard posed by LED sources may be determined by ocular and skin hazard due to actinic ultraviolet radiation and ocular blue light hazard. For the former case, the highest value of 17.5 % was obtained, relative to the exposure limit value that poses no hazard. However, values of 1 % were obtained as well. For the latter case of ocular blue light hazard, similar maximum values were obtained, but the lower limit was higher (9 % to 17 %). The hazard level depends mostly on the emitted luminous flux, light colour and the type of the LED source used.

By comparison of the values declared by the manufacturer (colour temperature and the value obtained by measurement), one may conclude that there is practically no difference between the values, whereas for the LED source manufactured by Philips, a very warm colour temperature of 2500 K was obtained, which is rare on the marker – but very sight friendly. For the colour rendering index, all tested sources feature a level of 80.

Based on an analysis of the obtained measurement results, it is to be concluded that the tested LED sources may be successfully used interchangeably with A-series light bulb in homes and offices.

ACKNOWLEDGEMENT

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Standard:

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DIRECTIVE 2006/25/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 April 2006 *on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents* (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC).

Vertical illumination requirements for pedestrian gaze estimation

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Abstract – The effect of vertical illuminance on the face and background luminance on the ability of a person to judge the gaze direction of an approaching pedestrian at a distance of 10 or 15 m was experimentally determined. Even relatively high face illuminances of 2 or 5 lux do not enable confident judgment of gaze direction in these situations, with the highest achieved probability of a correct gaze direction judgment about 70 % From the age of 39, performance is significantly worse. Remarkably, at a 5 lux face illuminance, performance of the older participants plummeted with increasing background luminance. The results however suggest that better performance could be achieved at face illuminance levels above 2 lux, combined with background luminances above 0.8 cd.m^{-2} .

Index Terms – **Road lighting, pedestrians, face perception, gaze perception, safety perception**

INTRODUCTION

The main reason to install lighting in our roads and streets, next to the prevention of traffic accidents, is to improve the safety and safety perception of the public. An important question for lighting professionals is how much light should be provided to fulfil this need. Road lighting should enable people to judge their physical environment and the possibilities it offers to see, hide for, or escape from a potential danger [1]. As the potential threat is often another pedestrian, it is important to be able to judge whether an approaching person actually is a risk for one's personal safety. Therefor we should be able to determine the required light levels from people's performance in viewing others.

We tend to base our judgment about oncoming people on body posture, dress, gait and facial characteristics, from which we determine their identity, mood and intention. As a proxy for all these personal characteristics determined from a face, Caminada and Van Bommel proposed in 1980 to use the recognition of a face as a test criterion [2]. Based on the 'zones of proximity' as defined by Hall [3], it was postulated that a pedestrian has to be able to see a face well enough to guarantee its identification at a distance of 4 m. However, Hall's theory was soon dismissed as being too generalized and stereotypical and lacking substantiation [4]. Apart from that, it was designed to describe voluntary, social meetings indoors, instead of possible hostile encounters in a much darker, lower visibility, outdoor environment. For the latter situation, a required distance for good facial perception of 15 meter was proposed, as one should still be able to avoid trouble or evade a person at this distance [5]. This was later confirmed in eye tracking studies as indeed being the distance at which pedestrians look attentively at the face of oncoming people, for a typical duration of 0.5 seconds [6].

Using the original observing distance of 4 meter, a required level of vertical illumination at face height (1.5 meter) of 5 lux (or 0.8 lux semi-cylindrical illumination) was experimentally determined [2], which was later confirmed [7], [8]. As is to be expected, it was also shown that at larger distances, higher light levels are needed for successful recognition, with vertical illuminances required for face perception at 10 to 15 meter distance varying between 10 to about 30 lux [9], [10].

For our research to be effective, we should obviously focus on the most difficult of all of the critical visual tasks, as these will determine the minimum required light levels. In pedestrian encounters, this seems to be establishing the gaze direction of the other [11]. This informs us about his intended walking direction [12], which helps to avoid collisions. Gaze direction is also a very powerful cue for where the other is directing his attention [13]. It might be that his face is expressing anger, but if his attention is directed towards his smartphone, companion or his dog, we can presume this person does not pose a danger to us.

