Energetic, Visual and Non-Visual Aspects of Office Lighting

THÈSE N^{O} 4634 (2010)

PRÉSENTÉE LE 16 AVRIL 2010

À LA FACULTÉ ENVIRONNEMENT NATUREL, ARCHITECTURAL ET CONSTRUIT
LABORATOIRE D'ÉNERGIE SOLAIRE ET PHYSIQUE DU BÂTIMENT
PROGRAMME DOCTORAL EN ENVIRONNEMENT

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Friedrich LINHART

acceptée sur proposition du jury:

Prof. A. Mermoud, président du jury
Prof. J.-L. Scartezzini, directeur de thèse
Dr C. Filleux, rapporteur
Prof. H. B. Püttgen, rapporteur
Prof. S. Wittkopf, rapporteur

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Suisse
2010

Abstract

Light has important visual and non-visual effects on humans and high-quality light should therefore be supplied inside buildings in sufficient quantities. On the other hand, artificial lighting is responsible for a large part of an office building's electricity needs. It is thus important to take into account at the same time visual comfort, non-visual effects of light and energy-efficiency when designing lighting systems for office buildings.

The general objective of this doctoral thesis was to combine knowledge from several scientific fields (e.g. daylighting technology, artificial lighting technology, lighting simulation and chronobiology) to discuss how sustainable lighting solutions (i.e. lighting solutions that are optimized in terms of energy-efficiency, visual comfort and performance as well as non-visual aspects of lighting) can be achieved in office rooms. A research strategy that used a test office room equipped with an Anidolic Daylighting System (ADS) as a starting point has been followed. This ADS was shown to be well-accepted by office occupants and to be able to supply sufficient daylight flux during large parts of most working days. Based on this ADS, a highly energy-efficient electric lighting system for complementary artificial lighting was developed and tested in a visual comfort and performance study with human subjects. In addition to that, the chronobiological properties of the test office room were assessed. It was shown that the ADS-equipped room performs extremely well under daylighting conditions in terms of non-visual aspects of office lighting. For the rare times when this is not the case, a back-up system for chronobiological lighting based on blue Light Emitting Diodes was developed. In order to get a deeper insight into chronobiological aspects of office lighting, a first applied chronobiological study at the Solar Energy and Building Physics Laboratory was initiated. Furthermore, possibilities to apply the concepts developed during this doctoral thesis to other types of buildings and other geographic regions were discussed.

In conclusion, this doctoral thesis successfully demonstrated that it is possible to achieve sustainable lighting scenarios that are optimized in terms of energy-efficiency, visual comfort and performance as well as non-visual aspects by combining day- and electric lighting technologies in an appropriate way.

Keywords: Office Lighting; Daylighting; Electric Lighting; Chronobiology; Energy-Efficiency

Zusammenfassung

Licht hat starke bildgebende, aber auch unsichtbare Effekte auf Menschen; qualitativ hochwertiges Licht sollte daher in ausreichender Menge in Gebäuden bereitgestellt werden. Auf der anderen Seite ist elektrische Beleuchtung für grosse Teile des Strombedarfs von Bürogebäuden verantwortlich. Es ist daher wichtig, beim Design von Beleuchtungssystemen für Bürogebäude sowohl Sehkomfort, unsichtbare Lichteffekte als auch Energieeffizienz zu berücksichtigen.

Das Ziel dieser Doktorarbeit war es, Wissen aus unterschiedlichen Bereichen (z.B. Tages- und Kunstlichttechnik, Lichtsimulation und Chronobiologie) zu verbinden, um zu diskutieren, wie nachhaltige Beleuchtungskonzepte (d.h. Beleuchtungskonzepte, die sowohl aus Sicht der Energieeffizienz, des Sehkomfort und der Sehleistung als auch der unsichtbaren Lichteffekte optimal sind) in Büroräumen erreicht werden können. Es wurde eine Forschungsstrategie verfolgt, welche ein mit einem Anidolischen Tageslichtsystem (ADS) ausgestattetes Testbüro zum Ausgangspunkt hat. Im Rahmen der Doktorarbeit wurde gezeigt, dass dieses Tageslichtsystem nicht nur hohe Akzeptanzwerte unter Büroinsassen erreicht, sondern auch über weite Teile normaler Arbeitstage die notwendigen Beleuchtungsstärken zur Verfügung stellen kann. Auf der Basis dieses Tageslichtsystems wurde ein passendes elektrisches Beleuchtungssystem entwickelt und im Rahmen einer Studie mit Versuchspersonen eingehend getestet. Zusätzlich wurden die chronobiologischen Eigenschaften des Testbüros untersucht. Es zeigte sich, dass das ADS auch aus chronobiologischer Sicht über weite Strecken normaler Arbeitstage sehr vorteilhaft ist. Für die seltenen Momente, wenn dies nicht der Fall ist, wurde ein zusätzliches Beleuchtungssystem auf Basis blauer lichtemittierender Dioden entwickelt. Um tiefere Einblicke in chronobiologische Aspekte der Bürobeleuchtung zu erhalten, wurde im Rahmen dieser Doktorarbeit am Labor für Solarenergie und Gebäudephysik eine erste angewandte chronobiologische Studie mit jungen Versuchspersonen initiiert. Desweiteren wurden Möglichkeiten diskutiert, die entwickelten Konzepte in anderen Gebäuden an unterschiedlichen Orten einzusetzen.

Zusammenfassend kann gesagt werden, dass diese Doktorarbeit Möglichkeiten aufgezeigt hat, wie Tages- und Kunstlichttechnologien in idealer Weise verbunden werden können, um nachhaltige Beleuchtungskonzepte zu realisieren.

Schlagwörter: Bürobeleuchtung; Tageslicht; Kunstlicht; Chronobiologie; Energie-Effizienz

Für Frieda und Nadine.

Acknowledgements

First of all, I would like to thank my thesis director Professor Jean-Louis Scartezzini for having faith in me and for giving me the opportunity to complete this thesis at the Solar Energy and Buidling Physics Laboratory (LESO-PB) of the Swiss Federal Institute of Technology in Lausanne. This work would not have been possible without his wide spectrum of knowledge, his visionary ideas, his encouragement and above all his human kindness.

I would also like to thank Professor Stephen Wittkopf for giving me the opportunity to join his team at the National University of Singapore in 2007 for several weeks. The insights into daylight simulation that I gained during this stay were extremely valuable input on the way to the accomplishment of this thesis. I would also like to thank him for reviewing my thesis and for having accepted to be on my thesis jury.

My warm thanks are due to Dr. Mirjam Münch for all the insights into chronobiology, for her kind help and her encouragement.

This work would not have been possible either without the help of Pierre Loesch, Apiparn Borisuit, Christian Roecker, Dr. Fred Haldi and David Daum. Thank you very much for all the time that you have spent helping me.

Special thanks are due to Suzanne, Sylvette and Barbara for their kindness and for keeping all sorts of administrative hassles away from me.

Thanks to the entire LESO team for creating an extremely comfortable and stimulating atmosphere. You guys are great!

I would not have been able to finish this thesis without the help of my friends David, Fred, Natalia, Vincent, Jonas, Tobi, Christian, Nele and ...YOU! Thanks are also due to everyone at Toastmasters.

Furthermore, I wish to thank Professor Anna Wirz-Justice for supporting me and for opening all those doors, Dr. Andreas Schüler for playing music and for letting me use the LEA infrastructure, Laurent Deschamps for the triathlon motivation, Dr. Maria Cristina Munari-Probst for more than three years of Building Physics, Professor Hans-Björn Püttgen, Dr. Charles Filleux and Professor André Mermoud for reviewing my thesis and for having accepted to be on my thesis jury as well as Hans-Ludwig Besenstiel for his persistent assistance.

Moreover, I am deeply indebted to Aditya Gabrani and Francesco Davila Alotto who have helped me a lot with their precise computer simulations on LEDs and Daylight.

In addition to that, I would like to thank the Swiss Federal Office of Energy (SFOE) for funding my work. Many thanks are also due to the TULUX AG, the Regent Beleuchtungskörper AG and OSRAM Switzerland for generously providing me with luminaires, lamps and control gear during my time work at LESO-PB. I am grateful to the Relux Informatik AG for their kind help with the Relux software tool and for kindly granting me the appropriate licenses and to LTI Optics (in particular Mark Jongewaard) for their help with the software tool Photopia. Thanks also to all study participants: you have made this thesis possible.

Last but not least, I would like to thank my parents Ingeborg and Dr. Friedrich Linhart, my brother Wolfgang Linhart (†), my sister Andrea Linhart, my wife Nadine Linhart, my daughter Frieda Linhart, the Drees family and all the rest of my family for their love, support and understanding.

Contents

List of Figures

List of Tables

Glossary

η_{perf}	Performance indicator for the acuity part of the FrACT.
λ	Wavelength.
Φ	Luminous Flux.
$\tau_{amb}, \tau_{task}, \tau_{blue}$	Average daily operating hours of ambient, task and blue lighting, respectively.
$\tau_{sequence}$	Total duration of the sequence during the acuity part of the FrACT.
A_{room}	Floor area of an office room.
$c(\lambda)$	Relative spectral sensitivity for nighttime melatonin suppression in humans.
$D(x)$	Daylight factor at a distance x from the façade.
DA	Daylight Autonomy.
DA_w, DA_c, DA_r	Daylight Autonomies for the window section, center section and rear section of a room, respectively
E	Illuminance, also Energy.
E_{av}	Average illuminance on a particular reference plane.
$E_{e\lambda}$	Spectral irradiance at a wavelength λ.
E_{ec}	$c(\lambda)$-corrected irradiance.
E_{he}	External horizontal illuminance.
$E_i(x)$	Internal horizontal illuminance at a distance x from the façade (measured on workplane).
$E_{lighting}$	Electricity consumption due to lighting.
g_1	Illuminance uniformity; minimum illuminance on a reference plane divided by the average illuminance on that specific reference plane.
LPD_{amb}	Lighting Power Density resulting from ambient lighting.
LPD_{blue}	Lighting Power Density resulting from blue lighting.
LPD_{eff}	Effective Lighting Power Density.

GLOSSARY

LPD_{task}	Lighting Power Density resulting from task lighting.
$N_{concerned}$	Number of occupants directly concerned by a certain problem.
$n_{correct}$	Total number of correctly identified Landolt rings per sequence during the acuity part of the FrACT.
P	Power.
p	Probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true.
P_{con}	Connected electric lighting power.
P_{el}	Electric power consumption.
pr	Accuracy mass of an n-back test.
$R_{x,n}$	Answer to statement x by study participant n.
$R_{x,opt}$	Optimal answer to statement x.
$total_{fa}$	Number of false alarms during an n-back test.
$total_{hits}$	Number of times where a person pushes the A-key during an n-back test.
$V(\lambda)$	Relative spectral sensitivity for photopic vision in humans.
[°C]	Degree Centigrade.
[CHF]	Swiss Francs.
[h]	Hours.
[K]	Kelvin.
[lm]	Lumen.
[Lux]	Lux.
[m]	Meter.
[mW]	Milliwatt.
[nm]	Nanometer.
[V]	Volt.
[W]	Watt.
ADS	Anidolic Daylighting System.
AIC	Anidolic Integrated Ceiling.
AL	Artificial Light.
ANOVA	Analysis of variance.
BlueLum	Luminaire with blue LEDs developed during this Thesis.

CCT	Correlated Color Temperature.
CFL	Compact Fluorescent Lamp.
CH1..CH4	Different DALI channels.
CHUV	Centre Hospitalier Universitaire du Canton du Vaud.
CIE	Commission Internationale de l'Eclairage.
CLC	Controlled Lighting Conditions.
CO_2	Carbon Dioxide.
CRI	Color Rendering Index.
DALI	Digital Addressable Lighting Interface.
DC	Direct Current.
DL	Daylight.
E27	Particular lamp socket designation.
ECG	Electronic Control Gear.
EEG	Electroencephalography.
EIB	European Installation Bus.
EMC	Electromagnetic Compatibility.
EPFL	Swiss Federal Institute of Technology in Lausanne.
EU	European Union.
FrACT	Freiburg Visual Acuity and Contrast Test.
GU10	Particular lamp socket designation.
HDR	High Dynamic Range.
HF	High Frequency.
HID	High Intensity Discharge.
IR	Infrared.
KSS	Karolinska Sleepiness Scale.
LCD	Liquid Crystal Display.
LED	Light Emitting Diode.
LESO-PB	Solar Energy and Building Physics Laboratory.
LPD	Lighting Power Density.
MAV	Mean Annoyance Value.

GLOSSARY

n-back	Computer-based performance test used during this Thesis, either 2-back or 3-back.
OLED	Organic Light Emitting Diode.
OLS	Office Lighting Survey.
OLS1,OLS2	Analogue versions of the OLS, used during the applied chronobiological study.
POE	Post Occupancy Evaluation
rANOVA	Repeated measurements analysis of variance.
RJ11	A telecommunication standard.
S1..S21	Different statements concerning subjective visual comfort.
SE,SEM	Standard Error (of the Mean).
T1,T2	Control lines for Touch Dim Sensors.
T5,T8	Diameter specifications for fluorescent tubes.
UGR	Unified Glare Rating.
UK	United Kingdom.
US	United States of America.
USB	Universal Serial Bus.
UV	Ultraviolet.
VAS	Visual Analogue Scale.
VAS-MWT	Visual Analog Scale for Mood, Wellbeing and Temperature.
VCS	Visual Comfort Scale.
VDU	Video Display Unit.
VSD	Virtual Sky Dome.

1

Introduction

1.1 General Context of the Doctoral Thesis

The sense of vision is one of man's most important senses. In order to make use of this sense, we need light. The latter is defined as that part of the electromagnetic spectrum that gives rise to a visual sensation. This light has to be supplied in sufficient quantities and has to be properly distributed if a situation of maximum visual comfort and performance is to be created. In addition to that, light has important non-visual effects on humans. Since the discovery of a third type of photoreceptor in the human eye in 2002 (11), researchers have been able to understand more and more how light influences our body's functioning, our health and wellbeing. Especially the influence of light on the circadian system (i.e. those parts of the human body that work together to maintain a regular cycle with a period of approximately 24 hours; from lat. "circa" = approximately and "dies" = day) is still subject to intensive research. On the other hand, artificial lighting is responsible for a large part of an office building's electricity needs. In order to reduce this electricity consumption, important efforts have been made during the last decades and will still have to be made in the future.

Designing lighting scenarios that are optimal from an energetic, visual and non-visual point of view at the same time is not an easy task because the requirements for each of these three optimization criteria are often conflictive (e.g. for good visual comfort, high illuminances are often needed, but these can lead to elevated electricity consumption and are thus negative from an energetic point of view). To discuss how Sustainable Lighting Solutions (i.e. lighting solutions that are optimal from an energetic, visual and non-visual point of view) can be achieved is the overall objective of this thesis. This overall objective is visualized in Figure 1.1.

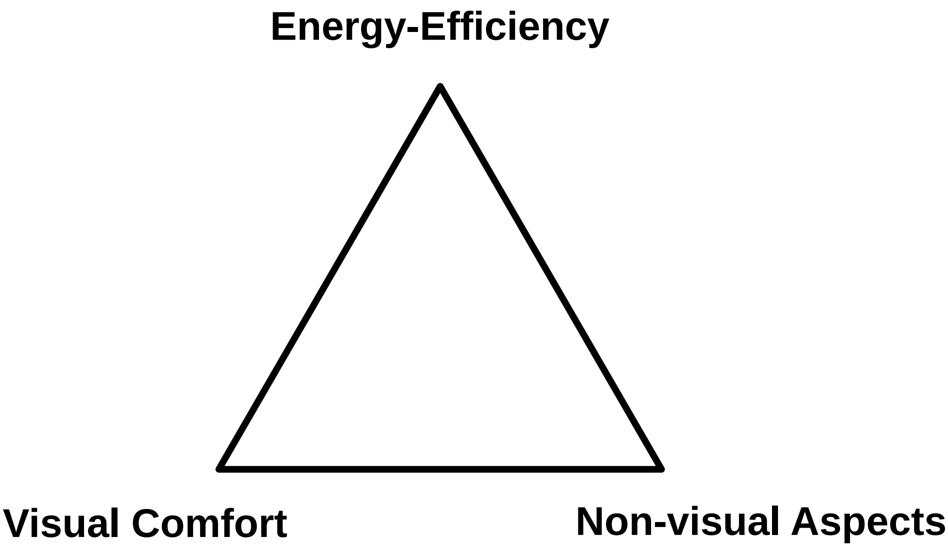


Figure 1.1: Objective of the Thesis. - The Figure visualizes the overall objective of this thesis: to discuss how Sustainable Lighting Solutions (i.e. lighting solutions that are optimal from an energetic, visual and non-visual point of view) can be achieved.

1.1.1 Electricity Consumption in Buildings due to Lighting

Large fractions of today's buildings' electricity needs are due to electric lighting: Hinnells (41) for example states that "*lighting in domestic and commercial sectors accounts for around 16% of all UK electricity demand*". Li and Lam (60) as well as Li et al. (61) suggest that artificial lighting can account for 20-30% of a typical non-domestic building's electricity consumption. Wen et al. estimate that in the US, "*roughly 40% of electricity consumption in commercial buildings is attributable to lighting*" (114). In 2009, the German Federal Ministry of Economics and Technology, together with several research institutions, has published a report which points out that almost 45% of the electricity consumption in German office buildings are due to lighting (92). According to Franzetti et al., "*it is generally assumed that about 30% of the energy consumption of office buildings come from artificial lighting*" (30). In 2007, Jenkins and Newborough wrote that "*the energy consumption of lighting in buildings is a major contributor to* *carbon emissions, often estimated as 20-40% of the total building energy consumption*" (50). Krarti et al. had already put forward that 25-40% of the "energy consumption" in US commercial buildings is due to artificial lighting (56). Even if those estimations are difficult to verify and might not be completely consistent (the difference between 20% of a building's *electricity consumption* and 40% of its *"energy consumption"* is likely to be huge in most cases), these figures lead to one important finding: around the world, the scientific community seems to agree that discussing the articial lighting loads of buildings is extremely important and that energy-efficient lighting solutions have to be adopted. It is furthermore important to understand that not only the elevated artificial lighting loads *as such* are problematic: Aries and Newsham point out that the demand for artificial lighting usually peaks at times of high electricity demand (i.e. during peak load) when fossil fuel consuming power generators are used to meet these electricity needs (9). Electric lighting therefore has a major impact on the CO_2-footprints of buildings.

1.1.2 Daylighting

We can thus assume that about one third of an office building's electricity consumption is caused by electric lighting. On the other hand, daylight generates outdoor illuminances that often exceed the required illuminances for office lighting by some orders of magnitude. Making daylight more available in office buildings can therefore contribute to important energy savings. In addition to that, it can enhance the occupants' performance and wellbeing (108).

Over the last decades, various daylighting technologies have been developed, some of them having proven to be highly efficient (91). Performance assessments (obtained through simulation, measurements and user satisfaction assessments) have recently become more and more available. Lightpipe applications for example (which typically collect daylight through heliostats or passive openings on a building's roof and then redistribute it into the building) (63; 71; 74; 86; 98) and façade-integrated daylighting systems (5; 32; 75; 87; 120; 121) have recently been subject to detailed analysis and have confirmed their energy saving potential. Thermotropic glass (48), solar film coatings (62), electrochromic windows (81) and various other applications of complex fenestration systems (100) are intensively discussed among scientists around the world.

One major problem often occurring in daylit office rooms is over-provision of daylight flux near the window. The rear of the room, on the other hand, often appears gloomy. Consequently, occupants working next to the windows are often disturbed by glare. They therefore lower the solar blinds and electric lighting becomes necessary although the room could be completely daylit if the daylight flux was properly distributed within the room. Daylighting systems therefore not only have to be able to provide office rooms with sufficient daylight fluxes, they must also be able to avoid discomfort glare.

Anidolic Daylighting Systems (ADS) (91) are one type of very effective façade-integrated daylighting systems; they are designed following the principles of non-imaging optics (113). ADS typically collect a maximal flux of daylight outside the building and redistribute it internally with a minimum number of reflections. They are specially designed to reduce the daylight flux that reaches the area next to the window and to raise the daylight flux to the rear of the room. Glare and gloomy areas can be avoided in this way.

1.1.3 Visual Comfort and Performance

However, electricity consumption and energy-efficiency are not the only topics to consider when it comes to designing appropriate lighting scenarios for buildings: good visual comfort and visual performance are of course equally important (109). In order to guarantee an appropriate visual comfort in office rooms, the horizontal illuminances (especially on the workplanes) must be sufficiently high, the light on the workplane has to be properly distributed (appropriate illuminance uniformities) and discomfort glare (e.g. from luminaires or through windows) must be avoided. It is obvious that it is not an easy task to reach the two objectives "energy-efficiency" and "good visual comfort/performance" at the same time. A significant reduction of the lighting load will in most cases result in lower illuminances and might therefore have a negative influence on the occupants' visual comfort and visual performance. However, it is not an *impossible* task: Akashi and Boyce (2) for example have shown ways to reduce the illuminances in an office environment without significantly jeopardizing visual comfort.

1.1.4 Non-visual Aspects of Light

Light is not just for vision: it is the most important synchronizer between external time and the endogenous biological clock in humans. Light has been identified as a major zeitgeber to the body's internal clock many years ago (110). For a very long time, scientists believed that the human body's only two receptors for light were the skin and the visual system, in particular the rods and cones of the eye (105). In 1999, Freedman et al. have made a thrilling discovery: they found that mice lacking rods and cones still responded to light as a zeitgeber for their internal clock. They came to the conclusion that there might be a third type of photoreceptor cell in the eye in addition to rods and cones (31). Berson et al. have identified melanopsin-containing retinal ganglion cells as this third type of photoreceptor in 2002 (11).

Since then, it has become ever more clear that, beside rods and cones, there is an additional so-called non-image-forming circadian photoreceptor in the human retinal ganglion cells (with a photopigment most sensitive to blue wavelengths), triggering many physiological and neurobehavioral responses. In particular, it has been shown that in humans, the circadian sensitivity to light as assessed by nocturnal melatonin suppression is highest in the blue range of visible light between 446-483 nm (13; 14; 101; 110). Melatonin is a hormone that has a major influence on our sleep-wake pattern. During periods of darkness, our body produces melatonin; this makes us feel tired and helps us to fall asleep. Bright light (especially of short wavelengths) suppresses the melatonin secretion, with the effect of us being more alert and being able to concentrate better.

Brainard et al. have suggested an action spectrum for melatonin suppression in humans in 2001 (13). Figure 1.2 shows this spectrum, with a peak in the bluish region of the electromagnetic spectrum at 464 nm. In analogy to the $V(\lambda)$-curve, which describes the human eye's photopic response to light, this action spectrum has recently been referred to as the $c(\lambda)$-curve (45). It can be used to quantify the non-visual effects of light on humans.

Three important key properties of the circadian system are:

1. Circadian rhythms continue in the absence of light/dark cycles with an endogenous period close to but not exactly 24 hours.

2. The exact period length is a function of prior environmental conditions.

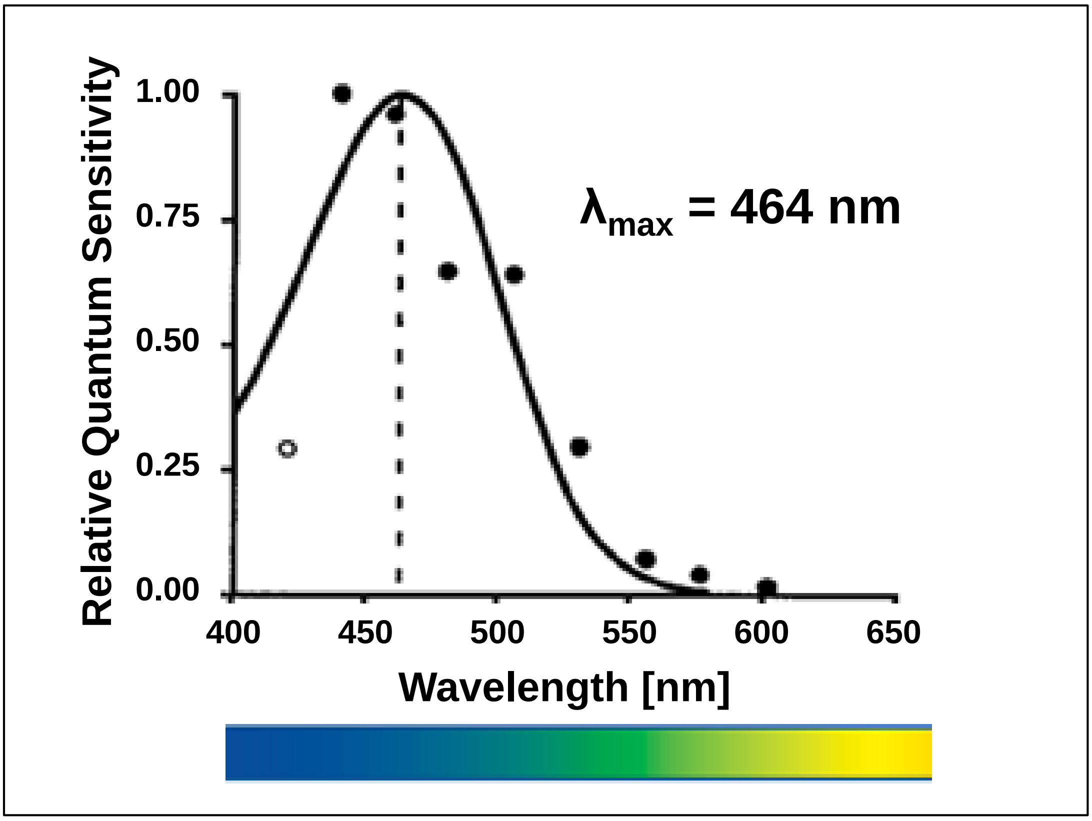


Figure 1.2: C(λ)-curve. - Action spectrum for melatonin suppression in humans, with a peak in the bluish region of the electromagnetic spectrum at 464 nm. In analogy to the V(λ)-curve, which describes the human eye's photopic response to light, this action spectrum has recently been referred to as the c(λ)-curve (45). It can be used to quantify the non-visual effects of light on humans. Figure adapted from (13).