Whereas a lot of research has been published on measuring gaze direction using electronic equipment, until now, only one paper has been published touching upon the lighting requirements for successful gaze perception by humans [11]. Describing a preliminary experiment, it shows that at the maximum distance of 10 meter and maximum screen luminance of 1 $cd.m^{-2}$ (corresponding to a vertical illuminance of 20 lux), using white metal halide lighting, the probability of correctly identifying gaze direction was only 56 %. Using high-pressure sodium light, performance remained at the chance level of 50 %. Only at a very short distance of 2 meter, a 75 % success rate was achieved at this highest light level. So, the light level required for successful, confident gaze perception at 10 or even 15 meters remains unknown.

The current CIE report on the requirements for road lighting [14] provides additional requirements for minimal vertical or semicylindrical illuminance levels in pedestrian and low speed traffic areas "*if facial recognition is necessary*", with the required minimal vertical illuminance ($E_{v,min}$) in a range of 0.6 lux to 5 lux, increasing with the average horizontal illuminance level. Although it sounds logical that the required illumination on the face would depend on the background light level, determining the adaptation state of the observer, there is no known experimental evidence for the chosen ratio between vertical and horizontal illuminance.

Looking at the above, a number of questions come up. Which level of vertical illuminance is needed for confident gaze perception at distances of 10 and 15 meter? And how does this level depend on the background illumination level?

II. Experimental design

To answer these questions a study design is set up to simulate the public environment by night, and an experiment has been carried out to evaluate the hypotheses. A lighting system with appropriate light conditions was installed. Participants were invited to experience these conditions and to mention if they could see the gaze direction of the other.

Test setup

The user study was conducted in a laboratory in the Netherlands, where a room of 27m long and 2m width was used. The participant's visual field included nothing more than the researcher, and the neutral white coloured walls, ceiling and floor, and a row of cupboards covered with white cloth. This should simulate a situation in an open public space as much as possible. The researcher acted as the oncoming pedestrian. The researcher had a notepad with a white A4 paper to check the sequence of head and gaze directions, and to write down the answers of the participant. A laptop was situated near the researcher, with software to drive the lighting conditions. The laptop screen did not influence the visual scene as seen by the subject. There were no windows in the room.

The electric lighting system consisted of a dimmable recessed ceiling Philips Savio LED Luminaire (600 x 600 mm, 4000K, Ra > 80, UGR < 16, 3400 lm), illuminating the background, and two Philips StyliD Compact Power LED spots (4000 K, Ra > 80, 2000 lm), lighting the face of the experimenter. Each light condition had a combination of background luminance and the face illuminance level. In earlier research [6] it was suggested to use an observation time of 500 ms. Therefore in each separate trial, the face was illuminated for this time only. To alert the participant that a next trial is coming, the laptop made a bleep sound one second in advance. Background luminance was changed every five seconds. This was repeated for three background luminance levels.

The background light levels were chosen according to the pedestrian and low-speed traffic areas lighting classes P3, P4 and P5 as defined in the current CIE recommendation [14]. Using Calculux software (Philips Lighting, The Netherlands) background luminances for installations typical for these lighting classes were calculated. The background was then illuminated to achieve these luminance levels. The face (vertical) illuminance levels were chosen according to the additional requirement 'if facial recognition is necessary' to be 0.5 lux, 1 lux, 2 lux or 5 lux. In total this resulted in a full factorial design with twelve lighting conditions.

The lighting conditions were commissioned using the average wall luminance, measured with a luminance camera (LMK5 Color with software package Technoteam LMK LabSoft Standard Color v12.7.23) and an illuminance meter (LMT 360 B), respectively. Figure 1 shows the luminance distribution images of the three different background conditions.

Participants

A total of N = 20 subjects participated in the study. N = 11 were male, and N = 9 were female, with an age varying from 22 to 66 years. Participants did not work in the field of lighting application and perception and had no visual disabilities that were not compensated by lenses or glasses.

Study design and user interface

The experiment was conducted during the end of May of 2017, on weekdays between 9am and 5pm. Each experimental session included one participant at a time with a total duration of 20 minutes. Each test day had 10 experimental time slots.

Participants were located at a red cross at the floor on 10 m or 15 m distance, and started with unconscious adaptation to the dark room. During this adaptation time, the researcher explained the experimental procedure, and the participant had the opportunity to ask questions. After the researcher started the software on the laptop, it took 15 seconds before the first light conditions occurred.

The task of the participant during the test was to name the gaze direction of the researcher as seen during during the illumination time. For each light condition seven different gaze directions were shown, by turning head and eyes either left, right or center, but never in opposite directions. The researcher had a white Caucasian origin. During the test the participants and the researcher did not talk to each other. The test consisted of a total of 84 light conditions at two observation distances.

Analyses

In each trial, the subject had to name the gaze direction (left, central, or right). The percentage of correct answers was used as the dependent variable. Given the large sample size and the normal distribution of the data, differences between the conditions are analyzed using a paired samples *t*-test and repeated measures analysis of variance. Statistical analyses are performed using IBM SPSS Statistics, using a required significance level of 0.05.

III. RESULTS

A. *Lighting conditions*

The probability of a correct gaze estimation for the different combinations of vertical illumination on the face and background luminance are shown in figure 2. A repeated analysis of variance test with two within-subject effects showed a significant interaction effect between face illuminance level and background luminance for the different lighting conditions (p = 0.018), and a significant main effect for face illuminance level in which the right answer was given during each condition (p = 0.018).

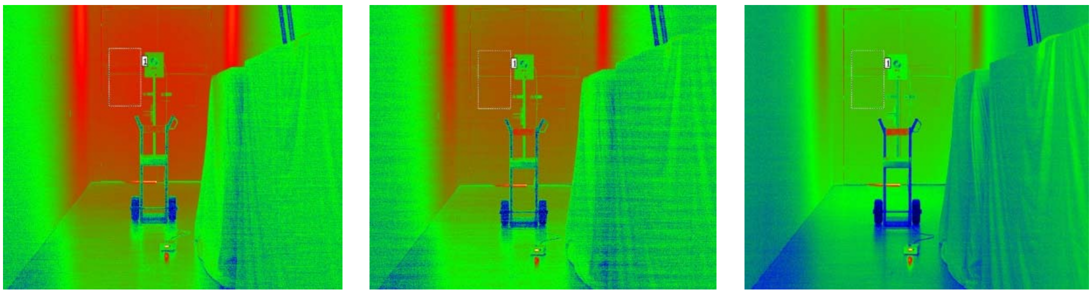

Figure 1. Luminance maps for the three background luminance conditions, from left to right: 0.8, 0.6, 0.3 cd.m^{-2}.

B. *Distance*

To analyse the effect of distance, pairs are created between the two distances of 10m and 15m with a similar background luminance and face illuminance level. A paired samples t-test has been performed for each pair. The lighting conditions resulting in a significant lower percentage of right answers at 15m distance than the 10m distance are indicated in figure 3.

A multivariate test is used to see if the effect occurs for the within-subject factor distance, but no significant interaction effect for light condition and distance was found (multivariate F(x,x) = 0.246, p = 0.060). This means the change in performance, averaged over all participants, with changing background luminance is equal for both distances. A within-subject comparison of the performance change with background luminance, using a repeated analysis of variance Huynh-Feldt test, showed a significant interaction effect between the two distances for the different lighting conditions (p = 0.001).

C. *Demographic characteristics*

By means of a repeated analysis of variance test with tests of between-subjects effects, the demographic characteristics of the subjects are evaluated for their effect on the subjects performance. No significant effect has been found for subjects' gender or visual corrections. Only the difference between the young (22 – 32 years) and old group (39 – 66 years) leads to a significant effect (p = 0.034).

Nevertheless the multivariate test shows that the effect that occurs for the within-subject factor has no significant interaction effect for light condition and age category (multivariate F(x,x) = 0.429, p = 0.839). This means the average decrease in correct answers is equal for both age groups.