3. Circadian phase can be reset by an appropriate exposure to light.

Based on these key properties, human physiology is further dependent on illuminance and irradiance levels, as well as the spectral composition of light, the time of day of exposure, the impact of age, photoreceptor sensitivity and prior light history (adaptation).

Possible consequences of these recent discoveries for **light therapy** are manifold: better treatment for depression (83; 110), bipolar disorder ("manic-depressive" persons) (117), dementia and Alzheimer (102), jet-lag (12), insomnia and the chronic fatigue syndrome (CFS) might become available in the near future due to better understanding of the human circadian clock's functioning and possible ways to influence it through controlled administration of light and darkness.

But not only persons suffering from the above diseases will benefit from the ever better understanding of non-visual effects of light on the human body: there are also major consequences when it comes to "keeping healthy people healthy" (105). Veitch (108), Webb (112) and van Bommel (105) have described possible consequences for **workplace improvement**. They all agree that the possibility to control alertness, concentration, fatigue, stress and mood through controlled administration of the right light at the right times could have a positive influence on health and well-being. Cancer prevention (97) and health during space flights (33) are two other fields to which the recent research results concerning non-visual effects of light can be of major interest.

The scientific community agrees that more research is needed in this very interesting field, especially concerning appropriate lighting designs for office buildings. Webb writes that "*..light has other implications for our health and well-being which merit consideration in the lighting, and use of daylighting, within buildings*" (112), and van Bommel concludes that "*...we are now able to start defining lighting situations that ensure that healthy people remain healthy...*" (105). Veitch underlines that "*Good quality lighting demands simultaneous resolution of requirements that sometimes conflict...*" (108).

1.1.5 Need for Integrating Work

Energetic aspects of office lighting and possible solutions for reducing elevated artificial lighting loads in office rooms have thus been a matter of worldwide academic discussion for many years. Questions on visual comfort and visual performance have also been playing an important role in these discussions. Quite recently, the "office lighting community" has started to discover the recent findings from the field of chronobiology and seems to agree that these findings should have an impact on the design of future office lighting scenarios. In her doctoral thesis "Human Lighting Demands - Healthy Lighting in an Office Environment", Ariës has attempted to develop "*...lighting concepts and system solutions that meet both visual and non-visual demands of humans.*" (8). In late 2009, the scientific journal "Lighting Research and Technology" has published a Special Isssue "Good Lighting with Less Energy", in which van Bommel has empahsized the need for integrating work: "*For lighting, sustainability can be defined as: balancing the positive effects of lighting on living beings with the negative impacts of that lighting on the environment. This definition means that energy efficient lighting should go hand in hand with providing safety, security, performance, health and well being.*" (106).

Detailed discussions on how to design office lighting scenarios that are at the same time energy-efficient, comfortable and optimized from a non-visual/chronobiological point of view are, however, still largely lacking. Filling a part of this lack was the objective of this doctoral thesis.

1.2 Constitutive Hypothesis and Research Work Strategy

The constitutive hypothesis of the doctoral thesis is the following:

> *Light has important visual and non-visual effects on humans and high-quality light should therefore be supplied inside buildings in sufficient quantities. On the other hand, artificial lighting is responsible for a large part of an office building's electricity needs. It is thus important to take into account at the same time visual comfort, non-visual effects of light and energy efficiency when designing lighting systems for office buildings.*

Based on this constitutive hypothesis, a research strategy that used an ADS-equipped test office room as a starting point has been followed. It was envisaged to develop a Sustainable Lighting Solution for this test office room, i.e. a lighting solution that is optimized in terms of energy-efficiency, visual comfort and non-visual (or chrono-biological) aspects. In parallel, it was seen as desirable to investigate the potential use of new lighting technologies, like Light Emitting Diodes (LED) or Organic Light Emitting Diodes (OLED), to achieve this main research objective. Furthermore, it was seen as desireable to initiate first applied chronobiological studies at the laboratory and eventually use the results to optimize the lighting design for the test office room. It was planned to generalize the results of this research in a last step in order to discuss possibilities for sustainable lighting in different contexts.

Figure 1.3 gives an overview of this research work strategy.

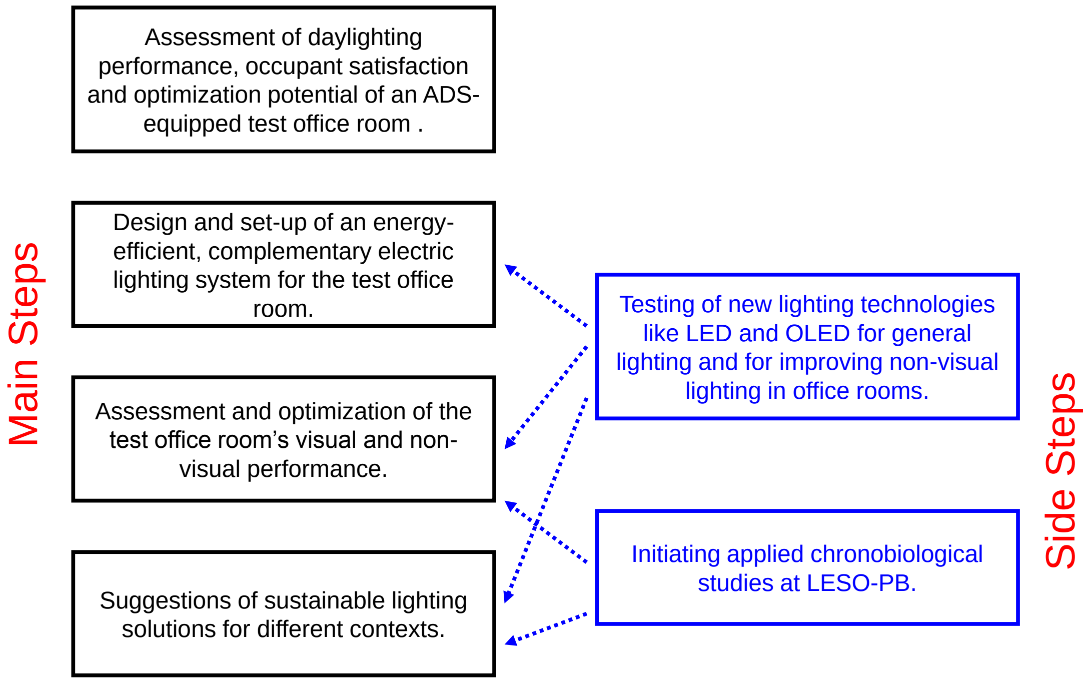


Figure 1.3: Research work strategy. - The Figure shows the research strategy of this doctoral thesis, composed of four main steps and two side steps.

1.3 Thesis Outline

Chapter 2 of this thesis gives an overview of the ADS-equipped test office room at the LESO-PB and its daylighting performance. It then presents the results of an occupant satisfaction assessment carried out amongst 23 office workers in similar office rooms.

Based on these results, optimization potential for this type of ADS is discussed. Even if the discussions in Chapter 2 reveal that sufficient daylight is available in the test office room during large parts of most working days, complementary electric lighting is still needed. Chapter 3 therefore gives an overview of the currently available technology for general lighting in office rooms. Computer simulations, which have been carried out during the described doctoral thesis in order to compare different options for complementary, energy-efficient electric lighting solutions for the test office room, are described in Chapter 4. Chapter 5 then describes how a highly energy-efficient electric lighting system has been installed in the test office room. The results of visual comfort and performance tests carried out under the new lighting scenario with twenty human subjects are presented and discussed in detail in Chapter 6. Chapter 7 then discusses the non-visual (or chronobiological) properties of the ADS-equipped test office room. Based on these discussions, an energy-efficient LED-luminaire for enhancing the chronobiological properties of office lighting scenarios has been developed. Chapter 8 describes the development of the device and compares its performance with that of fluorescent lamps for chronobiological lighting. Chapter 9 explains how a Controlled Lighting Conditions Exposure Room for applied chronobiological studies has been set up at the LESO-PB. Furthermore, it gives an overview of a first chronobiological study (currently running at the laboratory), that has been initiated during this doctoral thesis and presents some interesting preliminary results of this study. Two case studies, presenting scope for enabling Sustainable Lighting Solutions in other types of buildings and at other geographical locations, are finally presented in Chapter 10. The final discussion in Chapter 11 is followed by an Appendix, in which the most important devices, methods and questionnaires used during this doctoral thesis are described.

2

The Anidolic Daylighting System

2.1 Description of the Installation

The south-facing side of the LESO solar experimental building (LESO building), located on the campus of the Swiss Federal Institute of Technology in Lausanne/Switzerland (EPFL), is equipped with a façade-integrated Anidolic Daylighting System (ADS) (5; 121). The south elevation of the LESO building is shown in Figure 2.1. This southern façade is composed of 18 distinct ADS (six per floor of the building) which illuminate 14 office rooms, one seminar room and one mechanic's workshop.

Figure 2.2 shows a schematic overview of one of these ADS as well as a detailed façade sketch. The system collects direct and diffuse daylight issued from the sun and the sky vault through a zenithal collector, composed of an anidolic element covered by a double glazing. Once the daylight flux has entered the system through the double glazing, it is redirected onto the room's diffuse ceiling by the anidolic element. From there, it is evenly distributed throughout the entire room.

This system has two main advantages compared to a conventional vertical window:

1. The system blocks out large parts of the direct component of the daylight flux that would reach the room's window section through a vertical glazing. It therefore reduces the workplane illuminance as well as the luminances of objects and walls in this area. This contributes to reduced glare risks and improves visual comfort for occupants working next to the windows.

Figure 2.1: The Anidolic Daylighting System - This photograph shows a southern view of the LESO building with the façade-integrated Anidolic Daylighting Systems (ADS).

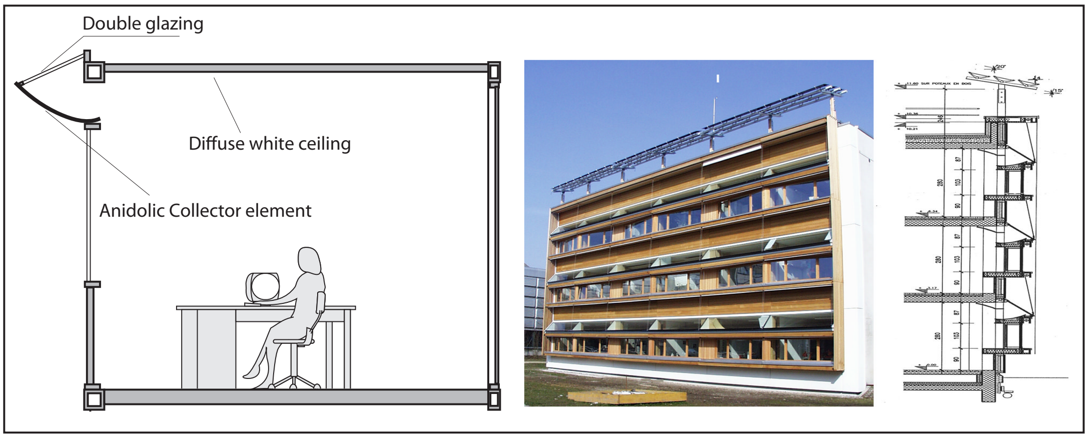


Figure 2.2: Schematic overview - The figure shows a schematic overview of one of the ADS-equipped LESO-PB office rooms (left) and detailed façade sketch (right).

2. The blocked daylight flux is not rejected but redirected towards the room's diffuse white ceiling. From there, it is distributed comparably evenly within the room. The results are higher workplane illuminances in the center and rear sections of the office room compared to the standard vertical window case.

The daylight performance of a given location in a specific office room can be characterized by the so-called daylight factor ($D(x)$):

$$D(x) = \frac{E_i(x)}{E_{he}} \quad [\%] \tag{2.1}$$

In the above equation, E_{he} stands for the external horizontal illuminance (measured in Lux) and $E_i(x)$ stands for the internal horizontal illuminance at the distance x from the window (measured on the workplane, i.e 75 to 80 cm above floor level). Altherr and Gay have compared the daylight factors inside the ADS-equipped office rooms at the LESO building to an identical office room equipped with a conventional double glazing. They reported daylight factors of 6.5% next to the windows, 5% in the centre of the room (2 m from window) and 2% at the rear (4 m from window) versus daylight factors of 11%, 3.5% and 1% in the corresponding parts of a room with a conventional double glazing (5).

The overall performance of the LESO building is continuously monitored via a European Installation Bus System (EIB system). The system monitors and stores external data such as radiation and illuminance, temperature and wind speed as well as internal data such as horizontal workplane illuminance, blind movements and positions or occupancy levels. A detailed description of the system and the recorded data over the last few years is far beyond the scope of this Thesis, such questions having been addressed in various other publications (37; 65). At this point, we will only take a look at the horizontal workplane illuminances measured in a test office room within the LESO building in order to get an idea on to what extent the lighting system in this office room is able to meet the lighting specifications for office lighting (such as workplane illuminances for instance).

Figures 2.3 and 2.4 show the annual workplane illuminance data within the considered test office room for the entire year of 2006. For every month of the year, the illuminance measurements have been sorted in 1-hour bins (e.g. from 09:00 to 10:00). Various interesting observation can be made from looking at Figures 2.3 and 2.4:

- Between 10:00 and 16:00, the medians of the binned illuminances were almost always higher than 1000 Lux. This indicates that "not enough light"-situations are rare during large parts of a normal working day in this type of office.

- The summer months of July, August and September are an exception from this observation with substantially lower illuminance medians. One possible reason for this surprising finding might be that the office occupants often lowered the window blinds more often than during the other months in order improve visual comfort (i.e. glare through direct sunlight) and thermal comfort (i.e. important heat gains from direct sunlight).

- If the illuminance medians drop to values lower than 500 Lux, this happens mostly before 09:00 and after 17:00. This indicates that electric lighting is most likely to be in use in the mornings and the evenings in such ADS-equipped office rooms (depending on the occupancy).

- During almost all months, very low illuminances (i.e. less than 100 Lux) occurred in the office room, even in summer and in the middle of the day (see outliers in August 2006 for example). This indicates that occupants not always switch on the artificial lighting installation instantaneously when the workplane illuminances drop to (a priori unacceptably) low values. This behavior has already been described by Lindelöf and Morel in 2006 (65).

- No illuminance values of more than 3500 Lux have been measured. This is probably due to the measurement range of the ceiling-mounted luminance meter (38) and can be considered to have no impact on the considerations presented in this Thesis.

In order to better compare the data displayed in the boxplots of Figures 2.3 and 2.4, the corresponding average workplane illuminances have been calculated for every time bin. The result is shown in Figure 2.5. Winter months (i.e. January to March) are plotted in blue, spring months (i.e. April to June) in green, summer months (i.e. July to September) in red and autumn months (i.e. October to December) in black. The required minimum illuminance (300 Lux) and the desirable illuminance (500 Lux) (94) are equally plotted in Figure 2.5. One can observe that during the entire year, the average workplane illuminances were largely sufficient from 09:30 to 16:00. Before 09:30, the average workplane illuminances were ranging for most months between 300 Lux and 500 Lux; for the months of December and January they were even lower than 300 Lux before 09:00. After 16:00, the average workplane illuminances dropped rapidly to values lower than 300 Lux in November, December and January. For all other months, the average workplane illuminances were higher than 500 Lux until at least 17:00.

The workplane illuminances plotted in Figures 2.3 to 2.5 are of course not exclusively due to daylight: the ceiling-mounted luminance-meter, on which the measurements of the illuminance data are based (65) senses both day- and artificial light. Figure 2.5 doesn't make it possible to determine at which times additional artificial lighting was switched on in the room.

The following Figures provide information on the number of times in 2006 when office occupants turned on electric lighting. Light switching actions are permanently monitored by the building integrated EIB system. Overall, artificial lighting in this test office room was manually switched on 119 times in 2006 by one of the office's occupants. Figure 2.6 shows the number of light switching-ons that occurred during each month of 2006. It is obvious that the most switching-ons occurred in January,

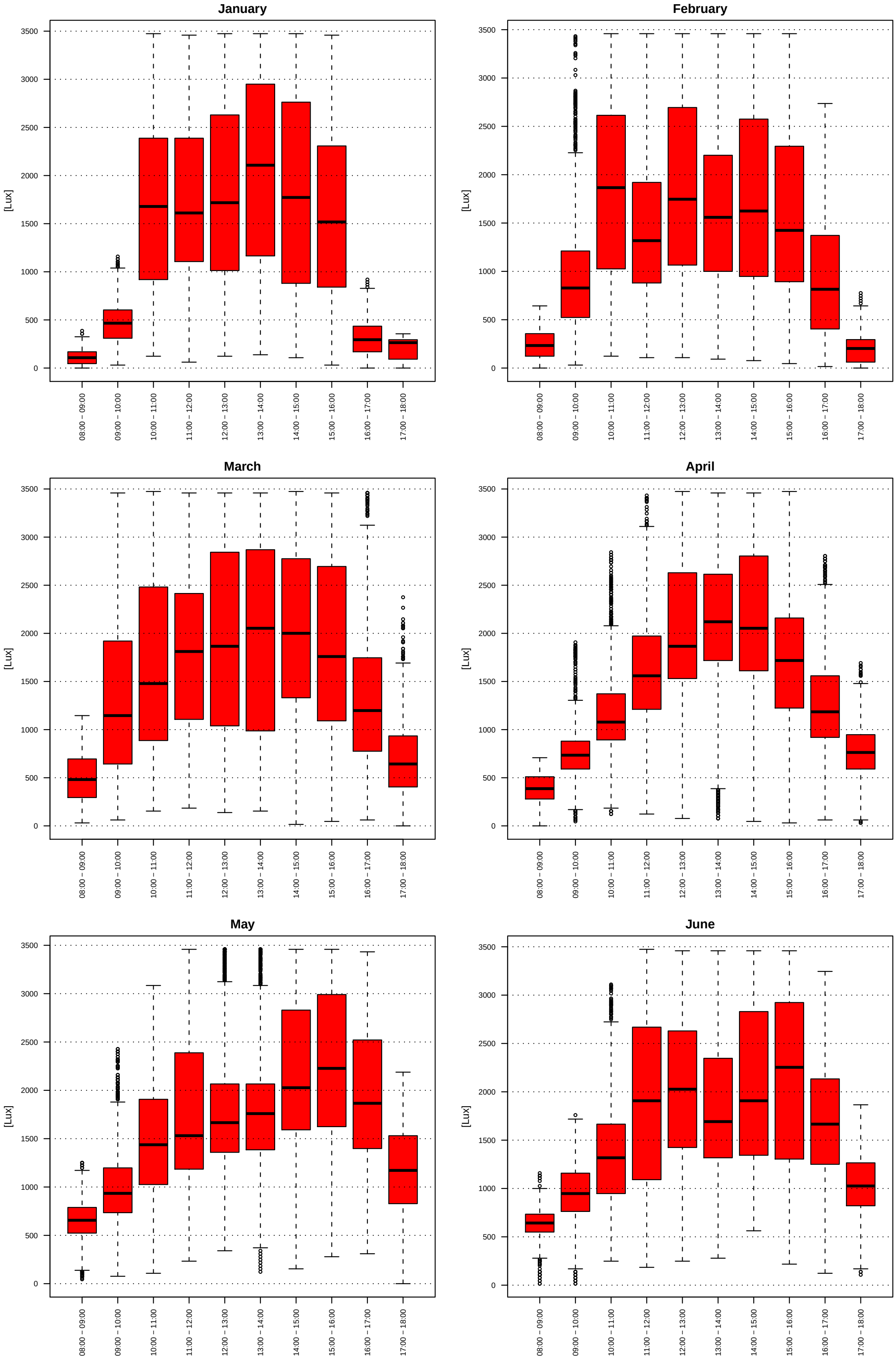


Figure 2.3: Boxplot of workplane illuminances 2006 - January to June. -

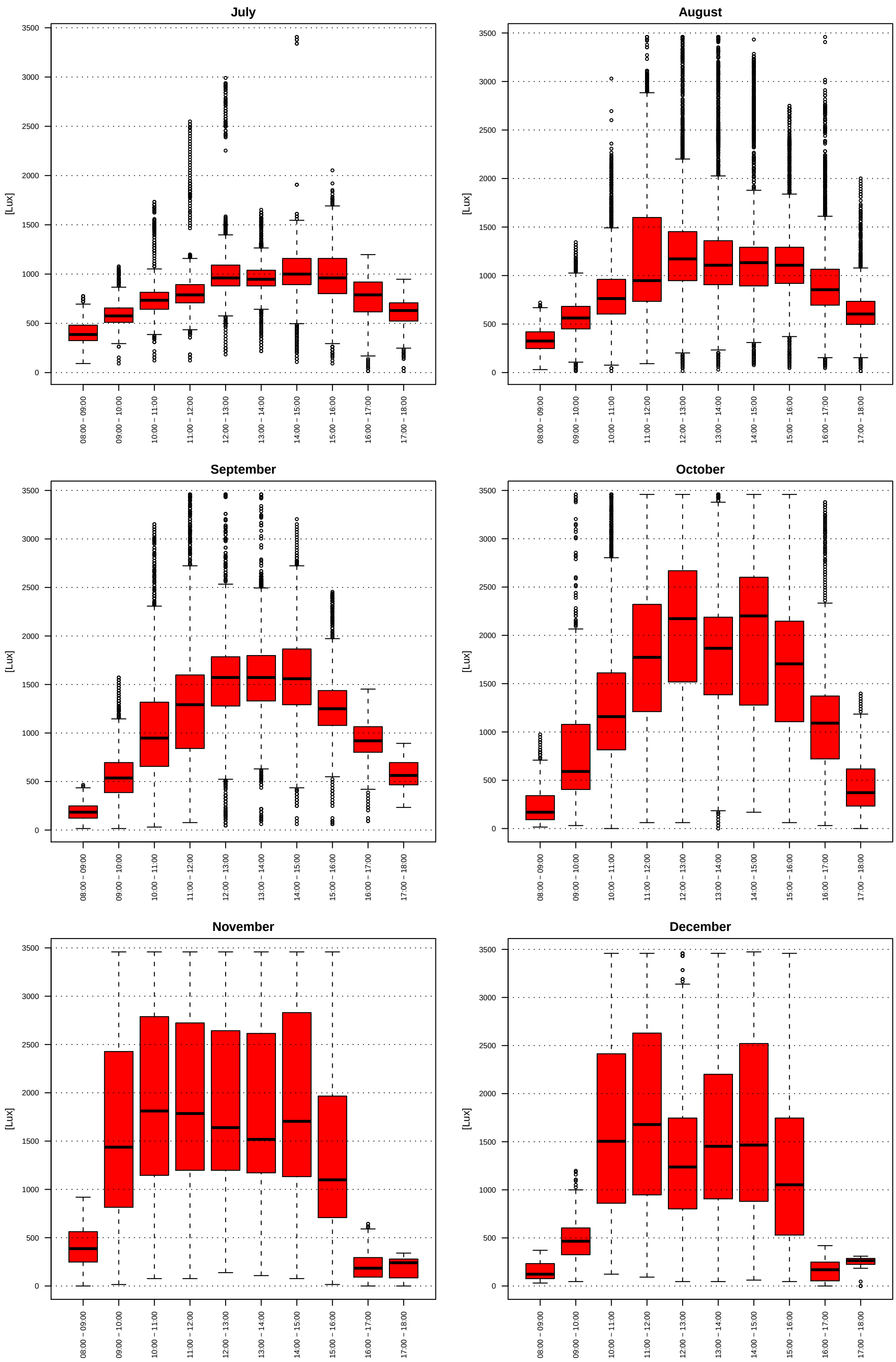


Figure 2.4: Boxplot of workplane illuminances 2006 - July to December. -

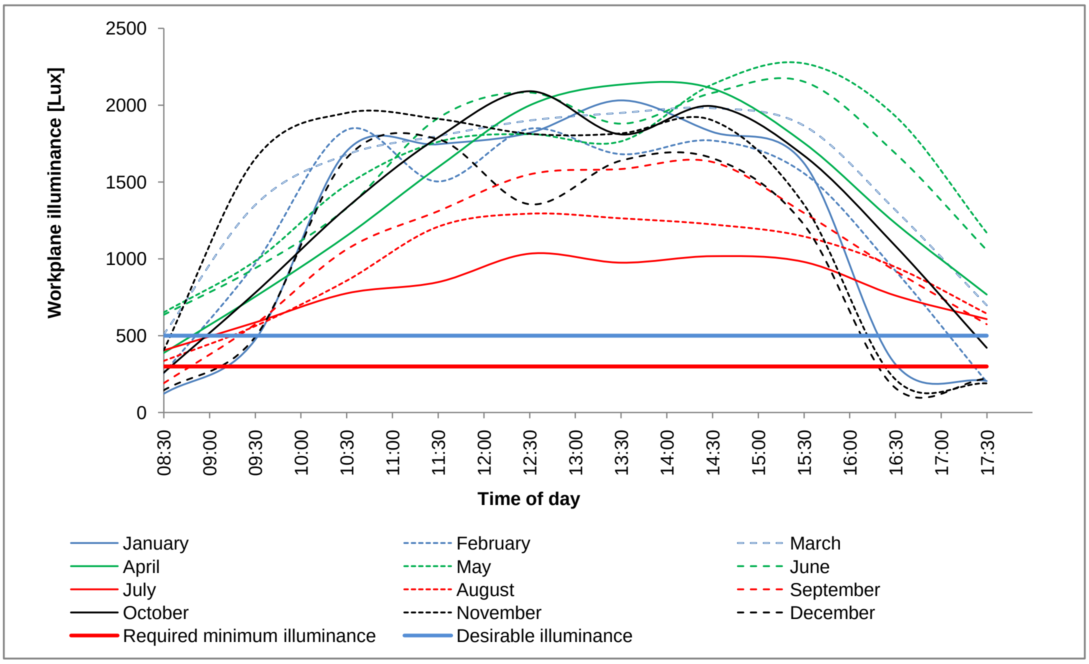


Figure 2.5: Annual workplane illuminance data in office room LE001. - The figure shows the hourly binned workplane illuminances for every month of 2006.

February, October and November. The comparably low value in December is due to maintenance work on the EIB system during that period. From March to September, less than 10 switching-ons per month were recorded.

Figure 2.7 shows the number of light switching-ons for 2-hour time bins. More than 77% of all switching-ons occurred after 16:00. Even if the light switching data of this office room might not be completely representative for the entire LESO building, these results suggest that most switching actions occur after 16:00 and during the autumn and winter months. This, in turn, means that a large fraction of the illuminance data displayed in Figure 2.5 is due to daylight (especially close to noon and during the spring and summer months).

These observations indicate that the ADS displayed in Figure 2.2 offers a high quality natural illumination during large parts of normal office hours over the entire year: this is particularly true as much as the workplane illuminance (i.e. "the amount of available light") is concerned. Complementary artificial lighting is mostly needed during evening hours in the autumn and winter months.

However, the performance of a daylighting system cannot be assessed only on the

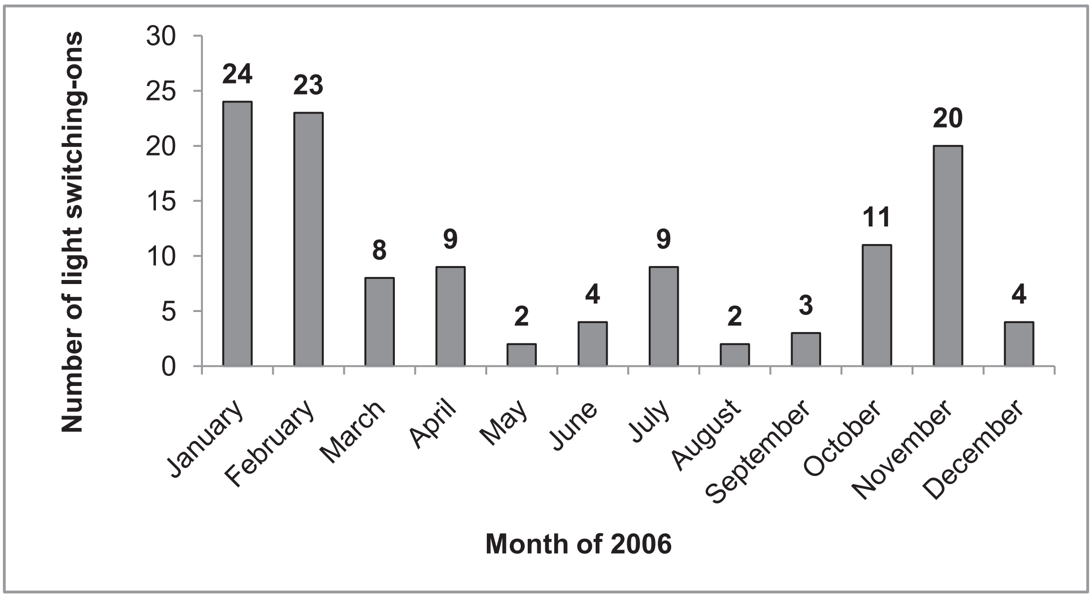


Figure 2.6: Number of light switching-ons that occurred during each month of 2006. - The figure shows the absolute number of light switching-ons that occurred during each month of 2006.

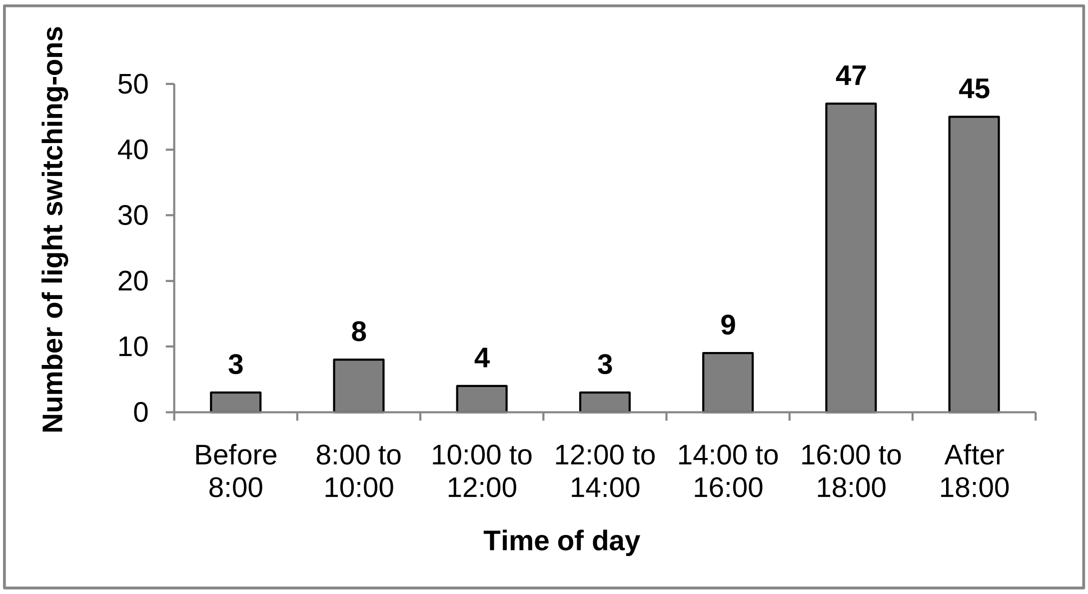


Figure 2.7: Number of light switching-ons for 2-hour time bins. - The figure shows the two-hourly binned light switching-ons in the test office room for the entire year of 2006.

basis of achieved workplane illuminances. The system must also make it possible to reduce the risk of glare (occurring through daylight overprovision for instance). In the case of the LESO building, glare control is carried out by means of diffusive-type textile blinds, two of which (one lower and one upper blind) are associated with each ADS (see Figure 2.8). The occupants manually operate these blinds at times when glare situations and too high illuminances occur. A detailed discussion of this blind configuration is given in Section 2.3.

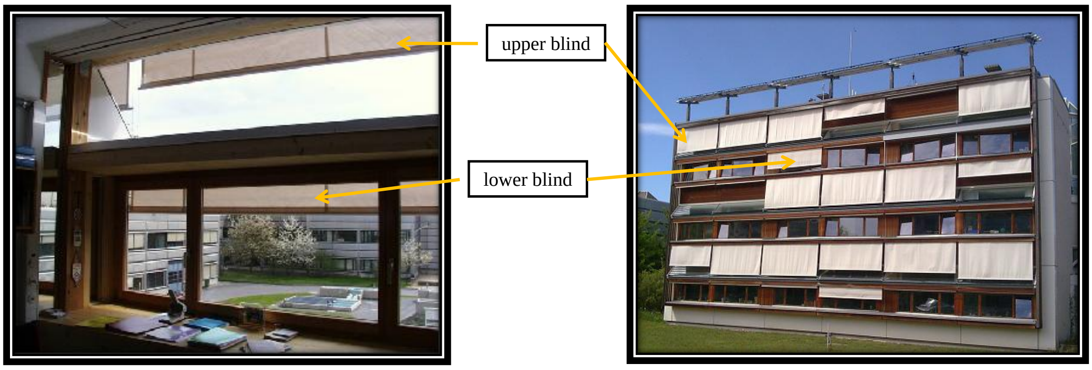


Figure 2.8: Fabric blinds for blocking out direct sunlight. - The figure gives a first idea of the blind configuration in place at the LESO building. Each office is equipped with one upper and one lower external blind.

Façade-integrated daylighting systems not only have to create a comfortable indoor lighting environment: an appealing external building appearance must also be offered. ADS are not only able to meet common aesthetic requirements of building design. They can even be used to emphasize a building's façade. The anidolic façade of the LESO building is well balanced from an architectural point of view. Its zigzag movement allows a clear distinction between the windows themselves and the anidolic elements (5). Another example of successful application of façade-integrated ADS is the refurbished building project of "Vakantiefonds Bouw" in Brussels/Belgium, suggested by Samyn and Partners in 1996 (15).

It is not yet possible to quantify the cost of ADS in a reasonable way. Nevertheless, it can be assumed that a commercial façade-integrated ADS should be no more than 20 to 30% more expensive than an average façade, depending on material and construction costs. A discussion on cost reduction during ADS design is given in Chapter 10 of this

Thesis. Costs for system maintenance of such systems are low, the ADS being a passive device; a bi-annual cleaning of the system is by far sufficient (66).

2.2 Occupant Satisfaction

2.2.1 Occupant satisfaction assessment method

During a study carried out in 2007 within the framework of this doctoral thesis, the occupant satisfaction within the LESO building was assessed by means of a Post Occupancy Evaluation (POE) (72). The objective was not the development or the validation of a complex assessment method for occupant satisfaction in office buildings, but rather the identification of "weak spots" within the described ADS at the LESO building and the discussion of possible ways to deal with them. It was decided to first assess the occupants' satisfaction with different aspects of their office lighting using a simple questionnaire. Twenty-nine persons working inside the building at the time of the study (May and June 2007) were addressed. The questionnaire had to be easy to understand and quick to fill out in order to maximize the number of returned questionnaires. A simple and reliable questionnaire-based assessment method for occupant satisfaction regarding office lighting (Office Lighting Survey - OLS) was presented by Eklund and Boyce in 1996 (25). Many questions within the OLS only allow an answer on a symmetrical, two-stage "Yes/No" scale. Akashi and Boyce, as well as Ramasoot and Fotios, have more recently used slightly modified versions of the OLS (2; 80). The original OLS has been adapted to the specific situation of the LESO building: a questionnaire with a mix of general, daylighting-specific and artificial lighting-specific statements was set up for that purpose. Occupants were asked to rate their agreement with each statement on a symmetric answering scale (i.e. without neutral choice) in order to avoid possible interpretation problems associated with neutral choices. In order to make the questionnaire more sensitive, a four-stage answering scale was used rather than the two-stage answering scale of the original OLS. This means that for each statement, occupants had the possibility to answer "1" (="yes"), "2" (="rather yes"), "3" (="rather no") or 4 (="no"). These four possible choices were assumed to correspond to 100%, 75%, 25% and 0% of agreement with the respective statement. Figure 2.9 shows the setup of the questionnaire; the entire questionnaire can be found in Appendix C.1.

(4)	Ce bureau me semble trop sombre.	OUI 1 2 3 4 NON
(5)	Il n'y a pas assez de lumière pour bien effectuer les différentes taches.	OUI 1 2 3 4 NON

Figure 2.9: Excerpt from the modified OLS used in the assessment. - The figure shows an excerpt of the OLS used during the POE occupant assessment in the LESO building in 2007.

The data collected with this four-stage answering scale can easily be transformed into "two-stage data" by simpling counting all "rather yes" as "yes" and all "rather no" and "no". The developed four-stage answering scale OLS thus offers the same possibilities as the initial OLS (25) but adds additional preciseness and flexibility. This flexibility has been made use of in Chapter 6 of this Thesis.

2.2.2 Results of occupant satisfaction assessment

Tables 2.1 and 2.2 show 18 statements of the optimized OLS directly or indirectly linked to the ADS and its usage. The average agreement is given for each statement, as well as a decision of the status: "OK" means that the found agreement is located close enough to the optimal agreement (100% for some questions, 0% for others). It was decided that average agreement values that differ no more than 12.5% from optimal agreements are acceptable. In turn, values that do differ more than 12.5% from optimal agreements need checking because they might indicate the presence of critical lighting situations. The choice of a 12.5% threshold is not arbitrary but follows the following logic: If we take as an example a statement where the optimal agreement is 100%, then any average agreement value that equals 87.5% or more (i.e. differs no more than 12.5% from 100%) is closer to the optimal agreement (in this case: 100%) than to an intermediate agreement value (in this case: 75%). Thus, the choice of a 12.5% threshold makes sense.

Figure 2.10 gives an idea of the standard errors associated with the different average agreement values obtained during the described occupant satisfaction assessment.

At the end of the questionnaire, the study participants were asked to compare the office lighting situation within the LESO building to lighting situations in office rooms of

No	Statement	Agreement [%]	Status
1	I like the lighting in my office.	89.13	OK
2	In general, the lighting in my office is comfortable.	86.96	CHECK
3	The installations in my office (windows, blinds, daylighting system, electric lighting system) allow me to create at all times a lighting situation under which I can properly see my work.	89.13	OK
4	My office often seems too bright.	33.70	CHECK
5	My office often seems too dim.	17.39	CHECK
6	I often have the impression that there is too much light on my workplane.	21.74	CHECK
7	I often have the impression that there is not enough light on my workplane.	14.13	CHECK
8	I often experience glare problems (contrasts too strong) in my office.	29.35	CHECK
9	Most of the time, I can easily resolve temporarily occurring glare problems (easy use of blinds).	84.78	CHECK

Table 2.1: Statements 1-9 - Statements directly or indirectly linked to the daylighting system and its usage, together with the corresponding average agreements and status, as used during our POE.

No	Statement	Agreement [%]	Status
10	I think that it is important to have natural light inside a building.	97.83	OK
11	*For me in particular*, it is important to have natural light in the office where I work.	92.39	OK
12	Visual contact with the outside world from a workplace seems important to me.	97.83	OK
13	I personally have visual contact with the outside world when sitting at my workplace.	98.91	OK
14	There is enough natural light in the office where I work.	98.91	OK
15	There is too much natural light in the office where I work.	19.57	CHECK
16	The natural light is well distributed in the office where I work.	86.96	CHECK
17	I can observe the changing of outside weather conditions (sun, clouds, rain etc.) from my workplace.	98.91	OK
18	The light in my office tells me the approximate time of day.	82.61	CHECK

Table 2.2: Statements 10-18 - Statements directly or indirectly linked to the daylighting system and its usage, together with the corresponding average agreements and status, as used during our POE.

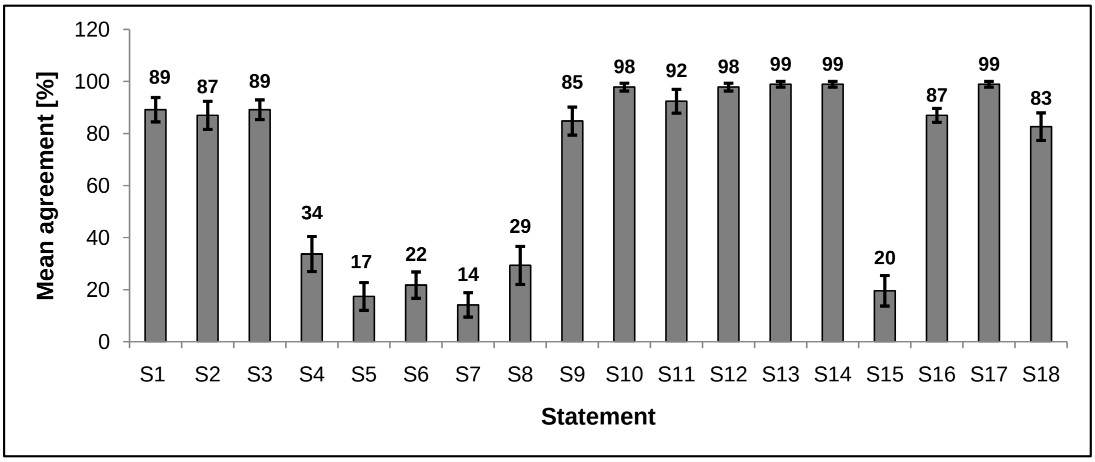


Figure 2.10: Mean agreements with statements S1 to S18. - The figure visualizes the results of the occupant satisfaction assessment concerning the ADS at the LESO building. Values are ±SE.

other buildings where they had previously worked. Figure 2.11 shows the percentage of occupants that have answered "rather better", "about the same" and "rather worse". Almost 80% of all study participants feel that the lighting environment within the ADS-equipped office rooms in the LESO building is better compared to those of their previous office rooms.

2.2.3 Discussion

The four-stage answering scale used in the modified OLS can be mathematically described by:

$$R_{x,n} \in \{0, 0.25, 0.75, 1\} \tag{2.2}$$

where $R_{x,n}$ stands for the respective answer to statement x by occupant n. As mentioned before, an optimal answer $R_{x,opt}$ was also defined for each statement. In some cases, this optimal answer would correspond to 100% of agreement (e.g. when the occupant rates his agreement with the statement "In general, the lighting in my office is comfortable."). In other cases, the optimal answer $R_{x,opt}$ would correspond to 0% of agreement (e.g. when the occupant rated his agreement with the statement "My office often seems too bright."). We can therefore write

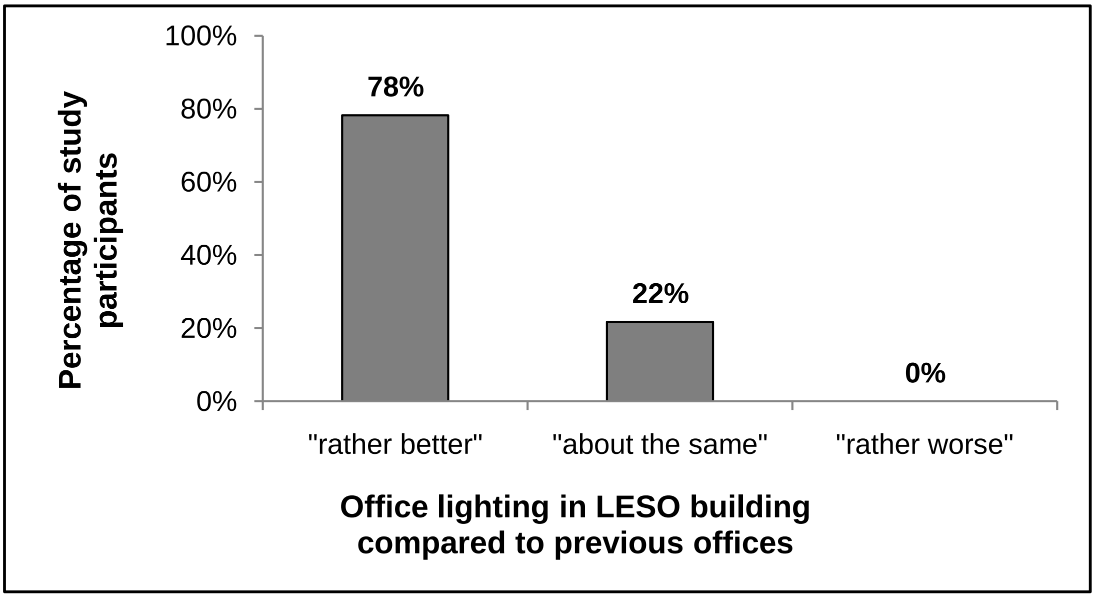


Figure 2.11: LESO building compared to other buildings. - The figure shows the percentage of occupants who think that the lighting conditions in the LESO building are "rather better", "about the same" and "rather worse" than those of their previous office rooms.

$$R_{x,opt} \in \{0, 1\} \tag{2.3}$$

where the appropriate value for $R_{x,opt}$ has to be chosen by the experimenter for each statement. In the modified OLS, every single statement can be associated with one common critical lighting situation often experienced in office lighting environments (e.g. glare occurrence, "not enough light"-situations, missing windows, etc.). As previously mentioned, the objective of this assessment was to identify the "weak spots" of the ADS installed in the LESO building. In other words, we wanted to find out, which of the commonly experienced critical lighting situation in office rooms were the most annoying to LESO building occupants. In order to quantify the specific annoyance of each of these specific problems within the building, a Mean Annoyance Value (MAV) (68) was calculated for each statement. MAVs are commonly used for quantifying the perceived annoyance of different coding artifacts in short video sequences (122) and are typically adapted to the specific needs of a study. For the visual comfort assessment described here, the MAV has been defined as follows:

$$MAV_x = \left| R_{x,opt} - N^{-1} \sum_{n-1}^{N} R_{x,n} \right| \tag{2.4}$$

where x stands for the respective statement and N stands for the overall number of persons who have returned the questionnaire. A MAV of 100% would correspond to a problem that is "totally annoying" to the occupants, whereas a MAV of 0% stands for "not annoying at all". The parameter MAV is used in the following for quantifying the extent to which a certain critical lighting situation applies to the LESO building. The lower the MAV, the less annoying is the corresponding critical situation. Another parameter used in the following is the number of occupants directly concerned by a certain problem $N_{concerned}$. A person is considered to be directly concerned when he or she has replied opposite to the optimal answer $R_{x,opt}$ to a certain question (e.g. "yes" or "rather yes" when the optimal answer is "no"). A detailed evaluation of the average agreement values (see Tables 2.1 and 2.2) determined by means of the 23 OLS returned by the LESO building occupants made it possible to get a good understanding of which typical critical lighting situations may concern occupants in ADS-equipped offices the most. The twelve most persistent problems are listed in Table 2.3. The MAV and $N_{concerned}$-values are used to quantify the annoyance of the different typical problems.

No	Critical Situation	MAV	$N_{concerned}$
1	Office seems too bright.	34	6
2	Glare problems.	29	6
3	Too much light on workplane.	22	3
4	Too much daylight in office.	20	3
5	Office seems too dim.	17	3
6	Glare problems difficult to handle.	15	3
7	Not enough light on workplane.	14	1
8	Daylight distribution not appropriate.	13	0
9	Difficult to find appropriate lighting configuration.	11	1
10	Outside view obstructed.	1	0
11	Not enough daylight in office.	1	0
12	Difficult to tell about outside weather conditions.	1	0

Table 2.3: Lighting-related problems - Most persistent critical lighting situations, associated MAVs and values of $N_{concerned}$.

It can be observed that the maximum MAV is 34% and the maximum number of directly concerned occupants is 6. These low values underline the general impression that occupant satisfaction within the examined ADS-equipped office room is good. Furthermore, Table 2.3 shows that all critical situations scoring MAVs of 20% or higher are related to situations where too much daylight is bothering the occupants. Specific interviews with the six concerned occupants revealed that four of them manage to quickly "resolve" those "daylight overprovision"-problems using the blind systems in most cases. Two of them, however, found it not so easy to quickly resolve these problems. When looking at the $N_{concerned}$-value of situation No. 6, one might find it surprising that it equals 3 instead of 2. This means that there is one occupant who is not particularly annoyed by "daylight overprovision"-problems, but who still feels that those situations are not so easy to overcome in the rare cases where they occur. The MAV of problem No. 5 was found to be 17% with three directly concerned occupants. The latter were found to often work with fully lowered window blinds and do therefore often not benefit from the daylight flux offered by the ADS. The workplace of the person directly concerned by problem No. 7 is located at a considerable distance from the window. Figure 2.12 summarizes the main issues and quantifies how annoying they are to the occupants.