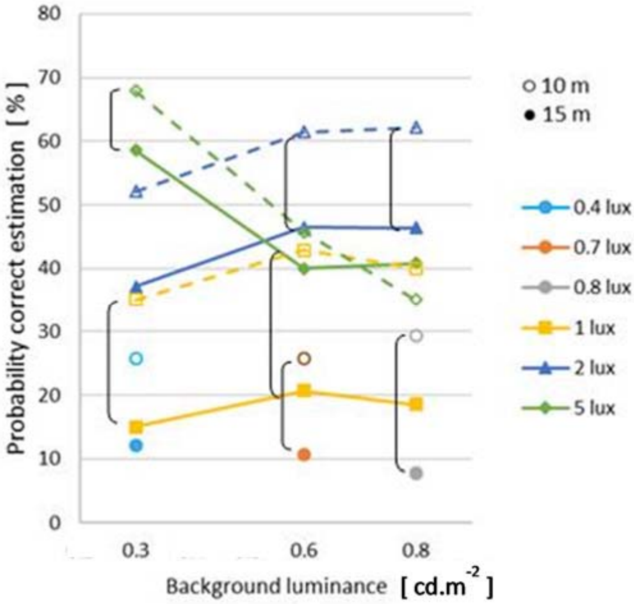

Figure 2. Probability of correct estimation of gaze direction versus background luminance for each level of vertical illuminance. Brackets indicate statistically significant differences ($p < 0.05$). Open markers represent observations at 10 meter distance; closed at 15 meter.

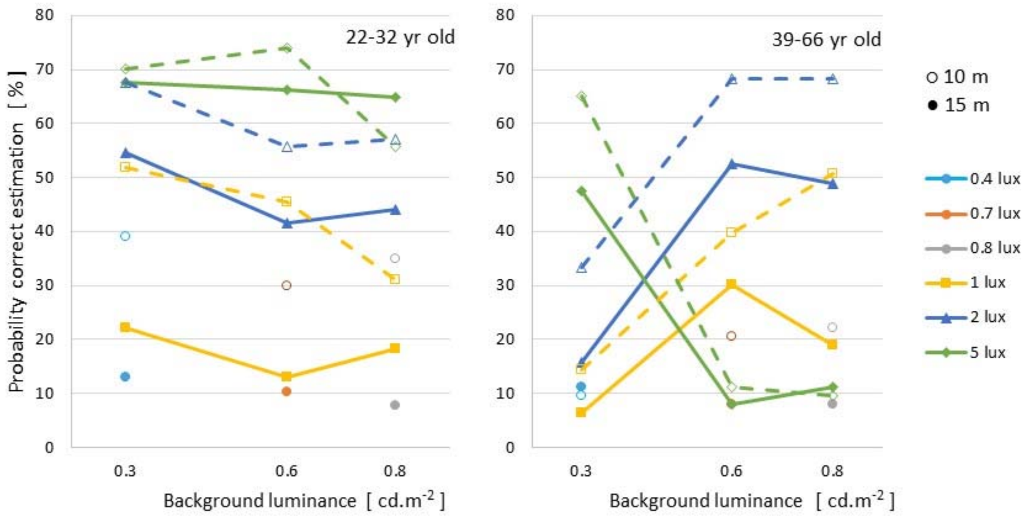

Figure 3. Probability of correct estimation of gaze direction versus background luminance for each level of vertical illuminance for the two age groups -left side young (22-32 year), right side old (39-66 year). Open markers represent observations at 10 meter distance; closed at 15 meter.

IV. Discussion

At the required distance of 15 m, for vertical illuminances of 1 lux or lower, performance stayed close to chance level (14 %). At 2 lux, the average probability of a correct answer never exceeded 46 %. For the highest level of 5 lux, performance ranged from 60 % to 40 %, with a yet unexplained decrease in performance with increasing background luminance. This could be related to the relatively low background luminances used together with the 5 lux vertical illuminance. The results suggest that better performance could be achieved at higher levels of face illuminance (above 2 lux) combined with a higher background luminance level (above 0.8 cd.m^{-2}, corresponding to an average horizontal illuminance higher than 7.5 lux), as suggested in the current international recommendation [14].

The older participants consistently showed a lower performance than the younger group (see figure 3). This confirms the results of two studies on face recognition where a similar effect of age was found [15], [16]. The observed decrease in performance with increasing background luminance at 5 lux vertical illuminance was most prominent in the older group of subjects (see figure 3). Considering the complete set of subjects, the best overall performance was achieved at a vertical illuminance of 2 lux, within the limited range of background luminances used here.

Assuming a skin reflectance of about 25 % [17], a 5 lux illuminance would correspond to a luminance of about 0.4 cd.m^{-2}. Whereas it has been assumed that performance at face perception is comparable looking at pictures or real faces, comparing at the same level of face luminance, the performance of our subjects is much better than that reported for subjects judging gaze direction from pictures [6].