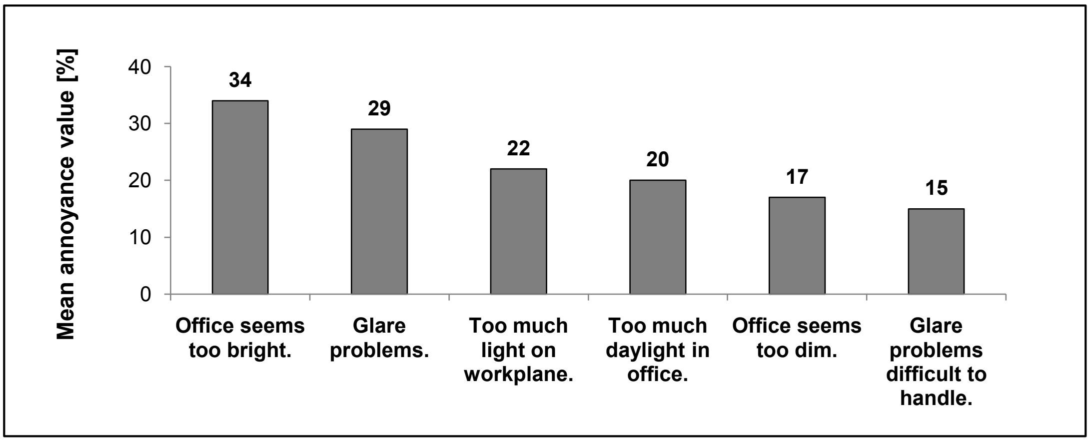


Figure 2.12: Main lighting-related issues. - The figure shows the main lighting-related issues in the LESO building and quantifies how annoying they are to the occupants.

The evaluation of the optimized OLS made it possible to identify the main critical lighting situations that concern the LESO building occupants the most. In order to find out which "weak spots" within the ADS are causing these problems, specific complementary interviews have been conducted with some occupants.

2.3 Global Performance Optimization

As explained in the previous Section, the critical lighting situations that concern LESO building occupants the most are due to daylight overprovision. It is therefore necessary to take a close look at the sunshading devices installed within the ADS-equipped office rooms, to identify their "weak spots" and to find ways to optimize them. Figure 2.13 shows the façade of the LESO building and the two types of fabric blinds that each office room is equipped with. These blinds can be controlled via four manual switches inside the office (one "up" and one "down" switch for each blind). The upper blinds cover the ADS and are regularly used to reduce the room's illuminance when the users feel that the daylight flux is too large in the office or that the office seems too bright; they are also used for glare control (i.e. to block out *direct* sunlight). The lower blinds are used less frequently by most users and serve mainly for thermal protection. However, the interviews carried out during the study presented in the previous Section have revealed one important "weak spot" of this blind configuration. For technical reasons, small gaps remain between the blinds of the different offices (see Figures 2.13 and Figure 2.14 a)). At some moments of the day, these gaps can lead to glare problems in an office even though its respective blinds are lowered. These critical situations get even worse when the blinds of a neighboring office are left open (e.g. due to occupant absence in this office). Figure 2.14 b) visualizes one potential way to deal with these problems: instead of installing all blinds at the same distance from the façade (as illustrated in Figure 2.14 a)), every second blind could be slightly shifted away from the façade, thus closing the gaps. On the other hand, such a modification might lead to shading of some offices by their neighboring offices' blinds and therefore to conflicts between the building occupants.

Another possibility to deal with the above mentioned critical situations would be to improve an internal, manual curtain system made out of fabric Californian blinds (see Figure 2.15) already installed within the offices. The occupants can manually open and close these curtains and also rotate the curtain elements around their vertical axes. However, these curtains do not seem to be frequently used and were described as

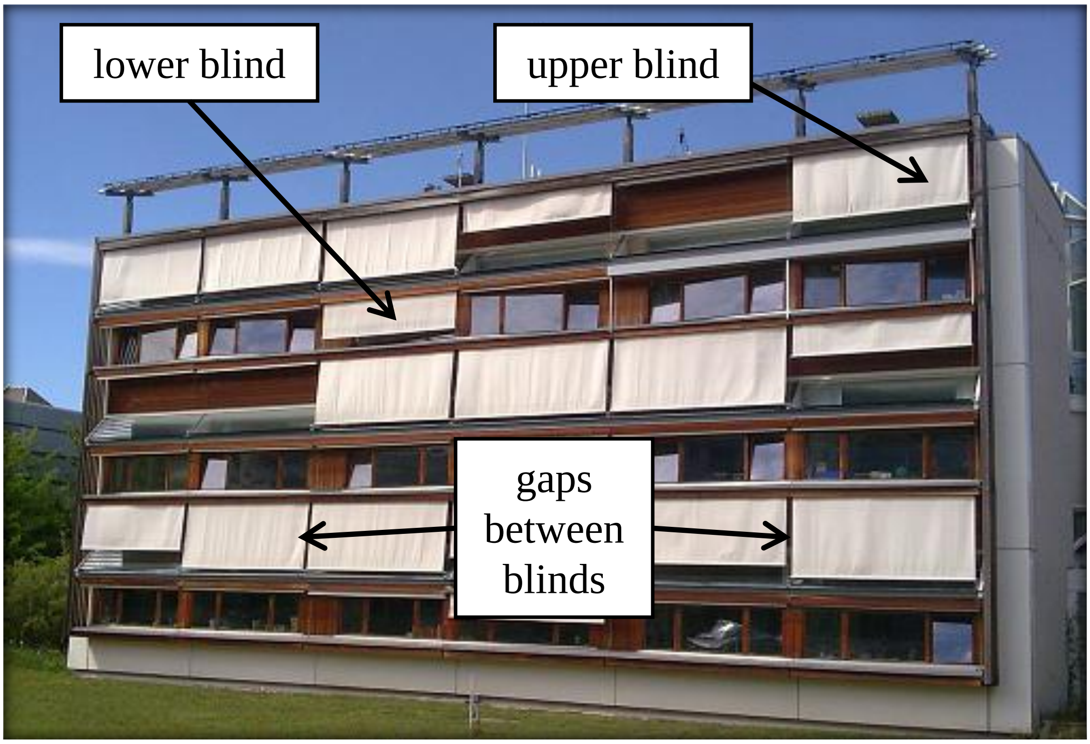


Figure 2.13: Gaps between blinds. - The figure shows the gaps between two office room's blinds which can lead to temporary glare problems.

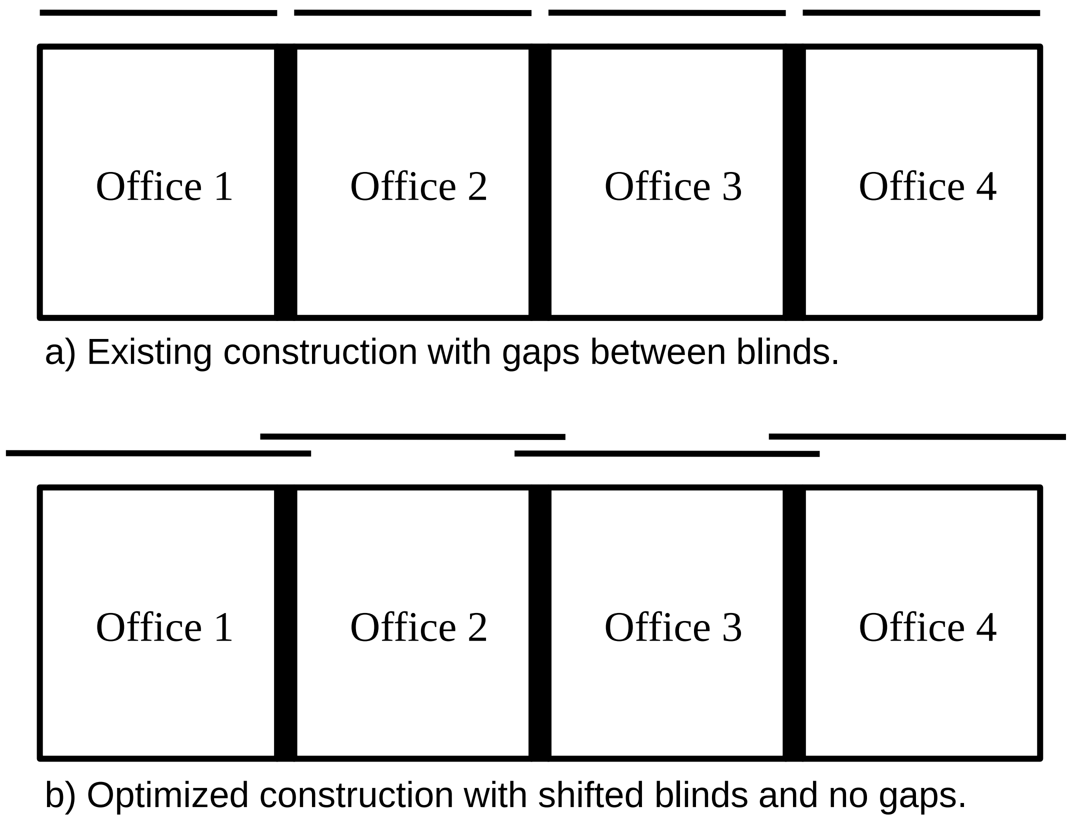


Figure 2.14: Improvement of blind configuration. - The figure visualizes a possibility to overcome the problems due to the gaps between two office rooms' blinds. Instead of installing all blinds at the same distance from the façade (as illustrated in a)), every second blind could be slightly shifted away from the façade, thus closing the gaps (b)).

"quite annoying" by some interviewed occupants. It might be indicated to think about installing a more adapted internal blind system. An additional "weak spot" pointed out by some occupants are the small lateral openings that exist between the different LESO building offices (see Figure 2.16). These lateral windows can sometimes cause glare to the occupants when the external blinds of their neighboring office are open. The resulting annoyances could easily be avoided by installing an additional small blind at this point of each office.

Figure 2.15: Internal Californian blinds for glare protection. - The figure shows the internal Californian blinds for manual glare protection installed in the ADS-equipped office rooms of the LESO building.

Another point that the analysis of the questionnaires and the interviews revealed is the positioning of the manual blind switches inside the office rooms. As previously mentioned, four blind switches are installed in every room (see Figure 2.17). In some cases, the switches can easily be reached by the office occupants. In other cases, their workplaces are located at a certain distance from the switches: occupants have to leave their workplace to operate the blinds. The situation is worst in offices occupied by two persons: in such offices, one person is typically seated next to the switches, the other occupant having always to ask his or her colleague to operate the blinds for him or her. Even though this ensures a minimum of communication between the office workers,

Figure 2.16: Small lateral opening between two LESO office rooms. - The figure shows the small lateral openings between two office rooms which can sometimes lead to temporary discomfort glare.

the regular demands for blind position adjustment can become a source of stress and distraction.

Possible ways to resolve this problem would be the installation of additional blind control switches in office rooms with two occupants as well as the shifting of workplaces towards the switches in office rooms with only one occupant. However, this might not be easily feasible in many cases, especially due to cost factors. The specific building services at the LESO building offer a much more elegant way to deal with the blind control problem. As explained in Section 2.1, all lighting, heating and blind devices are actually interconnected via an EIB-system. Most switches and sensors installed within the building are also connected to the EIB-system. It is also possible to connect computers to the EIB-system. Figure 2.18 shows a schematic overview of the technical installation. Within the framework of this doctoral thesis, the possibility of using a portable server device ("MyHomeBox") for blind and luminaire control via the EIB-system was explored (36). It was demonstrated that it would be easily possible to give LESO building occupants the possibility to control their luminaires and blinds

Figure 2.17: Switches for controlling the LESO building's external blinds. - This photograph shows the four blind switches installed in every room of the LESO building.

via a Flash^{TM} application installed on their PC (see Figure 2.19) that communicates with the portable server device. Installing this application on all occupants' PCs is a very interesting option towards a global comfort enhancement within ADS-equipped offices. Another possibility that is currently being explored at the LESO-PB is the use of Apple's iPhone for blind control (6).

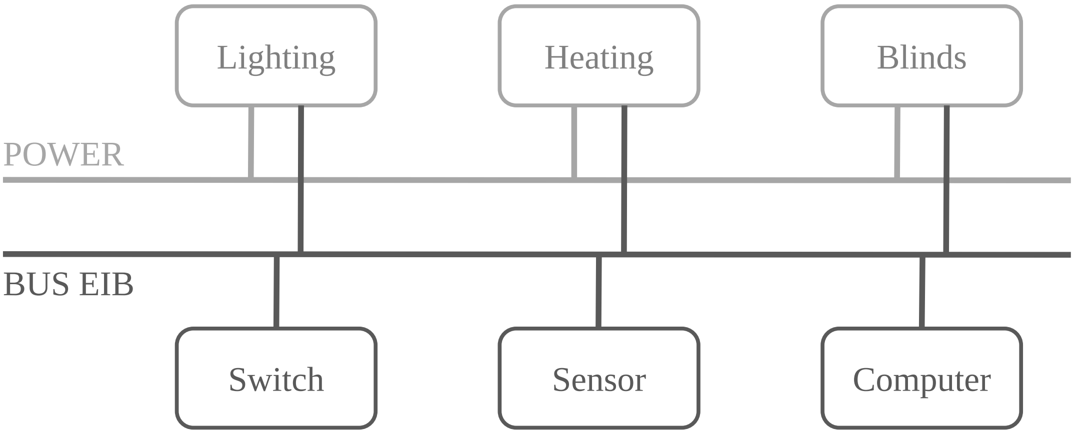


Figure 2.18: Overview of EIB system in the LESO building. - The figure gives an overview of the EIB system that is installed in the LESO building.

Some of the reported critical situations within the examined ADS-equipped office rooms could be avoided by giving a short introduction on optimal ADS handling to some office occupants. Many problems revealed during this study (e.g. occupants

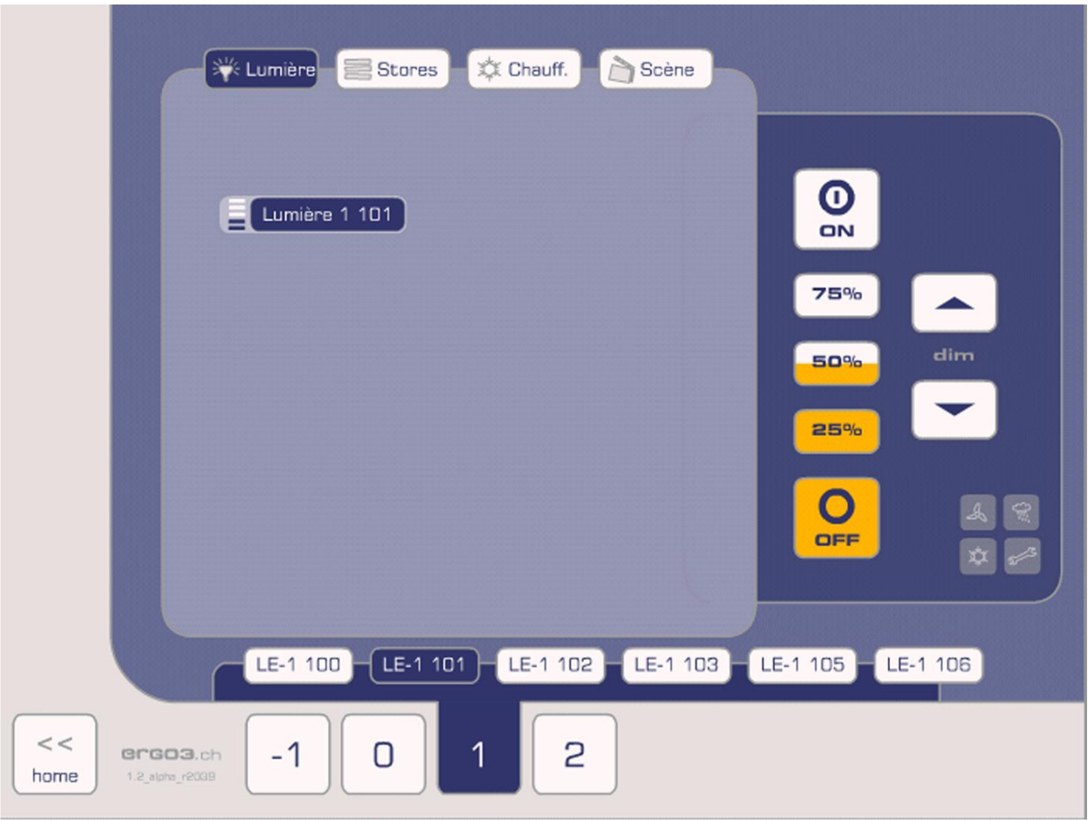


Figure 2.19: Flash^{TM} application for blind control. - The figure shows a screenshot of the Flash^{TM} application for blind control via PC.

feeling that their office is too dim or that they cannot find an appropriate lighting configuration) are indeed often the result of an inadequate ADS handling. Developing a comprehensive user manual for Anidolic Daylighting Systems could be an interesting option for further developments. One could also envisage setting up a 2-hour workshop, to be held from time to time in buildings with ADS-equipped office rooms, during which the positive effects of daylighting and the proper handling of ADS are explained.

Last but not least, one problem that has occurred from time to time at the LESO building is wind damage to the fabric blinds. Typically, strong gusts of wind rip some blinds off their fixtures (see Figure 2.20). Even though such damage has so far not caused elevated costs, it causes considerable annoyances. One possible way to avoid such damage could be to automatically open all blinds at times where high wind speeds occur. This could be done via the EIB-system, either based on wind speed recordings on the building's roof or based on current weather warnings (e.g. from Meteosuisse (73)). The first solution is currently on the way of being implemented in the LESO building.

2.4 Conclusion

The results presented in this Chapter clearly show that the ADS installed within most office rooms of the LESO building are in general very well accepted by the building's occupants. There are, however, some issues that should be taken into consideration when installing ADS in other buildings. This doctoral thesis has revealed that most of these critical situations are caused by temporary daylight overprovision inside the office rooms. It can be concluded that the annoyance of most critical situations revealed during this doctoral thesis could be drastically reduced by optimizing the blinds' configuration and control as well as by providing introductions on how to properly handle the ADS to the building's occupants. This can be of great interest to building designers and service engineers who may adopt similar systems for future buildings.

Figure 2.20: Wind damage. - The figure shows wind damage to the window blinds at the LESO building.

3

Complementary Electric Lighting

3.1 Introduction

As explained in Chapter 2, ADS have a large potential for becoming the basis of future energy-efficient office lighting designs. They can enable office workers to comfortably work under daylighting conditions during large parts of their working days, without even having to switch on any electric lighting. Nevertheless, even in such office rooms with abundant access to daylight and very effective glare control, the installation of complementary artificial lighting systems will always be necessary: office occupants have to be able to also work effectively during periods of darkness, for example in the early morning, late evening or when the outside sky is extremely dark (e.g. during thunderstorms). In addition to that, a minimum of light is always needed for reasons of work safety. As a matter of fact, accidents are more likely to happen in darkness than in well-lit spaces (52). It therefore makes sense to discuss available lighting technologies, relevant lighting specifications as well as possible targets for energy-efficient electric lighting in detail.

3.2 State-of-the-art Lighting Technology

3.2.1 Light Sources

The first versions of the **incandescent lamp** as we know it today was independently developed by Sir Joseph Swan in England and Thomas Edison in the USA during the second half of the 19th century. Edison patented his invention in 1879, and from then on, the invention spread rapidly into the entire world and became the commercial success that it has been for decades (83). A typical incandescent light bulb is shown in Figure 3.1.

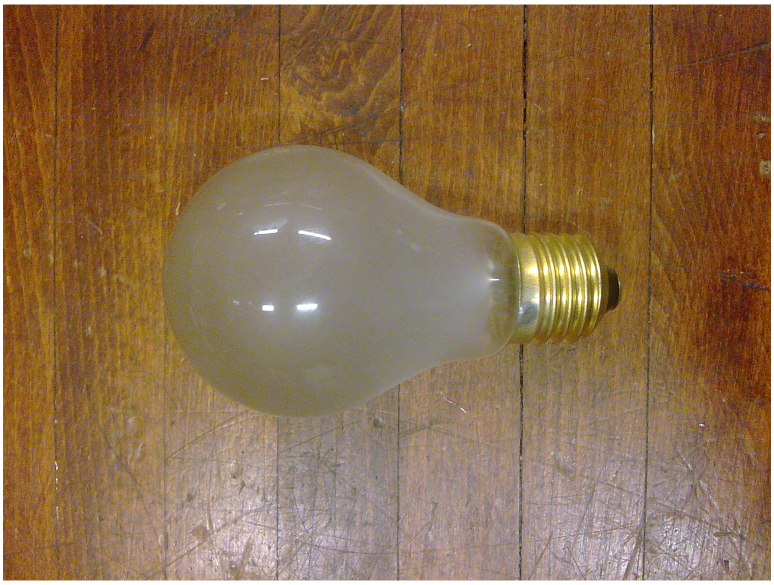


Figure 3.1: Incandescent light bulb. - The figure shows a typical incandescent light bulb.

The "heart" of this light source is a filament that is heated by means of an electric current: the higher the temperature, the more light is produced. During the gradual improvement of Edison's invention over several years, it rapidly showed that tungsten was a material highly appropriate for this application: it has a comparably elevated melting point (3382 °C) which permits elevated operating temperatures and consequently higher efficiencies. At its melting point, a tungsten wire has a luminous efficacy of 53 lm/W. However, in order to achieve acceptable lifetimes, incandescent lamps with tungsten filaments are operated at much lower temperatures with lower luminous efficacies. Typical values for incandescent lamps are situated between 10 and 20 lm/W, mainly depending on whether the bulb is gas filled or not. These luminous efficacies are low compared to alternative light sources. This is the reason why bans of incandescent lamps are currently discussed in many countries. Switzerland has banned incandescent lamps with very low efficacies (EU classes F and G) since 2009, but most commonly used incandescent light bulbs are still not affected by this ban. However, the corresponding EU regulations (that are also applied by many Swiss retailers) envisage a complete ban of most incandescent light bulbs by 2012. The incandescent light bulb as we know it therefore has to be seen as a phase-out model.

Tungsten-halogen incandescent lamps (often simply called **halogen lamps**) achieve higher luminous efficacies and longer lifetimes than simple incandescent lamps. Such lamps have their bulbs filled with halogen gas, typically iodine or bromine. The halogen particles allow "burnt" tungsten molecules to recombine with the filament. Consequently, the latter can be operated at higher temperatures without decreasing the lifetime and better luminous efficacies (up to 30 lm/W) can be achieved. Halogen lamps are likely to be not affected by the ban of incandescent lamps over the next few years and therefore remain an option for various lighting applications. Figure 3.2 shows a bulb-style halogen lamp.

Figure 3.2: Halogen light bulb. - The figure shows a bulb-style halogen lamp with an E27 socket.

Fluorescent tubes can mostly be found in commercial, industrial and office buildings. They are available in many different sizes (see Figure 3.3) and are typically composed of two electrodes that are connected via a long tubular light bulb.

The interior of the bulb is coated with a mixture of different fluorescent powders (also called "phosphors") and contains a mixture of mercury vapor and inert gas. When a voltage is applied to the electrodes, an electric arc develops based on the current flowing through the mercury vapor. This discharge arc produces mainly ultraviolet (UV)

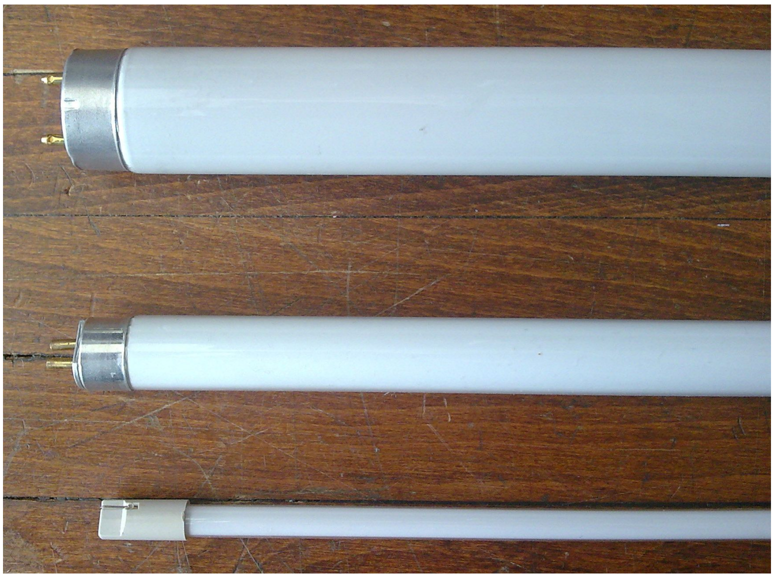


Figure 3.3: Different types of fluorescent tubes. - The figure shows a "T8", a "T5" and a "mini" fluorescent tube.

radiation which excites the phosphor coating. The fluorescent responses of these phosphors then lead to light emission at various wavelengths within the visible spectrum. Fluorescent tubes cannot be operated without special current-limiting devices, so-called ballasts (see Subsection 3.2.3). They can be easily dimmed with electronic ballasts, are available in various lengths and diameters and have comparably long lifetimes. Fluorescent tubes reach luminous efficacies of around 100 lm/W.