A last remark on ecological validity concerns the luminance of the wider background. In a typical outdoor scene, this can be much darker, and, or much less uniform. As it is unknown how this influences the result, further tests should perhaps be performed or at least validated in a realistic outdoor setting.

V. Conclusions

Even relatively high face illuminances of 2 or 5 lux do not enable confident judgment of gaze direction of an approaching pedestrian at a distance of 10 or 15 m. The highest achieved probability of a correct gaze direction judgment was about 70 %, at a vertical illuminance on the face of 2 lux. From the age of 39, performance is significantly worse. Remarkably, at a 5 lux face illuminance, performance of the older participants plummeted with increasing background luminance. The results however suggest that better performance could be achieved at face illuminance levels above 2 lux, combined with background luminances above 0.8 cd.m^{-2} .

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Limiting disturbance of bats by adapting the spectral composition of road lighting

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***Abstract* – Exterior lighting can have negative effects on the natural environment. One of the possible ways to mitigate this is to adapt the spectral power distribution of the light. A unique test set-up was built in the Netherlands to study long term ecological effects of outdoor lighting. At eight sites, a forest edge is traversed by four rows of lampposts of four different colours and a dark control. Over five years, the activity of bats was measured using automatic bat detectors, revealing marked differences in the reaction of bats to the different lights. Both bats which are known to hunt around street lights and light-averse bats react similarly to the 'red' (low blue and green content) light in our test, as in the dark control. This suggests that using this type of 'red' light can be used to mitigate bat habitat loss by outdoor lighting.**

***Index Terms* – Exterior lighting, ecology, conservation, bats, light pollution.**

INTRODUCTION

Public lighting is often concentrated in urban areas, but close to roads, industrial sites, logistics infrastructure and in natural areas within cities and in the peri-urban area, the natural environment can – unintentionally – be exposed to outdoor lighting. Lighting can however have effects on many species of nocturnal animals [1]-[3], particularly on bats [4]-[7]. A well-known effect of light is the attraction of bats. This is an indirect effect, as some bat species have learned to feed on the insects attracted by the lights [6], [8]-[12]. Not all bats show this opportunistic feeding behaviour. Slow-flying species, such as *Myotis* and *Plecotus*, seem to avoid light [9]. It is generally believed that slow-flying and less manoeuvrable bats species avoid areas with higher light levels [13], and emerge from their roosts later in the evening, when light levels are very low [14], [15]. These species tend to fly faster in light areas [14], [16] to avoid predators using vision to locate their prey, such as owls.

The response of animals to light often depends on the spectrum. This has been reported for non-light shy bats, which are less active around low-pressure sodium lights, presumably because of the lower insect density around these lamps compared to other lamp types [6], [17], [18]. For light-averse bats, the influence of the light spectrum is largely unknown. Whereas the eye sensitivity of many bat species seems to incline to shorter wavelengths [19], some bat species possess long-wavelength sensitive opsins [20], [21], [22].

This may offer a possibility for lighting solutions that supply the necessary level of illumination for humans, but with a low disturbance of bats. We explored the effect of lighting with different spectral compositions on the presence and activity of bats.

VI. METHOD

In order to test the impact of artificial light with different spectra on natural habitat, we have set up a unique field experiment in the Netherlands [23]. At eight previously dark sites located in natural habitat, we monitored bat activity for five successive years. At each individual site, we established four rows of five lampposts perpendicular to a forest edge (see figure 1). Each row was equipped with LED luminaires emitting one of four light colours: warm white (3500 K, Philips Fortimo LLM module), 'green' (ClearSky, Philips Lighting), 'red' (ClearField, Philips Lighting) and no light (dark control). The 'green' and 'red' light contain all wavelengths, with either strongly reduced output above or below 580 nm, as shown in figure 2. With a pole height of 4 m , a spacing of 25 m and a maximal horizontal illuminance about 7 lux, this lighting installation is typical for for example pedestrian or bike lanes or residential streets in or near natural areas [24]. The light post lamps were always on from sunset to sunrise, except for a maximum of eight nights per year in which insect (moth) sampling took place. The lamps emit no UV light and emit no sound between 0 and 120 kHz.

For the assessment of bat presence we recorded bat echolocation calls. Bat species were clustered into three groups: 1) slow-flying, light-shy bats, of the *Myotis* and *Plecotus* genus, species that are not abundant and typically emit low amplitude echolocation signals; 2) agile, non light-shy, common bats of the *Pipistrellus* genus, with relatively loud echolocation calls and known to utilize insects `accumulated around light posts; and 3) open-space foraging bats of the *Nyctalus* and *Eptesicus* genus, with loud echolocation sounds.

For two or three nights during one year, insect density was measured simultaneously with bat activity, using sticky sheet traps placed about 50 cm beneath the luminaires at the forest edge. These were also the closest to the bat detectors. To prevent an influence of the standard yellow color of commercial sticky sheets on the effect of the light color itself, we used custom made white sticky sheets. Insect density was determined using image processing [25].

Statistical analysis was performed using R version 3.3.1 [26], with a 0.05 significance level. We tested the impact of light color on bats using models with a negative binomial distribution with a logit link. As there was no interaction between year and light treatment or period (early or late summer) and light treatment, we pooled the data for all years per group and per transect.

VII. Results

Between 2012 and 2016, bat activity was recorded during an average of 54.4 ± 3.8 nights per site. Between 1 to 7 nights of insect (moth) sampling, with lights off, coincided with a period of bat recording. Light colour had a highly significant effect on the number of passes of the light-shy Myotis and Plecotus species (Group 1, see figure 3a). Compared to the dark control, the number of bat passes was significantly reduced around the white and ‘green’ lighted transects. There was however, no significant difference between the ‘red’ lighted transects and the dark controls. For the more opportunistic Pipistrellus (Group 2), for the nights with lights on, the number of passes was highest for white and green light. This can be nearly explained (with significance $p<0.06$) by the higher insect densities around these lamps, for the nights during which we measured bat and insect activity simultaneously. During the nights with lights off, the effect of light colour disappeared (see figure 3d). The number of passes of Group 3 bats did not correlate with light colour (figure 3c).

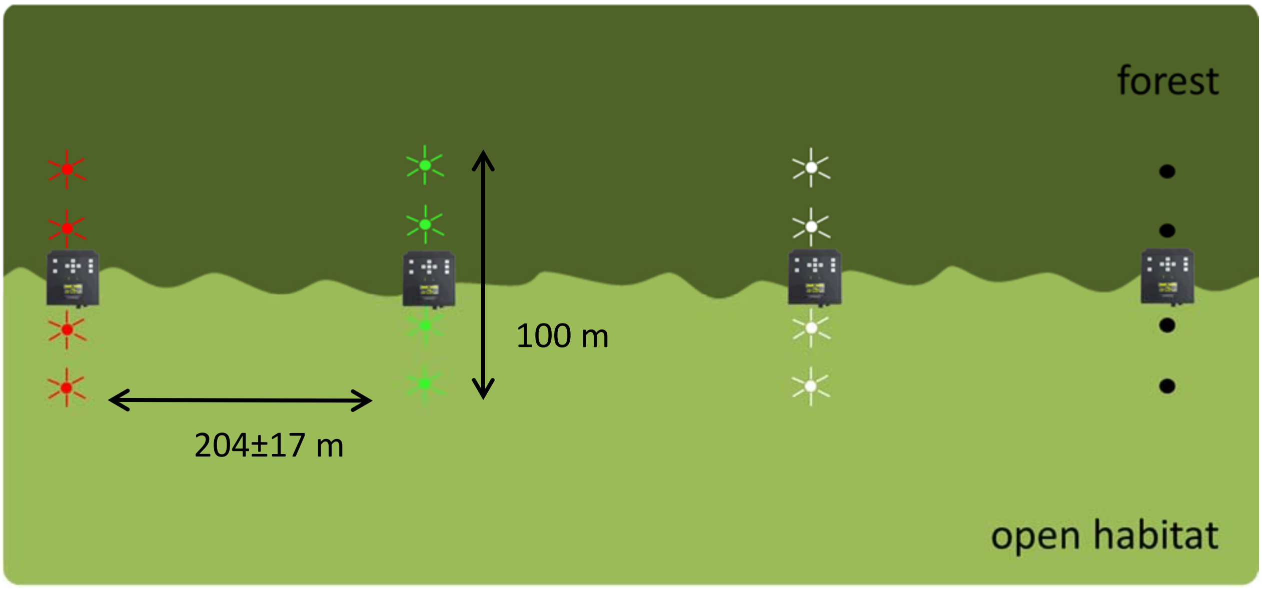

Figure 1. Layout of an experimental site in forest edge habitat, showing rows with light posts, each with a different light colour and dark control. We established this combination of four treatments at eight separate sites, with at each site the same combination of these four transects in randomized order. The bat recorders were placed near the middle light post in the forest edge.