Compact fluorescent lamps (CFL) are based on the same principles as fluorescent tubes, their main purpose being the replacement of conventional incandescent light bulbs. Figure 3.4 shows a typical CFL with an E27 socket and a bended glass tube. The electronic ballast is located between the socket and the tube. Due to the special geometry and the power limitations of the electronic ballast, CFLs are somewhat less efficient than fluorescent tubes. Nevertheless, they still reach luminous efficacies higher than 60 lm/W and therefore represent a very interesting option for replacing conventional incandescent lamps. There have been discussions in the past concerning the electromagnetic compatibility (EMC) of CFLs; in particular, potential negative effects on humans have been evoked. However, already in 2004, the Swiss Federal Office of Energy and the Swiss Federal Office of Public Health have published a technical report in which the authors come to the conclusion that CFLs do note represent a hazard for human health and that they can therefore be recommended for energy-efficient lighting (24).

Figure 3.4: Compact Fluorescent Lamps . - The figure shows a typical CFL with an E27 socket and a bended glass tube.

Another lamp group that can be considered for office lighting is the so-called **High Intensity Discharge Lamp** (HID lamp). All HID lamps produce light by means of two electrodes between which a discharge arc is established. Metals or halide compounds of metals are present in HID lamps, and when they evaporate into the arc, they emit light at characteristic wavelengths. Mercury lamps, sodium lamps and metal halide lamps are common types of HID lamps. The latter typically produce light by exciting several different atoms or molecules, for example sodium, scandium, thulium, holmium and dysprosium (83). Figure 3.5 shows an HID lamp with a E27 socket.

Much like fluorescent lamps, HID lamps cannot be operated without special ballasts or electronic control gear. They reach luminous efficacies between 50 and 80 lm/W (for typical indoor lighting applications, i.e. 35 to 100 W), depending on the lamp type and the used control gear. Dimming HID lamps can be somewhat problematic: immediate dimming is not always possible. In addition to that, HID lamp applications often need considerable times to cool down before they can be started again (in order to maintain

Figure 3.5: High Intensity Discharge Lamp. - The figure shows an HID lamp with a E27 socket.

long lifetime). These characteristics are potential drawbacks for widespread use in office lighting scenarios.

Over the last few years, **Light Emitting Diodes** (LED) have witnessed a breathtaking development and have become widely available for various consumer products. Colored LEDs have been introduced as a source for emergency and decorative lighting, as well as indicator lamps, traffic lights and automotive applications for example. White LEDs are becoming more and more common for portable lighting solutions, such as torches or bicycle lights; they are unfortunately not yet widely used as light sources for general lighting, such as office lighting. However, white LED lamps for replacing incandescent light bulbs during retrofits reaching luminous efficacies of 20 to 35 lm/W are already available. Figure 3.6 shows different LED lighting products currently available on the market.

There are several profoundly different methods for producing white light with LEDs. The first one consists of combining red, green and blue LED chips in the same package to produce white light. This type of white light is however not of good quality, persons with color deficiencies (i.e. color blinds) will not see the emitted light as white. The second method uses blue LEDs in combination with photoluminescent phosphors, much like

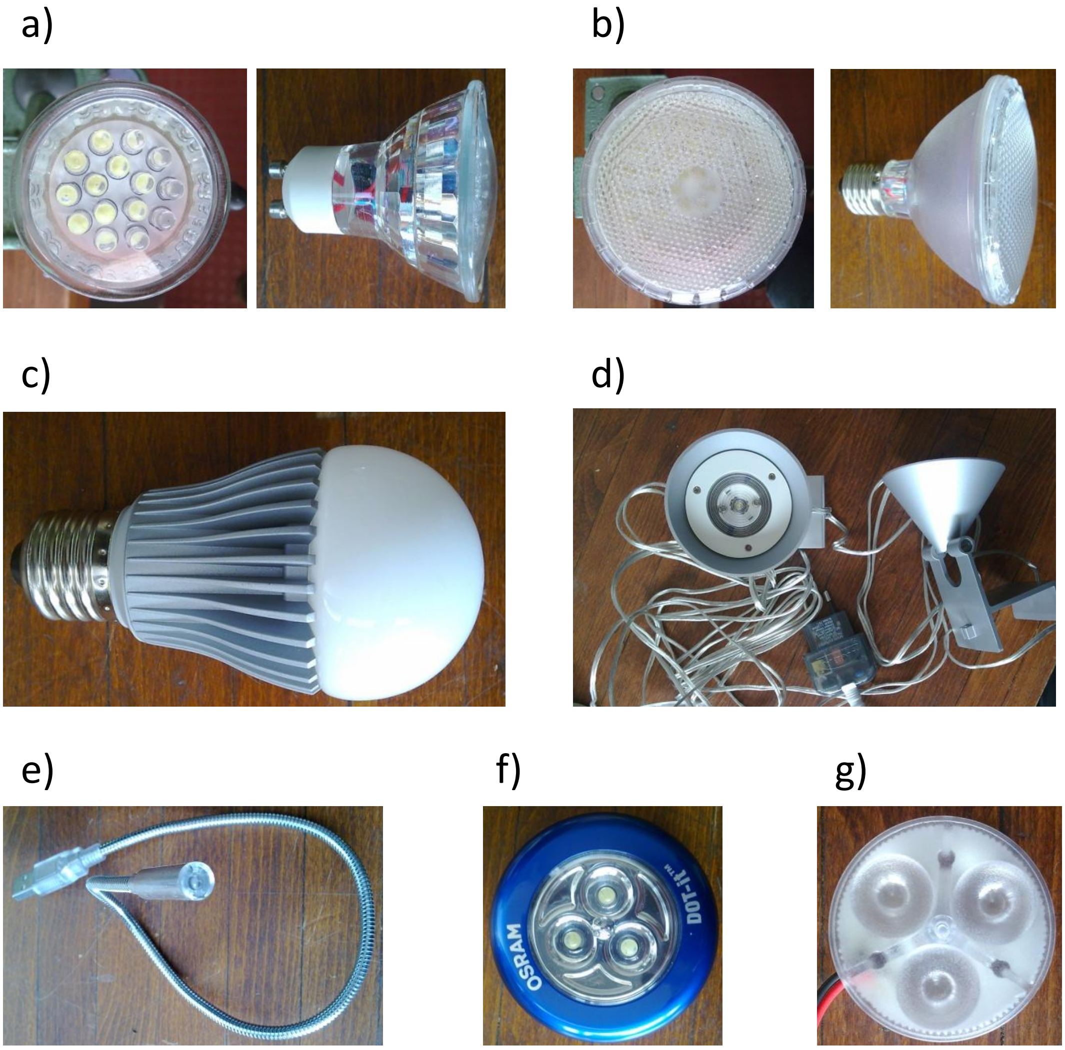


Figure 3.6: Various LED light sources. - a): 1 W white LED lamp with GU10 socket (Paulmann), b): 2.5 W white LED lamp with E27 socket (Paulmann), c): 7 W white LED bulb with E27 socket (PHILIPS), d) 1 W white LED task lighting application (IKEA), e) Swan neck white LED with USB socket, f) Battery-driven white LED task lighting application (OSRAM), g) 3.4 W white power-LED application (OSRAM).

in fluorescent tubes. In this way, a cool white light of better quality can be produced. Coating blue LEDs with quantum dots that emit white light in response to the blue light radiated by the LED is a way to produce a warmer, yellowish-white light similar to that produced by incandescent bulbs instead of the bluish light described above (34). Using LEDs with their emission shifted towards the UV part of the electromagnetic spectrum in combination with fluorescent coatings is yet another possible way to produce white light from LEDs (53; 54).

In addition to the LED products illustrated in this Figure, white "LED tubes", which can be mounted in luminaires for retrofit instead of regular fluorescent tubes, have recently become available on the market. Such an LED tube is shown in Figure 3.7. Towards the end of this doctoral thesis, in-depth tests with two such LED-tubes (one warm white and one pure white tube) were initiated. Figure 3.8 shows the "pure white" tube in operation in an experimental setup.

Figure 3.7: LED tube. - White LED tube for retrofit in luminaires instead of fluorescent tubes.

The LED tubes were obtained via an online retailer, their manufacturer is unknown and there is therefore no data about the lamps' output fluxes. In order to be able to quantify the luminous efficacy of these interesting lighting devices, a setup for measuring the luminous flux unit of such LED tubes was installed at the LESO-PB using an integrating sphere. We have used the "Absolute Integrating Sphere Method" as described in 1998 by Ohno (59; 76; 89), because it doesn't require a calibrated standard lamp. The method is described in detail in Appendix B.1 of this Thesis. Using the

Figure 3.8: White LED tube in operation. - This Figure shows a white LED tube for general lighting in operation at our laboratory.

integrating sphere in this context, it was first of all found that the light flux of the LED tubes was not constant, but was rather decreasing with increasing operating time. This is due to the temperature increase of the LED (93). Figure 3.9 (left) shows that after thirty minutes of operation, the tubes' light output flux has dropped to around 90% compared to the 100% upon switch-on. A zoom on the y-axis (see Figure 3.9 (right)) visualizes that the steepest drop occurs during the first ten minutes of operation.

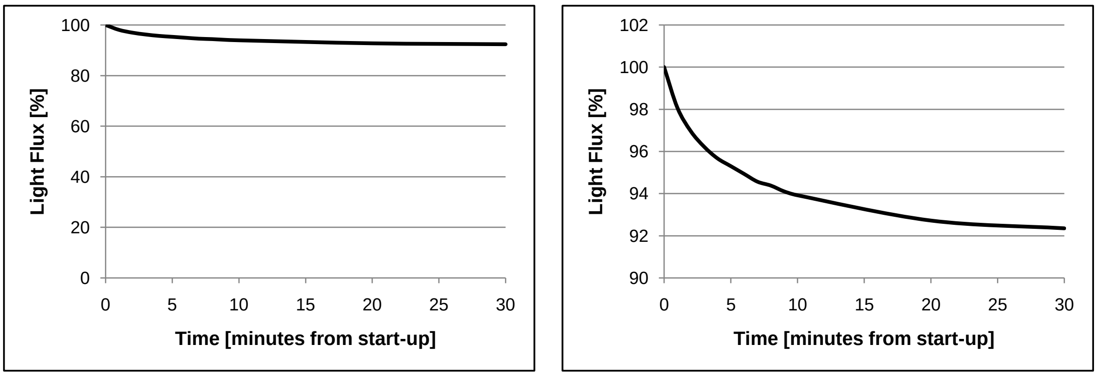


Figure 3.9: Light output flux decrease of the white LED tube over time. - This Figure visualizes the decrease in luminous flux of the white LED tube over time (left). A zoom on the y-axis is shown in the panel on the right.

Using the Absolute Integrating Sphere Method, a luminous flux of 1641 Lux ±21% and a power consumption of 22.4 W for the pure white LED tube was measured after 30 minutes of operation. This corresponds to a luminous efficacy between 57.6 and 88.4 lm/W.

Replacing fluorescent tubes with the described LED tubes is, however, not in all cases straightforward. In luminaires with conventional control gear (i.e. inductive ballasts) all one has to do is to remove the starter from the luminaire. Then, the fluorescent tube can be replaced with the LED tube. Replacing fluorescent tubes in modern luminaires with electronic control gear is unfortunately more complicated. In such luminaires, the wiring will have to be modified by an electrician before retrofitting the luminaire with an LED tube. This is likely to create practical problems in many cases. However, the described LED tubes might become an interesting option for office lighting solutions in the very new future, especially as luminous efficacies of white LEDs are further improving.

The LED technology described above is making use of inorganic semiconductor materials for light generation. However, it is also possible to use organic materials: devices based on this technology are referred to as **Organic Light Emitting Diodes** (OLED) (55; 64; 123). OLEDs have several advantages compared to inorganic LEDs (39). Coupling out the light from the semiconductor material is for example easier than in inorganic semiconductor materials because there are less reflection losses at internal boundary layers. This is due to the fact that organic semiconductors tend to have lower permittivities than inorganic semiconductors. Another advantage is the fact that it is easy to manufacture OLEDs in different geometrical shapes, which gives a large variety of different design options. There are, however, also a few disadvantages of OLEDs compared to LEDs. Lower thermal stability, corrosion problems due to the penetration of oxygen and water into the material as well as the management of extremely complex manufacturing processes are issues that have to be dealt with.

There are two main application fields for OLED: displays and general lighting. Using OLED displays instead of liquid crystal displays (LCD) has several advantages, such as lower electricity consumption and lower installation depths. These advantages make them particularly interesting for portable devices. Apple's iPhone (6) for example uses an OLED display. OLED displays are also often referred to as possible alternatives to "plasma" television screens. Companies like Samsung (90), Sony (95) and Toshiba (103) already have products on the market, but there are still significant problems to overcome. One of those problems is the fact that the different color pixels in OLED displays have different lifetimes. It is therefore difficult to guarantee appropriate color stability. The development of OLED devices for lighting applications is still at the very beginning and appropriate products are far from being widely available. Philips Lighting has started to promote their Lumiblade-line; the so-called "Lumiblade Experience Kits" (composed of small OLED panels and the corresponding electronic control gear) can be ordered via the Philips Lighting website (78). Such a demo-kit has been ordered for testing during this doctoral thesis. Figure 3.10 shows a white "Pixel"-Lumiblade in operation at the LESO-PB. A very unstable operation of the device has been experienced and detailed measurements of luminous flux have therefore not yet been carried out.

Table 3.1 summarizes the information given in this Subsection by giving examples

Figure 3.10: White OLED. - White Lumiblade OLED "Pixel" in operation at the LESO-PB.

of different light sources for office lighting, their electric power consumption P_{el}, their light flux Φ as well as their luminous efficacies.

3.2.2 Luminaires

In order to create a comfortable indoor lighting environment, the light sources described in Subsection 3.2.1 are most of the time mounted in luminaires. Luminaires can be ceiling-mounted (attached directly to the ceiling or suspended at a certain distance from the ceiling) or free-standing. The CIE classification system for luminaires provides a classification system based on the upward and downward directed light flux output (83):

- **Direct lighting**
  Luminaires that direct 90 to 100% of the lamps light flux downwards. The light distribution may be widespread or concentrated, depending on the reflector material, finish and contour.

- **Semi-direct lighting**
  Predominantly downward light distribution (60 to 90%), with a small upward component to illuminate the ceilings and walls.

- **General diffuse lighting**

Type	Product	$\mathbf{P}_{e}l$ [W]	ϕ [lm]	Lum. Eff. [lm/W]
Incandescent lamp	CLAS A CL 100 (OSRAM)	100	1340	13.4
Halogen Lamp	HALOSTAR 64447 ECO (OSRAM)	60	1650	27.5
Fluorescent tube T8	L 51 W/840 ES (OSRAM)	51	4800	94.1
CFL	GENIE WW 827 (PHILIPS)	8	420	52.5
LED bulb	MASTER LED BULB MV CW (PHILIPS)	7	230	32.9
LED tube	unknown *	22.4	1641 ±21%	57.6 to 88.4
Fluorescent tube T5	HE 28 W/840 (OSRAM)	28	2600	92.9
Fluorescent tube mini	FM 13 W/740 (OSRAM)	13	930	71.5
HID lamp	CDM-R 70W/830 10D (PHILIPS)	70	4850	69.3

Table 3.1: Overview of different light sources - Examples of different light sources for office lighting with their power consumption, light flux and luminous efficacies. * = measurement with Absolute Integrating Sphere Method.

Approximately equal downward and upward light distributions (40 to 60% in each direction).

- **Semi-indirect lighting**
  Luminaires that emit 60 to 90% of their output upwards towards ceiling and walls.

- **Indirect lighting**
  Mainly upward light emission (90 to 100%).

Figure 3.11 shows two ceiling-mounted luminaires for direct lighting (no light emitted upwards). The fluorescent light tube is mounted inside the luminaire and shielded by an acrylic glazing (left) or several vertically oriented battens (right). A luminaire for semi-indirect lighting is shown in Figure 3.12. This luminaire is not ceiling-mounted but free-standing. The advantages of such luminaires are their flexibility (office occupants can set them up where they like) and the fact that they create very comfortable lighting conditions (reducing glare risks). The drawback of such luminaires (and of semi-indirect lighting in general) is the fact that comparably large amounts of electric power are needed to create appropriate workplace illuminances.

In addition to the luminaires shown in Figures 3.11 and 3.12, which are mainly used for ambient and task lighting, there are also desk lamps which are mainly conceived for task lighting purposes. Such lamps typically offer direct lighting and can be used to complement ceiling-mounted or free-standing luminaires in office rooms. They can be switched on by the occupants at times where they need elevated illuminances for carrying out specific visual tasks (like reading or writing) on a very limited subsection of their workspace. Such a desk lamp is shown in Figure 3.13.

The choice of appropriate luminaires is highly important when it comes to the design of energy-efficient lighting scenarios for office buildings. The luminaire efficiency (i.e. the ratio of luminaire output flux and lamp flux) must be as good as possible. In other words: luminaire losses, caused by multiple reflexions and light absorption, should be minimal.

3.2.3 Lighting Control Gear

As previously mentioned, some lamp types (such as fluorescent tubes, CFLs, HID lamps and LEDs) cannot be operated without specific lighting control gear, so-called

Figure 3.11: Directly emitting luminaires. - The figure shows one luminaire for direct lighting shielded by an acrylic glazing (left) from the 1990's and one shielded by several vertically oriented battens (right) from the 1980's.

ballasts. Those ballasts are basically responsible for supplying the appropriate voltages and currents to the lamps' electrodes at the right times. In HID lamps, the ballasts are also used for thermal management (if the lamp is too hot, the ballast stops the lamp from re-starting). For many years, magnetic ballasts have been used to operate fluorescent tubes. Such ballasts have various shortcomings, mainly in terms of energy-efficiency, dimability and flickering susceptibility; they are therefore more and more often replaced by electronic ballasts which overcome most of these problems (83). In addition to simple electronic ballasts, entire electronic lighting control systems, which can be used to precisely address and control various types of lamp ballasts at the same time, become more and more current in office buildings. One of these lighting control systems is the Digital Addressable Lighting Interface (DALI) (1) . Electronic ballasts and control systems are commonly referred to as electronic control gear (ECG)

Figure 3.12: Indirectly emitting luminaire. - The figure shows a free-standing luminaire for semi-indirect lighting.

Figure 3.13: Portable desk lamp. - The figure shows a rather old-fashioned portable desk lamp for task lighting.

3.3 Specifications and Targets

The simplest design strategy for artificial lighting systems would be a dimensioning for the worst case scenario (i.e. night-time with no daylight at all); however, this is not the optimal strategy for the design of low-energy office buildings which are mainly occupied during daytime. Dimensioning an electric lighting system for the nocturnal worst-case scenario can lead to unnecessarily high lighting loads during daytime because occupants might simply close the window blinds all the time (35) (to avoid any kind of glare) and keep a powerful electric lighting installation switched on during the entire day. Taking this risk might make sense in some cases (e.g. in buildings where people regularly work at night), but definitely not in office buildings where people typically work during normal office hours (from 8:00 to 18:00, with some exceptions). It is possible to characterize the artificial lighting load of an office room by calculating the Lighting Power Density (LPD) for that room:

$$LPD = \frac{P_{con}}{A_{room}} \quad \left[\frac{W}{m^2}\right] \tag{3.1}$$

where P_{con} [W] is the overall connected lighting power in the office room and A_{room} [m^2] is the floor area. One very simple but yet extremely effective way to reduce the electric lighting load of an office building is to minimize its office rooms' LPDs.

In the beginning of this doctoral thesis, a target LPD value of 3 W/m^2 was chosen for the test office room in the LESO building: it was expected to reach this LPD target value through the use of highly efficient light sources, new fixture technologies and more appropriate light distributions.

Of course, the main purpose of an office lighting system is not to save electricity but to provide appropriate working conditions for the office occupants at all times. It has been shown in Chapter 2 that this is the case during large fractions of the working day in an ADS-equipped office room, especially when it is illuminated by daylight. When designing the complementary electric lighting system, the main concern is the necessity to offer an appropriate lighting environment when daylight is *not* available. Three extremely important questions concerning the visual comfort in an office room must be raised:

1. *Is there enough light on the workplane to properly carry out visual tasks?*
   This question can be answered by looking at the illuminance that a specific artificial lighting installation is able to provide on the workplane, typically at 75 to 80 cm above floor level. The Swiss Norm SN EN 12464-1 (94) specifies minimum average illuminances between 200 Lux (archiving work) to 750 Lux (industrial drawing) for office rooms. As mentioned in Chapter 2, a required minimum illuminance of 300 Lux and a desirable illuminance of 500 Lux for our specific situation can be chosen as target values.

2. *Is the light properly distributed on the workplane?*
   In order to offer an optimal visual comfort, it is not sufficient to simply achieve the necessary workplane illuminance: a certain illuminance uniformity must also be achieved. The Swiss Norm SN EN 12464-1 specifies that if the illuminance of a zone where a visual task is carried out is situated around 300 Lux, then the illuminances of the neighboring zones should be situated around 200 Lux. Furthermore, the uniformities g_1 (i.e. the minimum illuminance on a reference plane divided by the average illuminance on that specific reference plane) must not be lower than 0.7 for zones where a visual task is carried out and not lower than 0.5 for the neighboring zones (94).

3. *Is the lighting installation causing significant discomfort glare?*
   Light sources can cause considerable discomfort if they have too large luminances or if they are inappropriately placed. Glare is not necessarily caused by the lamps themselves but can also occur due to light reflexions (e.g. on walls, furniture, screens or windows). By taking into account the workspace positions inside an office room when placing the lamps and luminaires in the room, glare risks can be reduced. This is particularly important for office rooms where the occupants mainly work with Video Display Units (VDU) (e.g. with computers). One other way to reduce glare risks is the fostering of matt-finished rather than shiny surfaces. A possibility to quantify glare risks associated with a particular luminaire is to examine the so-called Unified Glare Rating (UGR). This value is often given by luminaire manufacturers for different viewing angles and room configurations. The Swiss Norm SN EN 12464-1 specifies maximum UGR values from 16 (industrial drawing) to 25 (archiving work) for office rooms (16; 94).

In Chapter 4, ways to minimize the LPDs in ADS-equipped office rooms while maintaining the necessary visual comfort conditions are discussed in detail.

3.4 Electric Lighting Situation in the LESO Building

In the beginning of this doctoral thesis, the LPDs were determined for every south-facing office room of the LESO building. It was found that the LPD was not identical for all ADS-equipped office rooms in the building. Figure 3.14 shows the corresponding LPDs of the 15 south-facing LESO office rooms (all equipped with the ADS shown in Figure 2.2). Various combinations of different ambient and task lighting solutions lead to LPDs ranging from 4.5 to 13.7 W/m^2, with an average of 9.1 W/m^2 (69). Common values for average LPDs in Swiss office rooms normally range from 10 to 15 W/m^2 (82). Li et al. have recently described a comparable office room in the US with a value of 16.7 W/m^2 (61).

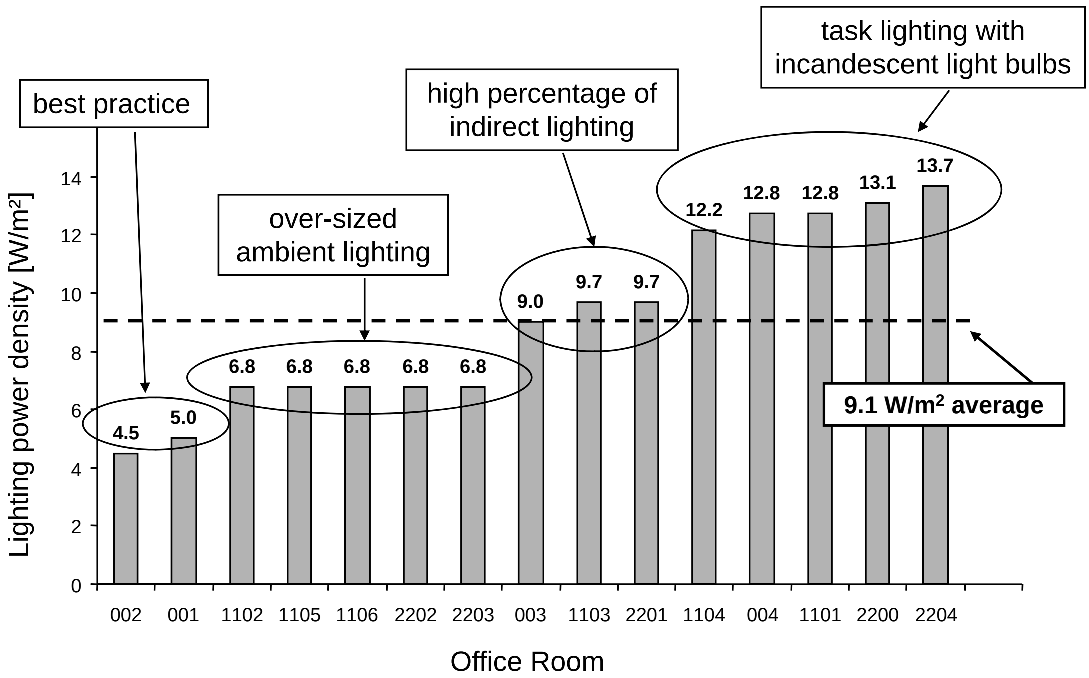


Figure 3.14: Lighting Power Densities of the LESO office rooms. - The figure shows the Lighting Power Densities of the 15 south-facing, ADS-equipped LESO office rooms.

The differences in LPD for the office rooms shown in Figure 3.14 have three main reasons:

1. **Task lighting with incandescent lamps**
   Some occupants still use desk lamps with incandescent light bulbs (100 W, 80 W or 60 W) for individual task lighting. Compared to modern CFLs, those light bulbs are very inefficient; they cause a significant increase in LPD and can therefore lead to comparably large artificial lighting loads in the corresponding office rooms.

2. **High fraction of indirect lighting**
   Some office rooms are equipped with mainly indirectly emitting luminaires (see Figure 3.12, power consumption of 144 W per free-standing luminaire). Most of the light flux is directed towards the room's ceiling and reflected from there. This creates a lighting environment that is in general highly appreciated by people, the drawback being that it also leads to comparably elevated LPDs. Such luminaires are therefore not optimal from an energy point of view.

3. **Slightly over-sized ambient lighting**
   Compared to the "Best Practice" cases, some office rooms of the LESO building are equipped with three ceiling-mounted luminaires instead of two (connected power of 108 W instead of 72 W). However, the following discussions will reveal that two ceiling-mounted luminaires seem to be sufficient in this particular building equipped with façade-integrated ADS.

The two "Best Practice" Office Rooms, with lighting power densities of 4.5 and 5 W/m^2, respectively, are both equipped with two ceiling-mounted luminaires with an optical efficiency of 69% (31% of the light emitted by the source is absorbed by the fixture). Figure 3.15 shows the ceiling-mounted luminaire used in the two "Best Practice" Office Rooms. It is a "Lip" luminaire manufactured by Regent Beleuchtungskörper AG (84). The manufacturer describes this luminaire's reflector/diffuser unit as a *light directing element in clear synthetic material with prismatic cover in longitudinal axis and specular reflector Batwing in transvers axis.* The incorporated high frequency (HF) electronic ballast is a Philips HF-R 136 TLD 220-240 with an announced power factor of 0.95 (78). It is analogically dimmable by application of a DC voltage between 0

V and 10 V. The switch/dimmer is located next to the door of the offic room. Each luminaire is equipped with one 36 W T8 fluorescent tube by Sylvania (99)(CRI > 80, CCT = 3000 K, light flux = 3350 lm).

Figure 3.15: The "Lip" luminaire. - The figure shows a "Lip" luminaire by Regent (84) as mounted in many office rooms of the LESO building.

Both "Best Practice" Office Rooms are occupied by two persons; one person uses a desk lamp equipped with an 8 W CFL for individual task lighting. Figure 3.16 visualizes in which way the average LPD within the LESO building would decrease if the three weaknesses mentioned above would be eliminated one after the other. Replacing all incandescent light bulbs by comparable CFLs would already decrease the average LPD within the LESO building to 8.3 W/m^2. Replacing indirectly emitting luminaires by ceiling-mounted directly emitting luminaires would further decrease the average LPD to 7 W/m^2. Avoiding all over-sizing would lead to an average LPD of 5.5 W/m^2: for this last case, the assumption was made that all occupants are using an 8 W CFL desk lamp for temporary task lighting in addition to the ceiling-mounted luminaires. As explained before, an LPD reduction down to approximately 3 W/m^2 seems achievable.

In Chapter 2, results of an occupant satisfaction assessment (POE) carried out within the LESO building were presented. To assess the building occupants' satis-

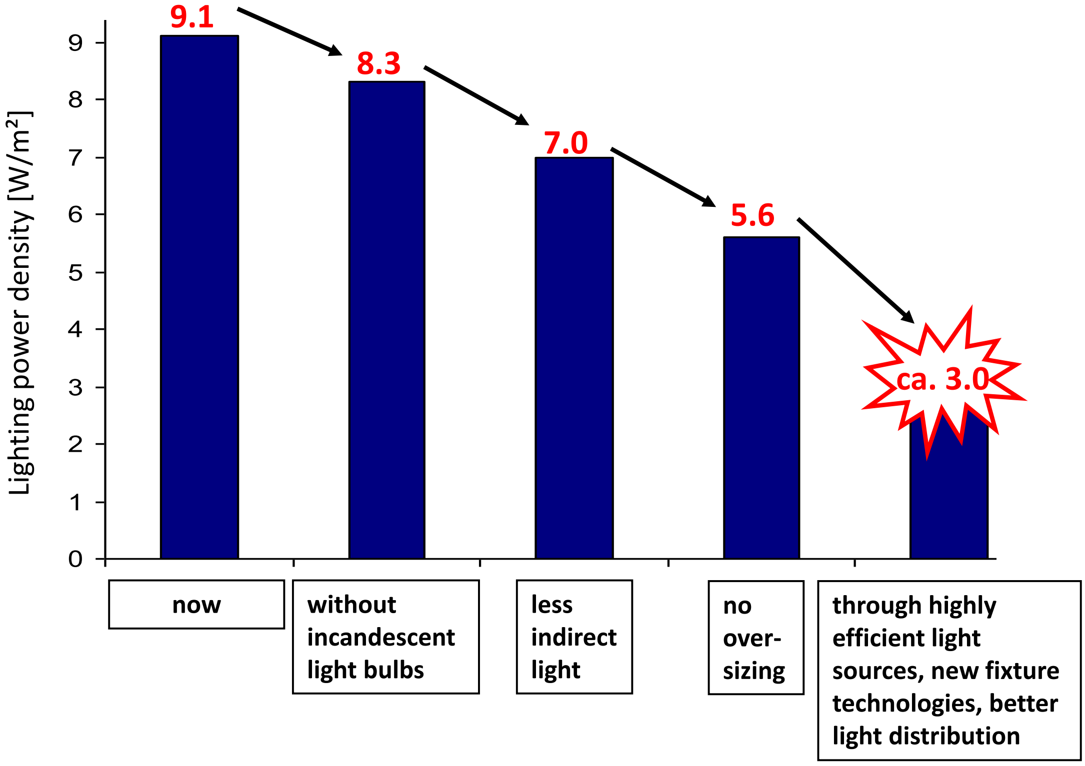


Figure 3.16: LPD reduction potential. - The Figure visualizes in which way the average LPD within the LESO building would decrease if the three weaknesses mentioned above would be eliminated one after the other.

faction with the lighting environment of their offices, a questionnaire with general, daylighting-related and artificial lighting-related questions was distributed and evaluated. The results presented in Chapter 2 were considering the overall LESO building. Here, some of the statements relevant for electric lighting issues are split up into the two categories "Best Practice" Office Rooms and Other Office Rooms. Figure 3.17 shows the occupants' agreements to the five following statements:

S 2: "In general, the lighting in my office is comfortable."
S 5: "My office often seems too dim."
S 7: "I often have the impression that there is not enough light on my workplane."
S 19: "The electric lighting system in my office is able to supply enough light."
S 21: "The lamps in my office are in the right place."

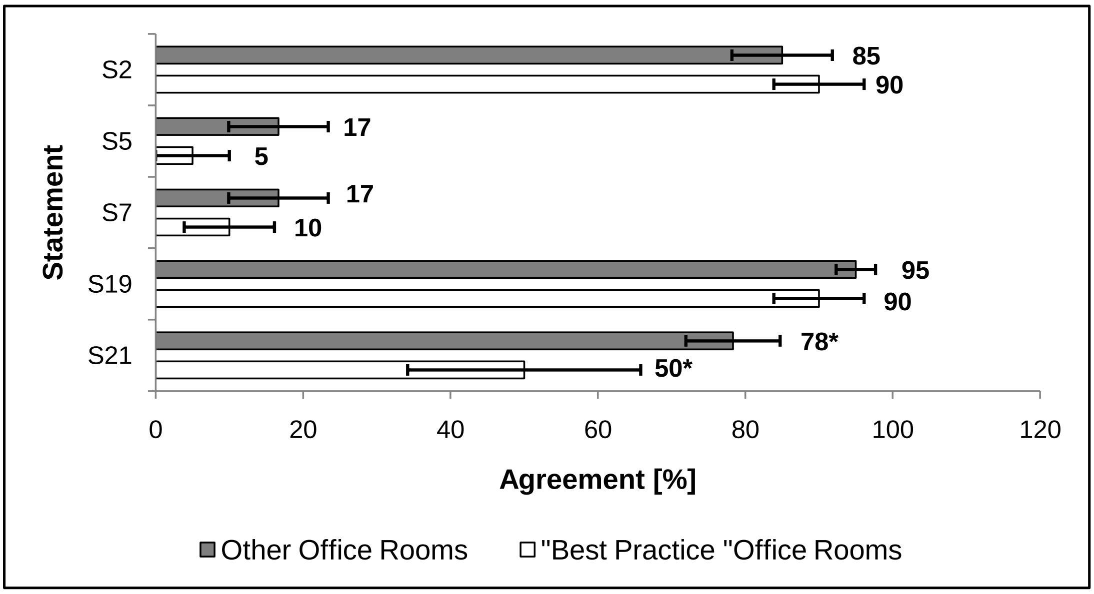


Figure 3.17: Mean agreements for five statements. - The figure shows the occupants' agreements to the statements S2, S5, S7, S19 and S21.

The agreement values have been derived from the questionnaires as explained in Chapter 2. The average agreement with statement S2 was found to be 90% for the "Best Practice" Office Rooms and 85% for the Other Office Rooms of the LESO building, the difference not being statistically significant. Recent studies have found that agreement with statement S2 is typically around 70% in the US (2). Supposing that the situation in Switzerland is comparable, all office rooms within this experimental building can be considered extremely comfortable as far as lighting is concerned. The high percentages of agreement with statement S19 indicate that the electric lighting is appropriate in all offices (no significant difference between the "Best Practice" Office Rooms and the Other Office Rooms). The very low agreement levels to statements S5 and S7 indicate that "not enough light"-situations are rare (no significant difference between the "Best Practice" Office Rooms and the Other Office Rooms). Agreement values for statement S21 show that lamp positioning within the LESO building is not always ideal, especially in the case of the "Best Practice" Office Rooms (trend for significant difference between the two means, Student's two-sided t-test yields $p < 0.1$).

Figure 3.18 shows that there is no correlation between the LPD in an office room and its occupants satisfaction with the lighting conditions.

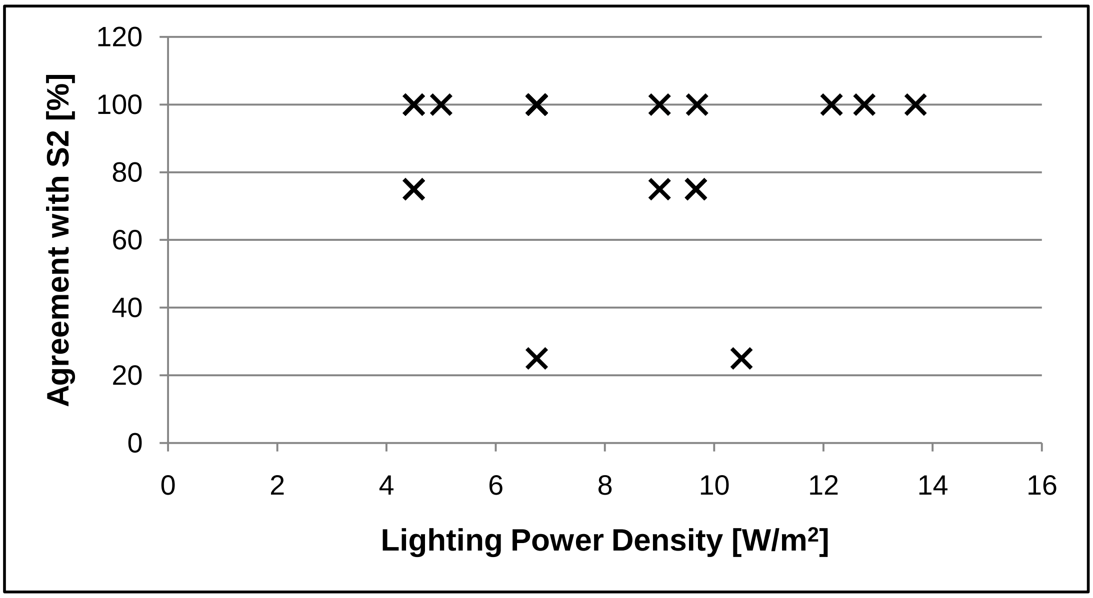


Figure 3.18: Satisfaction with lighting conditions vs. Lighting Power Density. - The figure shows that there is no correlation between the LPD in an office and its occupants satisfaction with the lighting conditions in the LESO building.

These results illustrate that all building occupants are highly satisfied with their office lighting environment (and especially the artificial lighting system) and that this satisfaction does not depend on their offices' LPDs. In other words, occupants who work in the two "Best Practice" Office Rooms are as happy with their office lighting as their colleagues working in offices with more powerful electric lighting systems. In general, within the described ADS-equipped office rooms, occupant annoyance does rather arise from situations where there is too much light than from situations where there is not enough light (see Chapter 2).

3.5 Conclusion

It can be concluded that the most appropriate light sources for energy-efficient and yet comfortable office lighting scenarios are highly efficient fluorescent tubes and CFLs. However, white LEDs become more and more available and have a great potential for replacing parts of the fluorescent lighting installations over the next few years, especially in task lighting applications. As much as luminaires are concerned, directly emitting luminaires lead to the most energy-efficient lighting solutions, but indirectly emitting luminaires often offer better visual comfort. However, this enhanced visual comfort might not be necessary in all office rooms (e.g. in office rooms where artificial lighting is mainly complementary). For task lighting purposes, the use of portable desk lamps still makes sense. Electronic control gear has many advantages compared to conventional control gear, for example in terms of dimability, energy-efficiency and flickering susceptibility. In addition to that, electronic control gear makes it possible to use advanced lighting control systems (e.g. DALI technology). In order to keep the lighting load in office rooms as low as possible, it makes sense to minimize the Lighting Power Densities (LPDs): power that is not installed cannot be switched on and can therefore not consume electricity. Of course, while minimizing LPDs in office rooms, one must not forget visual comfort: the illuminances inside the office rooms must be sufficiently high and must lead to appropriate uniformities. In addition to that, excessive discomfort glare must be avoided. In the beginning of this doctoral thesis, the electric lighting situation in the LESO building has been assessed. The 15 ADS-equipped office rooms have an average LPD of 9.1 W/m^2, with a "Best Practice" LPD of less than 5 W/m^2. Visual comfort in the office rooms of the LESO building is not correlated with their LPDs.

4

Lighting System Design - Computer Simulations

4.1 Introduction

In the previous Chapter, it was shown that the current electric lighting system in the test office room, which is at the same time the "Best Practice" lighting scenario in the entire LESO building with an LPD of 4.5 W/m^2, is highly appreciated by office occupants. It was therefore decided to take this "Best Practice" lighting scenario as a starting point for the development of yet more energy-efficient lighting scenarios for the test office room.

In order to properly assess the performance of the "Best Practice" artificial lighting system composed of two ceiling-mounted Lip luminaires, a computer model of the LESO building office room 001 (the test office room) has been set up using the ray-tracing software RELUX Vision (85). Figure 4.1 shows the computer model of the test office room. The exact room geometry, the ADS as well as most material properties (for example reflexion factors of walls, ceiling and floor, see Table 4.1) have been measured and introduced into the model.

4.2 Current "Best Practice"-System

Figure 4.2 shows the illuminance distribution in the test office room for the "Best Practice" lighting scenario (2 Lip luminaires, LPD of 4.5 W/m^2): only the electric lighting (and no daylight) has been simulated with RELUX Vision. Five different reference

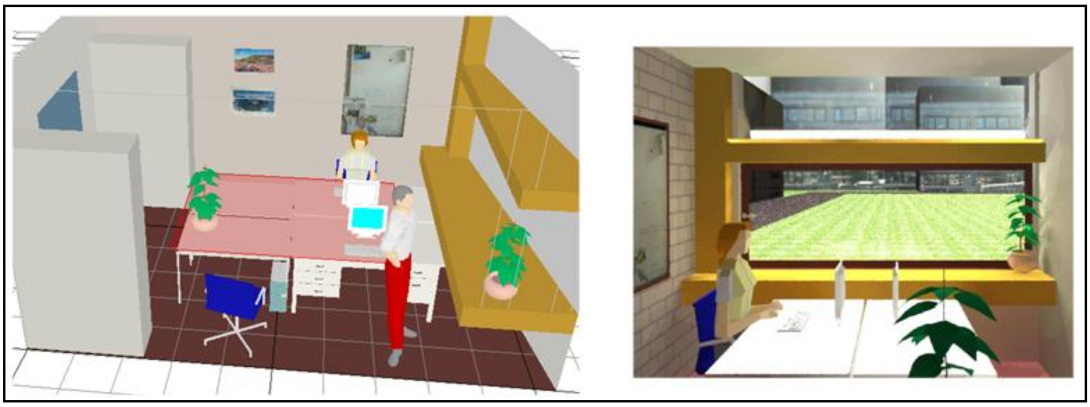


Figure 4.1: The RELUX model. - RELUX Vision model of the test office room (4.7 m depth, 3.4 m width, 2.8 m height.

Room Element	Mean Reflectance [%]	SD [%]
Ceiling (window section)	81.57	0.39
Ceiling (rear section)	75.82	0.39
Wall (gray)	44.12	1.41
Wall (white)	85.22	0.58
Floor	11.57	0.54
Wood elements	31.12	4.03

Table 4.1: Material properties in test office room. - This Table gives an overview of the mean reflectance values of the test office room's elements.

planes (all 75 cm above floor level) have been considered during the simulations: entire office, larger workplane, workplane, as well as two individual workspaces. These individual workspaces have a size of 0.6 m x 0.6 m and are located on those workplane areas where the two office occupants carry out specific visual tasks (e.g. writing or reading) that require reasonably high illuminances. This is a usual choice for designing energy-efficient lighting situations (44). The simulated room contained no furniture in order to keep these initial simulations as transparent as possible.

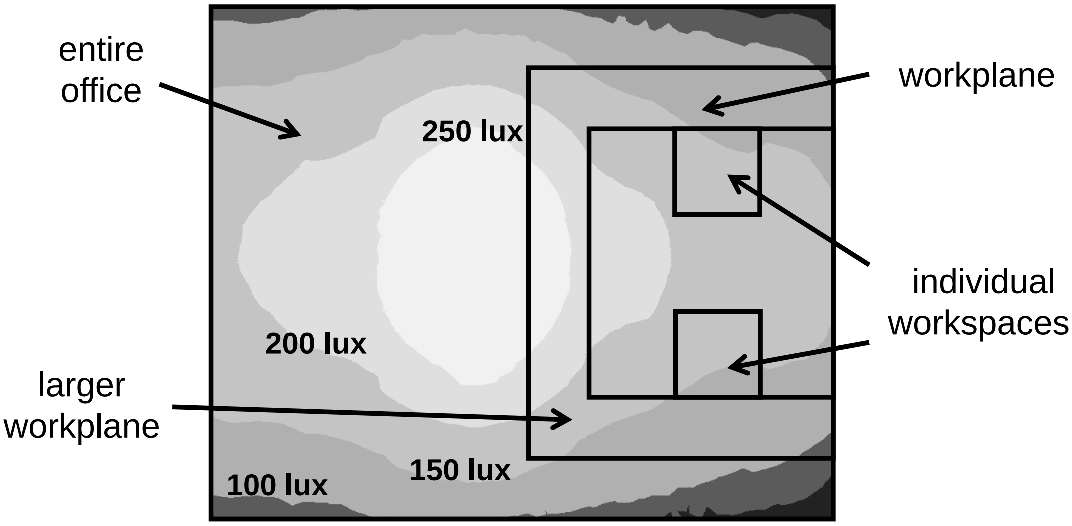


Figure 4.2: Illuminance distribution - "Best Practice". - The figure shows the illuminance distribution in the test office room for the "Best Practice" lighting scenario (2 Lip luminaires, LPD of 4.5 W/m^2): only the electric lighting (and no daylight) has been simulated with RELUX Vision. Five different reference planes (all 75 cm above floor level) have been considered during the simulations: entire office, larger workplane, workplane, as well as two individual workspaces.

The simulation results clearly show an illuminance maximum in the middle of the room, with illuminances ranging from 250 to 300 Lux. This is coherent with the occupants' impression that lamps within this office might not be in the "right place". Figure 4.3 summarizes the results of these first simulations in terms of average illuminances and uniformities.

It is important to note that (according to these initial simulations) illuminances are substantially lower than the values suggested by the corresponding standards (see

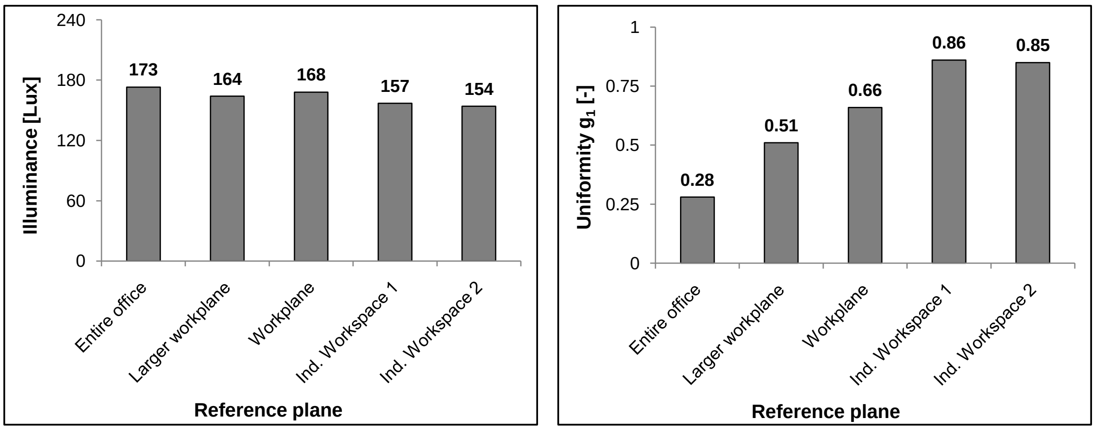


Figure 4.3: Illuminances and uniformities - "Best Practice". - The Figure summarizes the results of the first simulations in terms of average illuminances and uniformities.

Chapter 3). Nevertheless, the building's occupants feel that this lighting environment is extremely comfortable (see strong agreement with statement S2 in Figure 3.17) and that the electric lighting systems are powerful enough (see strong agreement with statement S19). One might argue that the academic usage of this building might not ensure that enough "old people" were represented in the study. As a matter of fact, older people tend to prefer higher illuminance levels (29). The POE described in Chapters 2 and 3, however, included six people aged over 45 (three out of them even older than 55). All of them found that their office lighting was in general very comfortable and none of them judged low illuminances to be a problem. However, temporary task lighting seemed to be used somewhat more regularly by the older occupants than by the younger ones.

One might further argue that any electric lighting system should be able to provide adequate illuminance levels at night (i.e. dimensioning for the worst case with no daylight at all). As explained in Chapter 3, this is however not the optimal strategy for office rooms with well-performing ADS where electric lighting is mainly complementary. The results of Chapters 2 and 3 clearly show that an appropriate combination of Anidolic Daylighting Systems, thriftily dimensioned ambient lighting and temporary task lighting can lead to high acceptance levels amongst office workers. In particular, it has been shown that the lighting conditions within the "Best Practice" Office Rooms are comparable to those of the other LESO office rooms.