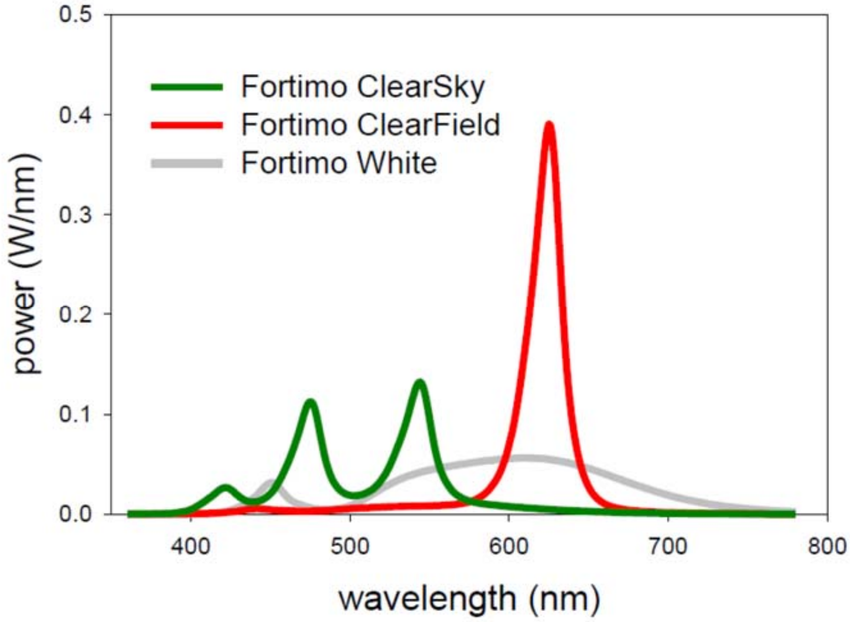

Figure 2. Spectral power distribution of the three light colours used: white, ClearSky ('green') and ClearField ('red'). (Figure from Spoelstra et al. (2017), Proc. R. Soc. B, DOI 10.1098/rspb.2017.0075)