Furthermore, Chapter 5 will reveal that the RELUX Vision model presented here is very conservative and that the real illuminances on the office room's reference planes are in reality higher than the simulated values.

Taking the situation within these "Best Practice" Office Rooms as a starting point for developing new and even more energy-efficient electric lighting systems is therefore an appropriate choice. If these new systems create lighting conditions similar to the one illustrated in Figures 4.2 and 4.3, one could assume that user satisfaction with the new lighting design will also be very high.

4.3 A New System Based on Fluorescent Tubes

Various designs of electric lighting systems were therefore simulated for the test office room using the RELUX Vision software. Figure 4.4 shows the illuminance distribution for two of them.

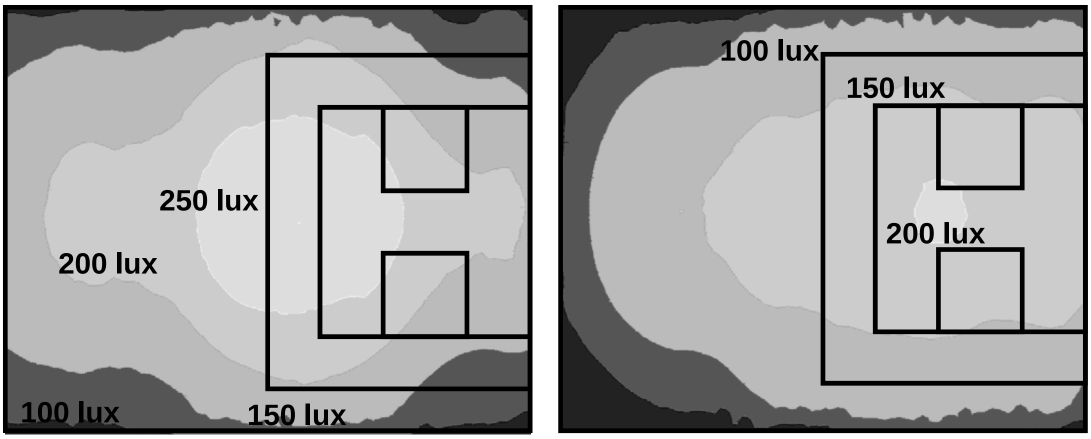


Figure 4.4: New illuminance distributions - Fluorescent lighting. - The figure shows the illuminance distribution for the two low-LPD lighting scenarios based on fluorescent technology.

In both cases, two ceiling-mounted luminaires with 96% optical efficiency have been chosen (Tulux ZEN3, (104)). Despite the fact that the manufacturer is not claiming that the latter is based on non-imaging optics, such a high efficiency can only be explained by the use of an étendue conserving optical design (113) (while additionally assuring the use of highly reflective coating materials). This luminaire type is shown in Figure 4.5.

The ZEN3 luminaires leading to the illuminance distribution in Figure 4.4 (left) are

Figure 4.5: The ZEN3 luminaire. - The figure shows a ZEN3 luminaire by Tulux (104) mounted on the test office room's rail system.

each equipped with one T5 fluorescent tube (28 W) and the corresponding ECG. The total power consumption of if this combination was measured and equals 31 W. The LPD for the simulated office room thus equals 3.9 W/m^2, including the ECG's power consumption. The simulation represented in Figure 4.4 (right) uses one T5 fluorescent tube (21 W) in each luminaire (system power consumption of 24 W). The resulting LPD (ECG included) is equal to 3 W/m^2. Compared to the current "Best Practice" situation represented in Figure 4.2, the new luminaires have been slightly displaced to the right. One can observe that the illuminance maximum has, therefore, also shifted to the right. This leads to higher illuminance levels on the workplane, compared to the rest of the room. Figure 4.6 compares the current "Best Practice" installation with the two new lighting designs in terms of average simulated reference plane illuminances.

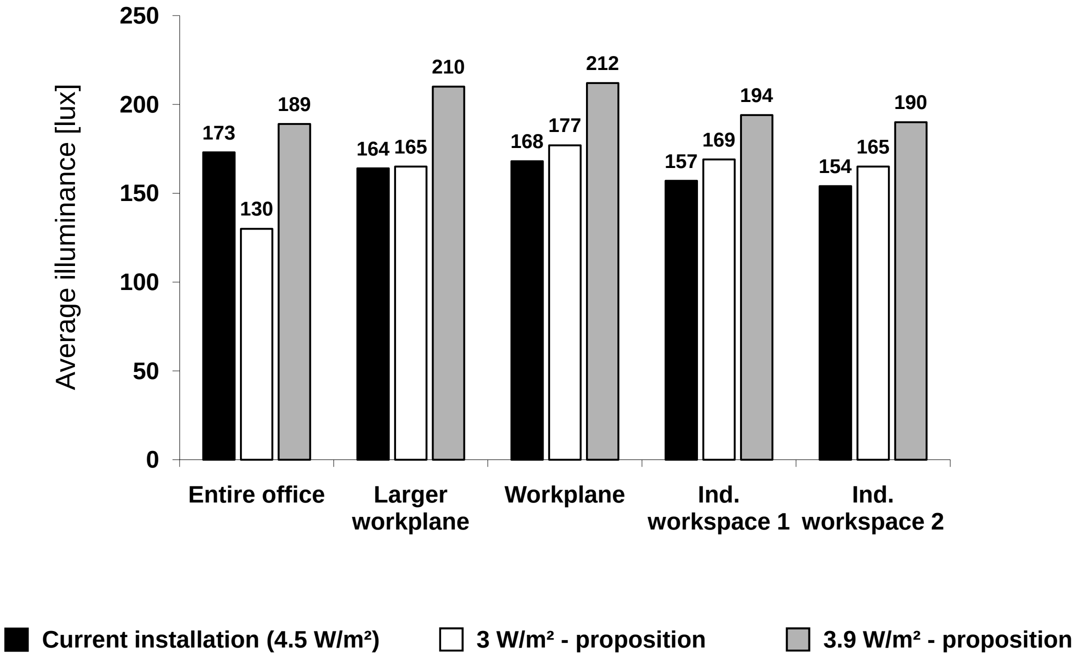


Figure 4.6: Illuminance comparisons - Fluorescent lighting. - This Figure compares the current "Best Practice" installation with the two new lighting designs in terms of average simulated reference plane illuminances.

It can be observed that the 3.9 W/m^2-design leads to higher mean illuminances on every reference plane than the current installation. We can thus assume that this solution will not cause major difficulties as much as horizontal illuminances are concerned. The 3 W/m^2-design is also a potentially interesting option: except for the reference plane "entire office", the mean illuminances are slightly higher than those offered by the current installation. The lower illuminances towards the rear of the room might not cause major annoyances to the office occupants, since this is where the room's entrance is located.

However, as explained in Chapter 3, satisfaction with the lighting installation in an office room does not only depend on the supplied horizontal illuminances; another very important issue is the illuminance uniformity. Figure 4.7 shows a comparison between the current lighting installation and the two new designs in terms of uniformities g_1 (i.e. the lowest illuminance on each reference plane divided by the corresponding average illuminance).

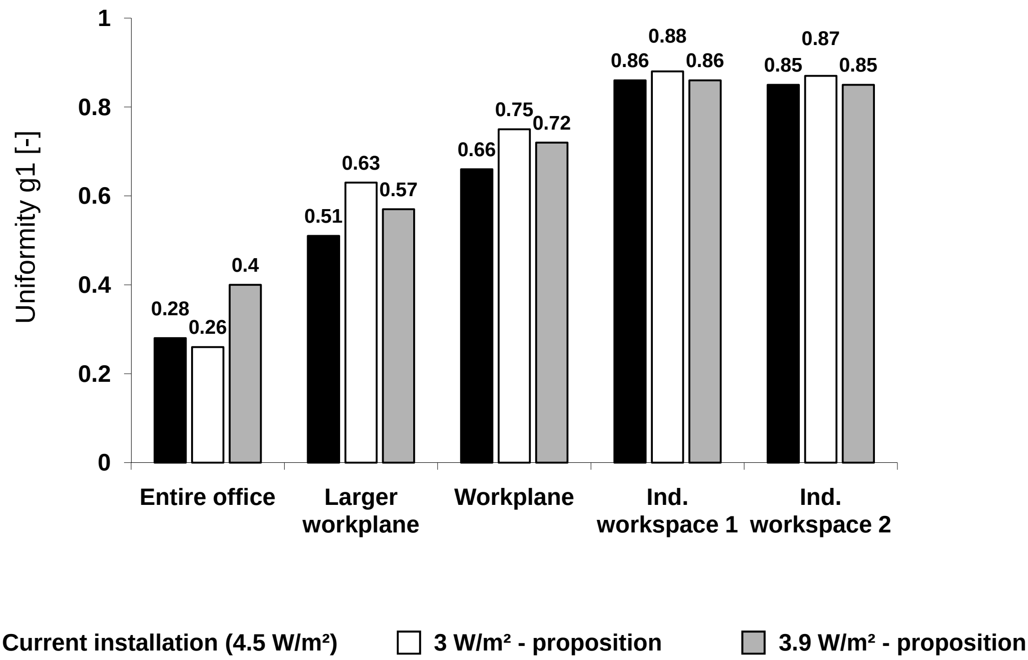


Figure 4.7: Uniformity comparisons - Fluorescent lighting. - This Figure compares the current "Best Practice" installation with the two new lighting designs in terms of average simulated illuminance uniformities on the different workplanes.

It can be observed that the 3 W/m^2-design outperforms the current "Best Practice" installation and the 3.9 W/m^2-design on every reference plane, except for the "entire office" plane. The uniformity values obtained with the 3.9 W/m^2-design are also equal or better than the values obtained for the current "Best Practice" solution. In conclusion, the simulation results show that, at least as much as horizontal illuminances and uniformities are concerned, the two new lighting designs are fully comparable to the current "Best Practice" solution (or even slightly better).

4.4 A new system based on white LEDs

In 2007 and 2008, the impact of using white LEDs instead of conventional light sources in an office environment has been studied within the framework of this doctoral thesis(34). After identifying suitable LED products, the RELUX Vision software tool was used for simulating energy-efficient lighting solutions based on LED technology for the test office room. In particular, the use of white LED light sources in ceiling mounted spot luminaires (Altea LED Bianco 180 mm, manufactured by ARES S.R.L, (7)) has been considered (see Figure 4.8). Those luminaires were initially equipped with five white LEDs (1.2 W power consumption each) and designed rather for decorative than for general lighting. In absence of specific LED luminaires for general lighting (during the year 2007), it was assumed that these luminaires could be used for this purpose by simply raising their simulated light output flux in RELUX Vision.

During the simulations, the luminaires' output flux was gradually increased to luminous efficacies between 60 and 100 lm/W, corresponding to values achieved by the most advanced LED technology. Figures 4.9 to 4.11 show the resulting illuminance distributions. The illuminance distribution over the entire workplane and on the other reference planes introduced in Section 4.2 can be observed in the Figure 4.9. The source's luminous efficacy in this case is equal to 60 lm/W. Figures 4.10 and 4.11 show the simulation results with lamp efficacies of 80 and 100 lm/W, respectively, for the same room.

The bar chart in Figure 4.12 shows the average illuminances on the different reference planes of the current installation, as well as those of the considered LED-simulations with luminous efficacies ranging from 60 to 100 lm/W. The dependency between the average illuminances and the LED efficacies is quasi-linear. One can observe that the 80 and 100 lm/W LED-lighting solutions perform better than the current "Best Practice" installation for all reference planes. The bar chart in Figure 4.13 shows the corresponding illuminance uniformities g_1. One can observe that LEDs with an efficacy of 80 lm/W provide the best illuminance uniformities on the different reference

Figure 4.8: The AlteaLED luminaire. - The figure shows the Altea LED Bianco 180 mm, manufactured by ARES S.R.L, (7), which has been used during the simulations.

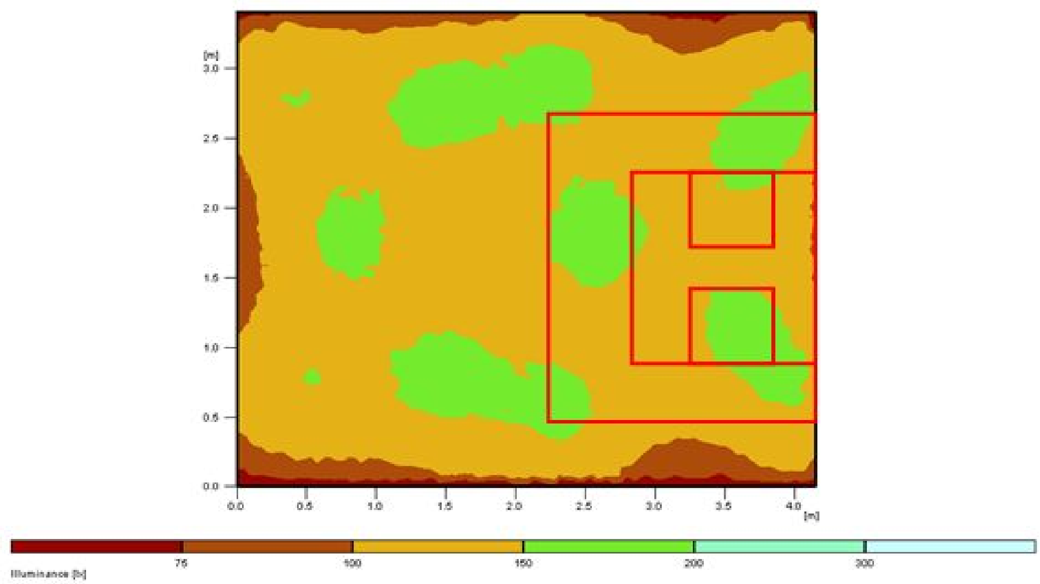


Figure 4.9: LED lighting scenario - 60 lm/W. - The figure shows the simulated LED lighting scenario for a simulated luminous efficacy of 60 lm/W.

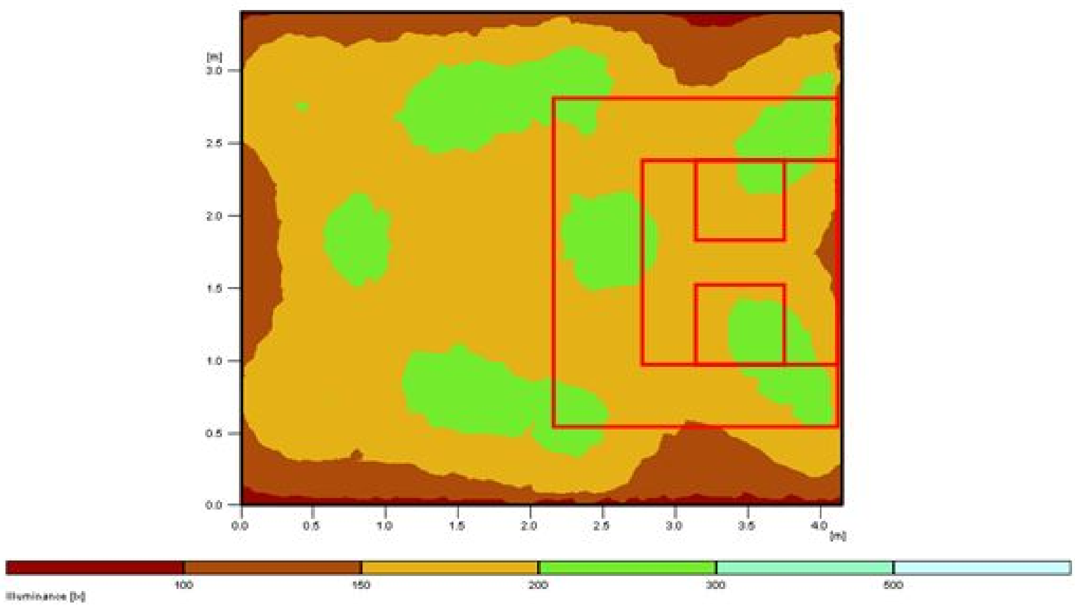


Figure 4.10: LED lighting scenario - 80 lm/W. - The figure shows the simulated LED lighting scenario for a simulated luminous efficacy of 80 lm/W.

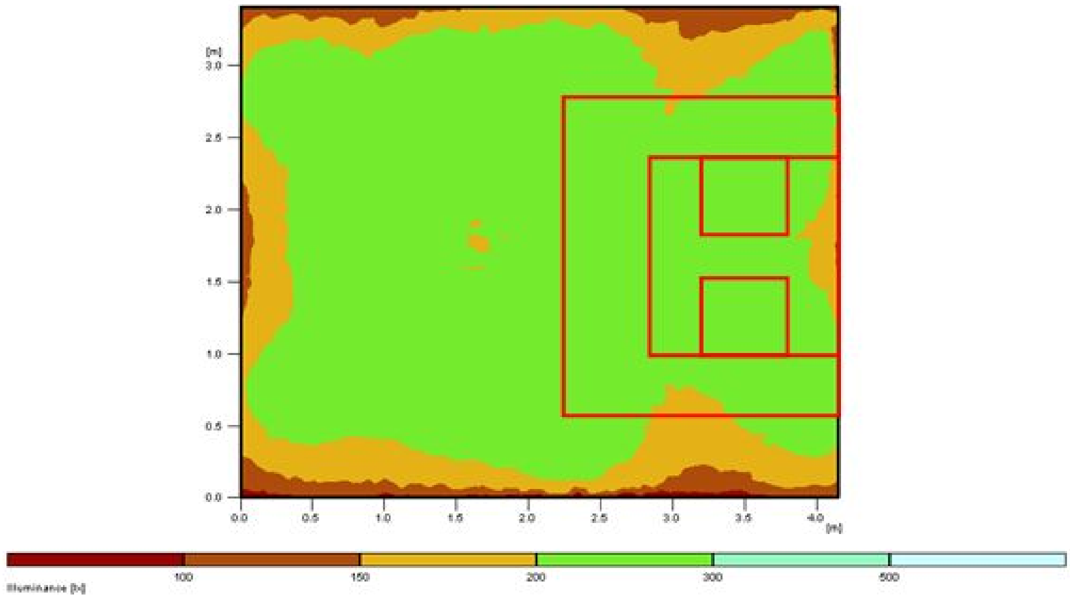


Figure 4.11: LED lighting scenario - 100 lm/W. - The figure shows the simulated LED lighting scenario for a simulated luminous efficacy of 100 lm/W.

planes. On most reference planes, uniformities achieved by the 100 lm/W LED-solution are slightly lower than those achieved by the 80 lm/W LED-solution. This leads to the conclusion that the best trade-off between average illuminance and uniformity for this particular situation is obtained for a lamp efficacy of 80 lm/W; it suggests that white LEDs would become a real alternative for the substitution of fluorescent tubes once they reach luminous efficacies of 80 lm/W. Additional simulations, assuming an 80 lm/W lamp efficacy, were run in consequence.

The luminaires used during these additional simulations were identical to those used previously (Altea LED Bianco, 5 x 1.2 W); their number and positions were however modified with the aim of reducing the LPD of the test office room. The reference for this set of simulations with lamp efficacies of 80 lm/W is the one already shown in Figure 4.10 ("LED Case 1"). Figure 4.14 illustrates an alternative design including ten luminaires and the resulting illuminance distribution within the office room. The LPD in this case is 3.75 W/m^2, which is referred to as "LED Case 2".

"LED Case 3" is shown in Figure 4.15. Ten LED-luminaires were also used in this case, but their positions on the ceiling have been substantially modified. Eight of the

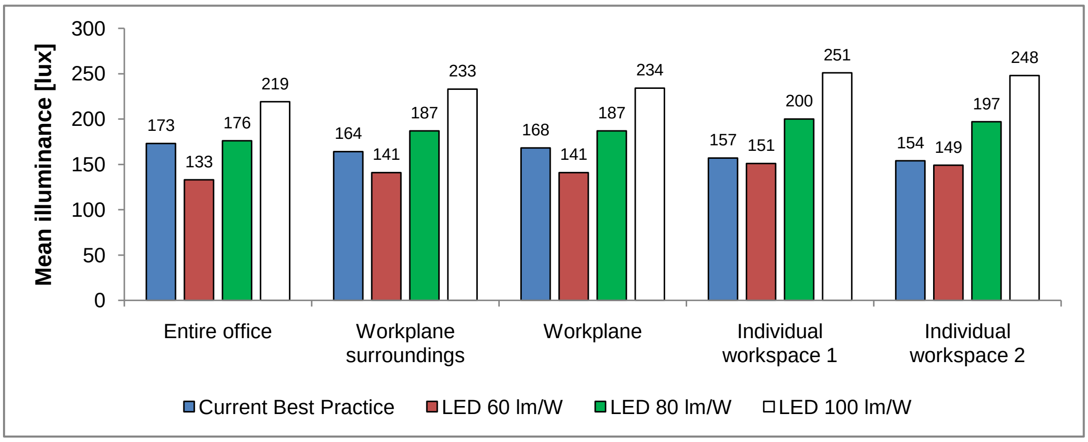


Figure 4.12: Illuminance comparisons - LED lighting. - The figure shows the average illuminances on the different reference planes of the current installation, as well as those of the considered LED-simulations with luminous efficacies ranging from 60 to 100 lm/W.

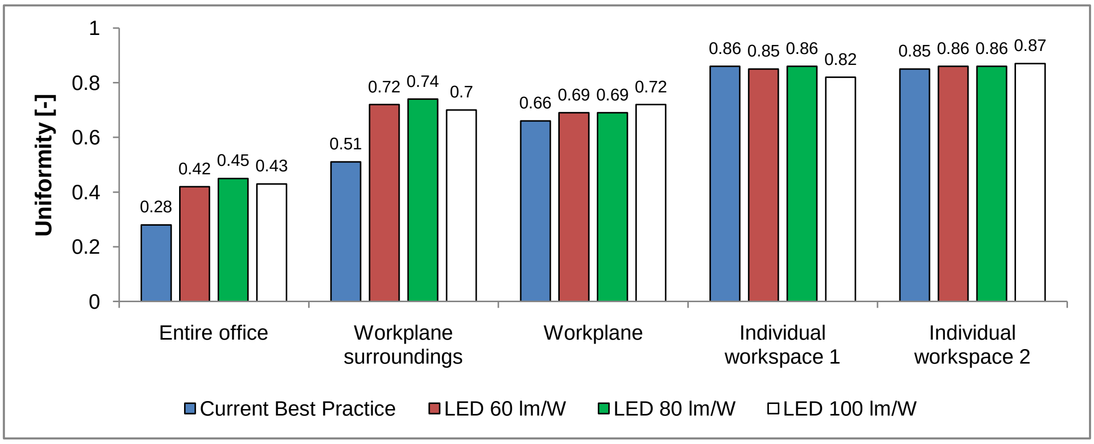


Figure 4.13: Uniformity comparisons - LED lighting. - The figure shows the illuminance uniformities g_1 on the different reference planes of the current installation, as well as those of the considered LED-simulations with luminous efficacies ranging from 60 to 100 lm/W.

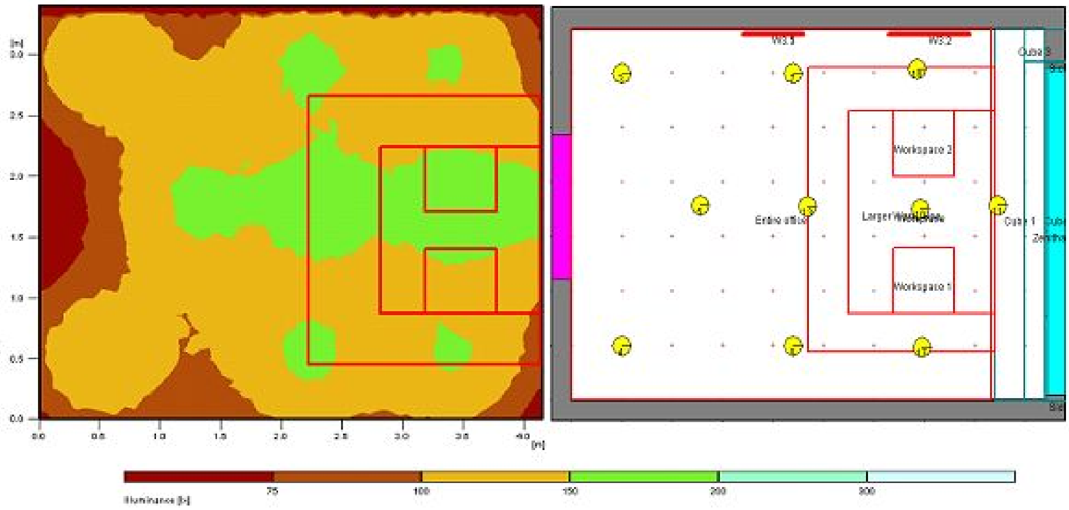


Figure 4.14: 80 lm/W LED lighting - LED Case 2. - The figure illustrates an alternative LED design including ten luminaires and the resulting illuminance distribution within the office room. The LPD in this case is 3.75 W/m^2.

ten luminaires are not pointing directly downwards but are aligned in the directions indicated by the black arrows. One can observe that the illuminance distribution is very different to the one of "LED Case 2".