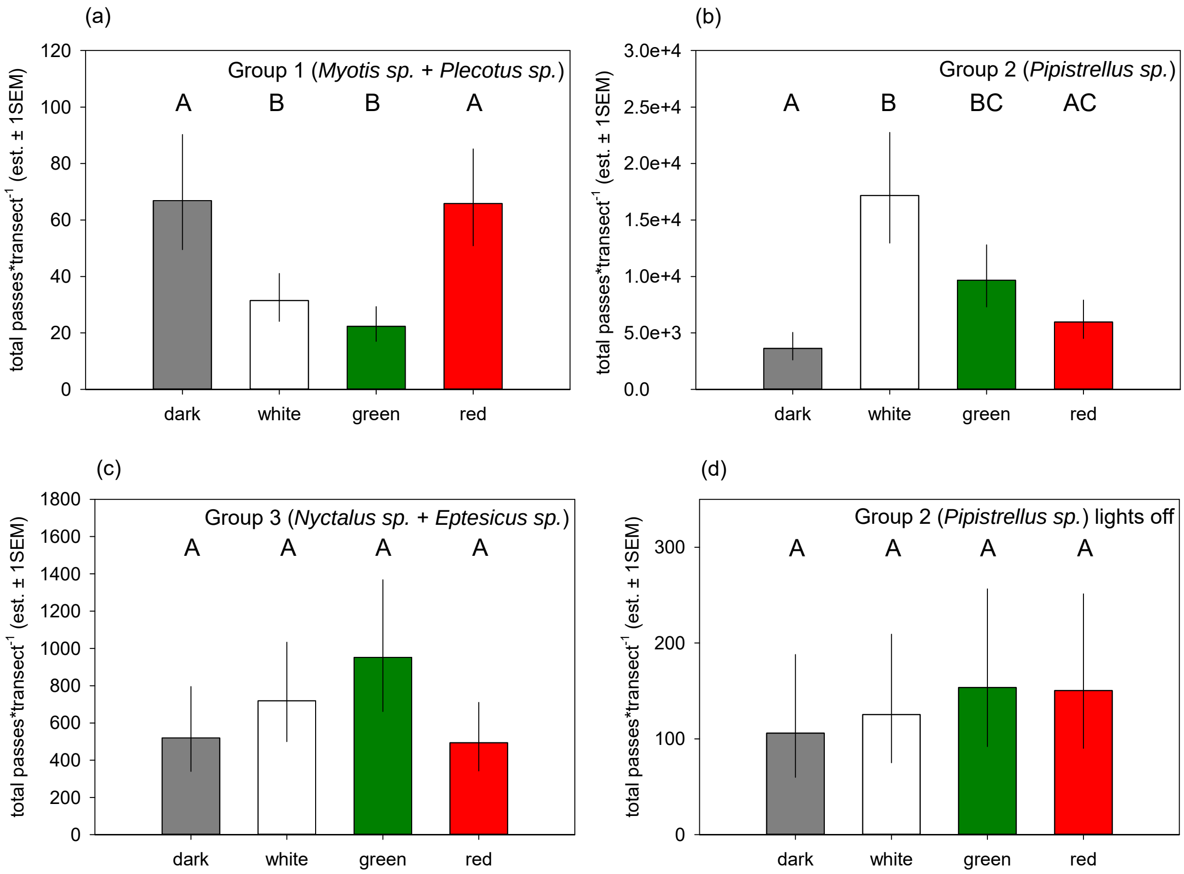

Figure 3. Total bat passes (summed over all nights measured per transect) during all years 2012 – 2016 (back transformed estimates from negative binomial generalized linear models with bat passes and site as fixed effects) for (a) group 1 (*Myotis* and *Plecotus* species), (b) group 2 (*Pipistrellus* species), (c) group 3 (*Nyctalus* and *Eptesicus* species) and (d) passes of group 2 bats during nights when the lights were off for moth sampling (table S2). Capitals identify groups which significantly differ from each other in post-hoc tests (table S3). (Figure from Spoelstra et al. (2017), Proc. R. Soc. B, DOI 10.1098/rspb.2017.0075)

VIII. Discussion

The slow-flying, light-averse Plecotus and Myotis species, which are also in general the more endangered bat species, clearly avoid white light as well as 'green' light. This is in line with the observations that, at least in Europe, these species are only rarely [27] or not at all [6] present around streetlights. The 'red' light however did not cause any reduction in activity of Plecotus and Myotis bats – the number of passes was equal to that in the dark controls. This is in line with our hypothesis and may be related to the eye sensitivity curve being inclined more to shorter wavelengths [19], which are strongly reduced in the 'red' light. When comparing the presence of Pippistrellus to the presence of Group 1 species over time, it was shown that the low Group 1 bat density in 'green' and white light could not be explained by a repulsion effect of the more abundant Pippistrellus bats, as was suggested earlier [28].

The agile Pippistrellus bats are equally active in 'red' light and in dark control as well. In the green and white light they are more abundant, which can be explained by the higher number of insects being attracted to these light colours [6], [9], [12]. Earlier work has shown that this 'red' light attracts a significantly lower number of insects than the white or 'green' light [29], [30], which was confirmed by our present data. During the single nights that our lights were switched off, to facilitate insect (moth) trapping, there was no effect of light colour on Pippistrellus activity, which demonstrates a direct response to switching off the lights.

The Group 3 species are known to hunt above large lighted areas [31]. They also produce loud echolocation calls and were manually observed to pass over our test sites well above our streetlights. This can explain why there was no significant effect of light colour on their activity level.

IX. Conclusion

White and 'green' light has a marked effect on the activity of both light-shy and non-light shy bat species. While facilitating the latter, more opportunistic species, these light colours may cause a loss of habitat and food for the light-averse bats. Our setup is relatively small; lighting installations along longer stretches along roads may cause loss of habitat at a larger scale and have considerable effects on local populations. Our results demonstrate that compared to darkness, LED light with high red and low blue-to-green content, as used in this test, has no effect on the activity level of both light-averse and non-light shy bat species. In cases where outdoor lighting is warranted in or near natural habitats, this offers a possibility to prevent habitat loss for bats.

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