Figure 4.16 shows another configuration referred to as "LED Case 4". This installation is derived from "LED Case 3", but the two downwards-pointing LED-luminaires have been removed. This leads to an LPD of only 3 W/m^2.

Figure 4.17 illustrates the average illuminances for the five reference planes for each of the four cases as well as for the current "Best Practice" installation. It can be observed that the 4.5 W/m^2 LED-solution (LED Case 1) clearly outperforms the current "Best Practice" installation (with an LPD of equally 4.5 W/m^2). The average illuminances of the 3 W/m^2 LED-design (LED Case 4) are substantially lower than those of the current installation. The design showing an LPD of 3.75 W/m^2 (LED Case 2) performs worse than the current installation in terms of average illuminances; "LED Case 3" yields average illuminances comparable to those of the current installation. It is interesting to note that that "LED Case 3" offers a 10.4% average illuminance enhancement compared to "LED Case 2". This improvement has been achieved only through a different luminaire positioning. It underlines the significance of a proper planning when designing energy-efficient lighting solutions.

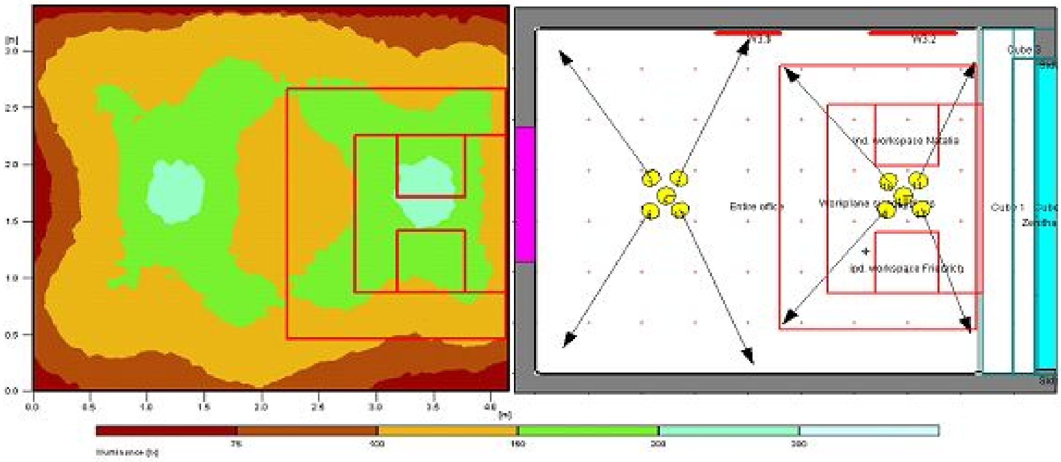


Figure 4.15: 80 lm/W LED lighting - LED Case 3. - The figure shows an alternative LED design with modified lamp pointing directions.

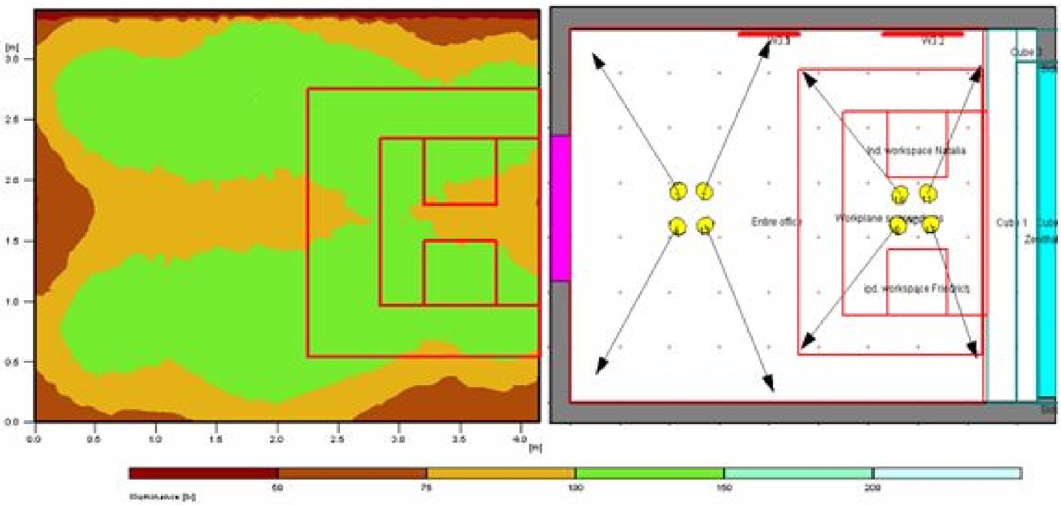


Figure 4.16: 80 lm/W LED lighting - LED Case 4. - The figure shows another configuration referred to as "LED Case 4". This installation is derived from "LED Case 3", but the two downwards-pointing LED-luminaires have been removed.

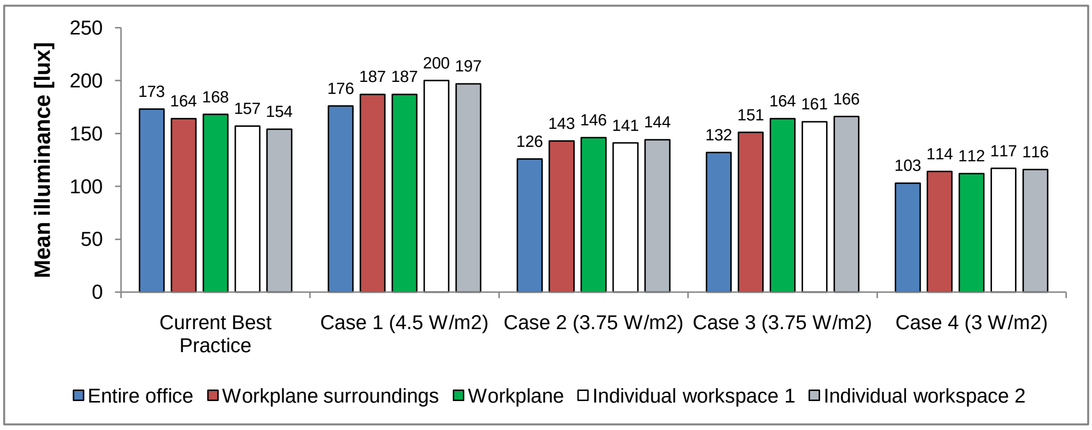


Figure 4.17: Illuminance comparisons - 80 lm/W LED lighting. - The figure shows the average illuminances for the five reference planes for each of the four cases as well as for the current "Best Practice" installation.

The corresponding illuminance uniformities for the different reference planes are shown in Figure 4.18. Cases 1 through 4 yield uniformities comparable to those of the current lighting installation. All cases can therefore be expected to provide an appropriate visual comfort in terms of lighting uniformities.

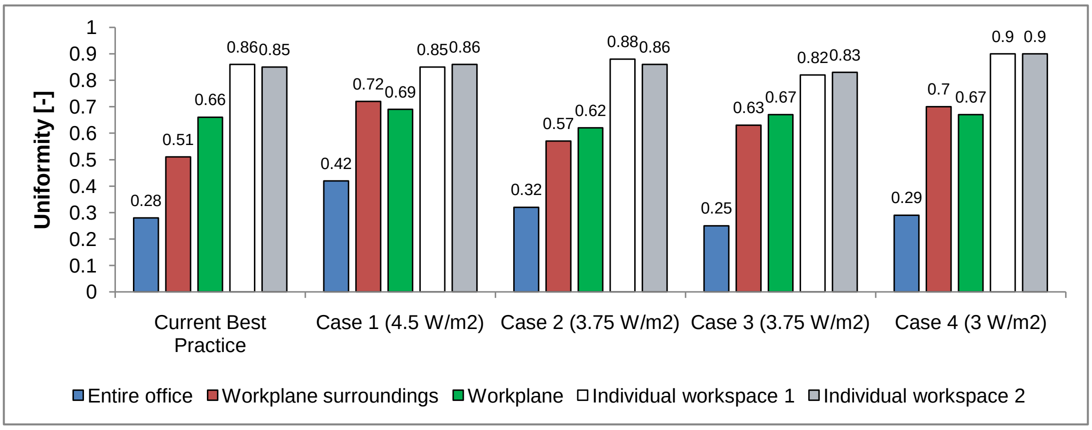


Figure 4.18: Uniformity comparisons - 80 lm/W LED lighting. - The figure shows the resulting illuminance uniformities for the five reference planes for each of the four cases as well as for the current "Best Practice" installation.

Figure 4.19 illustrates the simulation of a 3.25 W/m^2 LED-lighting design where eight Altea LED Bianco luminaires were used and two additional high power LED sources (OSRAM, (77)) were placed right above the individual workspaces. The resulting illuminance distribution at a reference height of 75 cm above floor level is shown in Figure 4.19 (left) whereas Figure 4.19 (right) shows the positioning of the LED luminaires on the office room's ceiling.

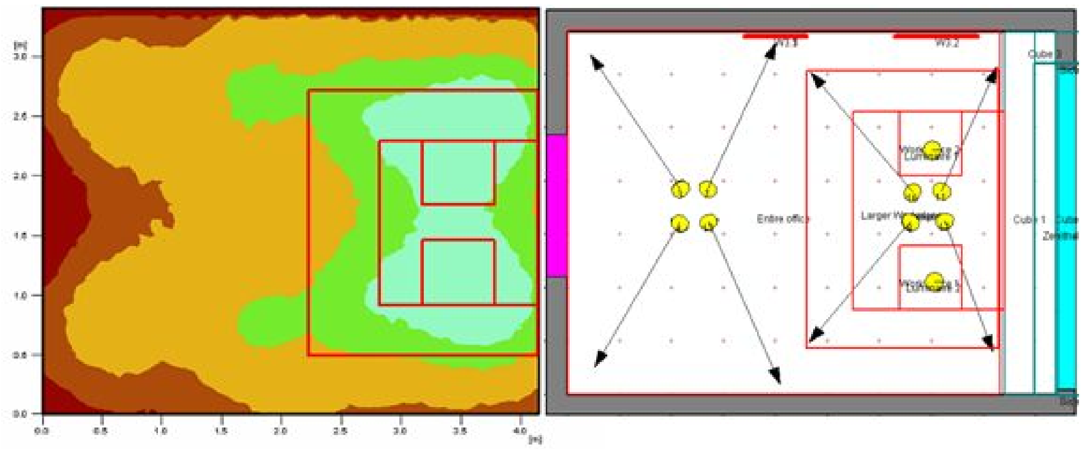


Figure 4.19: Combined LED lighting scenario. - The figure shows the simulation of a 3.25 W/m^2 LED-lighting design where eight Altea LED Bianco luminaires were used and two additional high power LED sources (OSRAM, (77)) were placed right above the individual workspaces.

Figure 4.20 shows the resulting average illuminances and uniformities g_1 for the lighting design illustrated in Figure 4.19. The obtained illuminance values are comparable to the "Best Practice" lighting scenario, the uniformities being reasonably good. The lower values for the reference plane "entire office" are due to very low illuminances near the door, what might not be too annoying to office workers. In any case, this simulated lighting design is a promising configuration to be tested in a future POE study in the LESO building.

These simulations involving white LED light sources have been carried out in 2007 and 2008. At that time, very few LED luminaires for general lighting were available and almost none of them were implemented in the RELUX software tool. As previously explained, a modified version of the Altea LED Bianco 180 mm LED luminaire (generally employed for decorative lighting) was used for that reason. There are still few LED luminaires available today for office lighting, but the situation is evolving rapidly (see Chapter 3 for descriptions of more recent LED products).

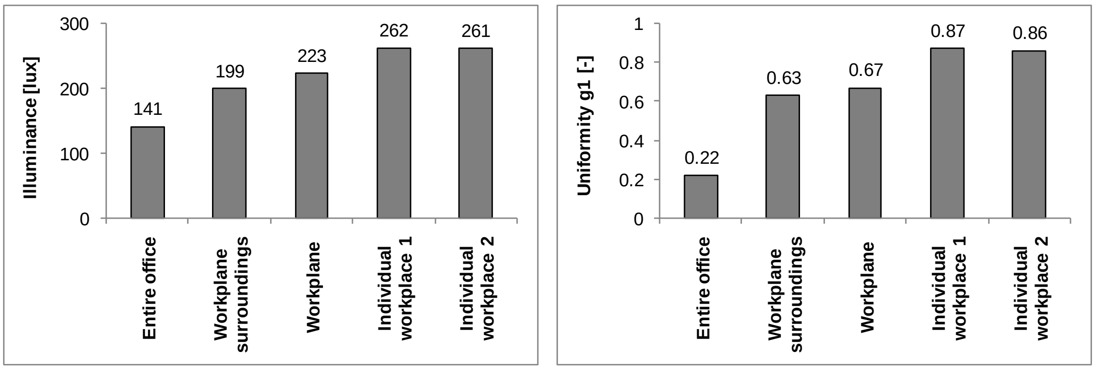


Figure 4.20: Combined LED lighting scenario - Illuminances and uniformities. - The figure shows the resulting average illuminances and uniformities g_1 for the lighting design illustrated in Figure 4.19.

4.5 Conclusion

In order to design more energy-efficient lighting scenarios for the ADS-equipped test office room in the LESO building, a computer model of the room has been set up with the lighting simulation software tool RELUX Vision (85). After having simulated the current "Best Practice" lighting scenario in the test office room, different more energy-efficient lighting scenarios with lower LPDs and yet comparable illuminances and uniformities on the office room's reference planes have been developed. These new lighting scenarios can thus be assumed to be equally well accepted by the office occupants as the current "Best Practice" lighting scenario. This assumption was verified during this doctroral thesis for one of the new lighting scenarios (see Chapter 6). The results of the simulations described in this Chapter further show that fluorescent as well as LED lighting technology have a great potential for energy-efficient, low-LPD office lighting.

5

Installation of a new Electric Lighting System in the Test Office Room

5.1 Introduction

Due to the encouraging simulation results described in Chapter 4, it was decided to set up one of the highly energy-efficient lighting scenarios in the test office room. Since the most efficient and reliable technology for office lighting is for the time being fluorescent lighting, it was decided to implement the 3.9 W/m^2-solution based on two ZEN3 luminaires (see Chapter 4) for ambient lighting. This is a conservative but yet flexible choice. For temporary task lighting, a portable desk lamp equipped with an LED light bulb was chosen.

5.2 Installation of the Ambient Lighting system

In order to make the new lighting installation of the test office room in the LESO building as flexible as possible, a rail system was mounted on the room's ceiling. This rail system is composed of aluminum rails on movable carriages, which allow the quick interchange and precise positioning of different luminaire types. Figure 5.1 shows the rail system with two mounted Tulux ZEN3 luminaires.

The two ZEN3 luminaires were equipped with one 28 W warm-white T5 fluorescent tube (OSRAM FH 28W/830 HE) each and positioned as determined through the pre-

Figure 5.1: Ceiling-mounted rail system. - The figure shows the rail system with two mounted Tulux ZEN3 luminaires.

vious simulations carried out with RELUX Vision in order to achieve the illuminance distribution of Figure 4.4 (left). Each luminaire was equipped with a DALI compatible ECG (OSRAM Quicktronic Intelligent QTi DALI 1x28/54 DIM); this control gear is shown in Figure 5.2.

Figure 5.2: Electronic Control Gear. - The figure shows the Electronic Control Gear mounted in the ZEN3 luminiares.

Three different ways to control the ceiling-mounted luminaires have been tested during this doctoral thesis. The first two use the DALI-functions of the ECG shown in Figure 5.2. This requires an additional electronic component, a so called DALI controller. One of the most basic DALI controllers available, the OSRAM DALI Easy II, has been chosen for the project; it is shown in Figure 5.3.

This controller is able to drive a maximum of 32 ECGs (as well as the associated luminaires and light sources). ECGs for halogen lamps and LEDs can also be controlled via the DALI Easy II. Figure 5.4 shows the schematic wiring diagram of the test office room within the LESO building for the case where a DALI controller is used. Each

Figure 5.3: DALI Easy II lighting control unit. - The figure shows the DALI Easy II lighting control unit installed in the test office room of the LESO building.

of the two ECGs as well as the DALI controller are separately connected to the 240 V power supply of the room. The DALI ports of the two ECGs are controlled via the output channels CH1 and CH3 of the DALI Easy II device, respectively. The input signal for the DALI Easy II control unit is issued either from a standard push button coupler, from a connected PC or from a remote control and associated infrared (IR) receiver.

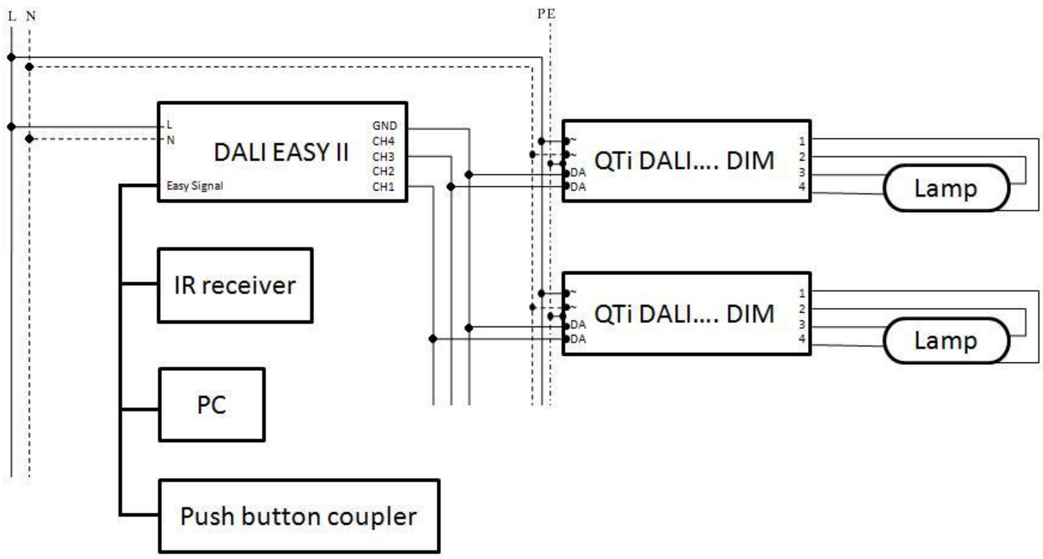


Figure 5.4: DALI lighting control - Wiring diagram. - The figure shows the the schematic wiring diagram of the test office room within the LESO building for the case where a DALI controller is used.

During this doctoral thesis, the control options "Remote control / IR receiver" and

"PC" were tested. Figure 5.5 shows the remote control as well as the IR receiver. The latter can be connected to the "Easy Signal" input of the DALI Easy II controller via a cable (2 m of length) and an RJ 11 connector.

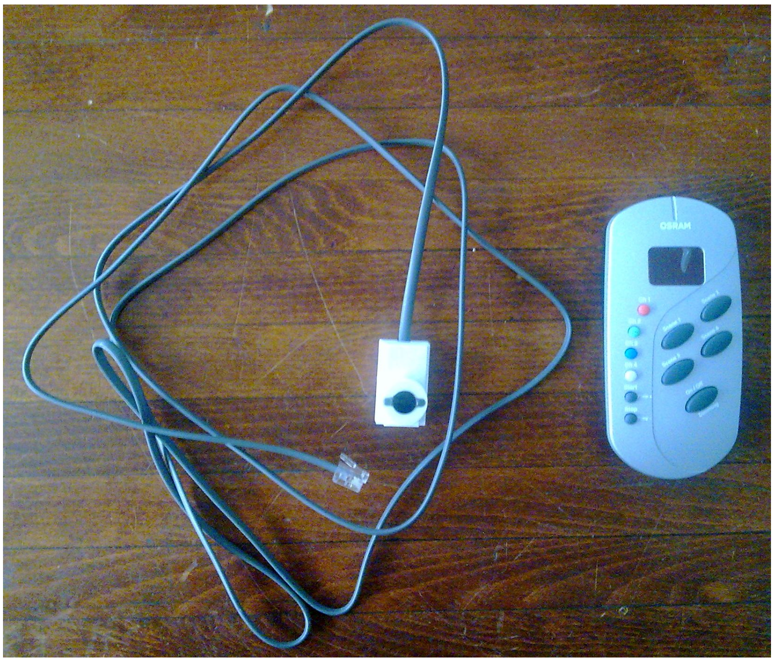


Figure 5.5: Infrared sensor and remote control. - The figure shows the remote control as well as the IR receiver connected to the DALI controller.

Each of the two ECGs and lamps shown in Figure 5.4 can be switched "on / off" and dimmed separately using the remote control. In addition to that, four lighting scenarios can be stored and easily selected afterwards.

The second possibility to drive the two Tulux ZEN3 luminaires tested during the project is to connect a PC to the "Easy Signal" input of the DALI Easy II control unit (see Figure 5.3); this is done via a USB / RJ 11 adapter. The OSRAM software tool "EASY Color Control" can then be used to communicate with the two ECGs (see Figure 5.2) and the attached luminaires via the DALI Easy II control unit. Figure 5.6 shows a picture of the USB / RJ 11 adapter and a screenshot of the software tool.

The name of the software tool already indicates that its main purpose is color control, and not simply office lighting control. As a matter of fact, EASY Color Control is capable to drive not only white fluorescent tubes of different color temperatures,

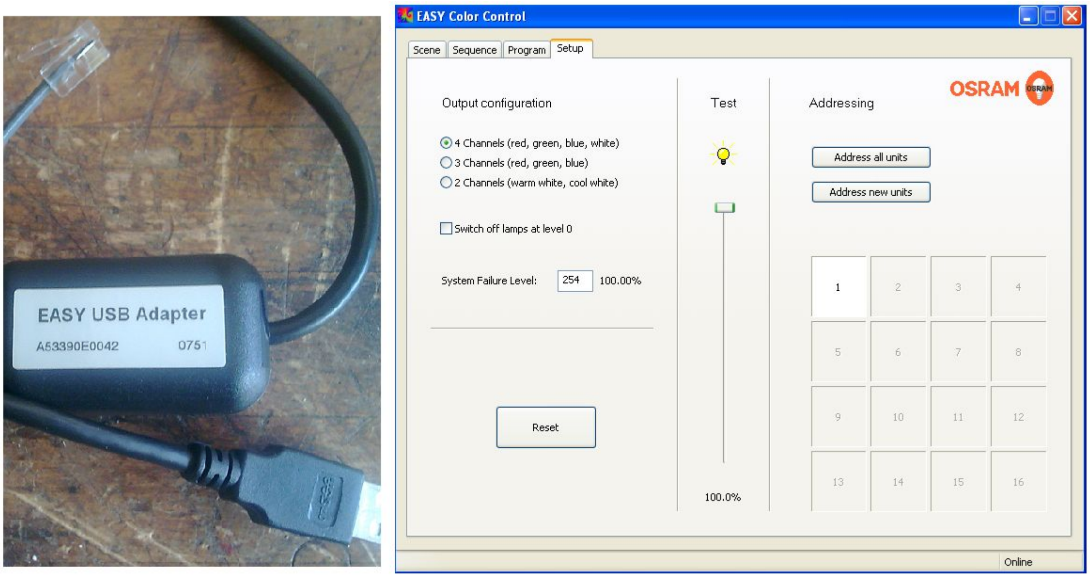


Figure 5.6: Lighting control via PC. - The figure shows a picture of the USB / RJ 11 adapter and a screenshot of the software tool.

but also colored fluorescent tubes, colored LEDs as well as white LEDs. It is however possible to use the tool for simple switching and dimming actions, as well as for the definition of various lighting scenarios. The main advantage of this type of lighting control in terms of comfort is that the occupants can easily switch "on / off" and dim the two Tulux ZEN3 luminaires via their PCs. However, two important drawbacks were experienced during an in-depth test of the software. First of all, the driver for the USB adapter caused significant problems under Windows Vista; this is of course not acceptable for such an important building service as office lighting. In addition to that, the EASY Color Control tool might be appropriate for managing complex color changes, sequences or daylight imitations. For our scope (i.e. office lighting control), it was oversized and confusing. Switching and dimming of only two white fluorescent tubes is simply not as straightforward as it should with this software tool be to represent a real alternative to the previously introduced remote control.

The third possibility for controlling the two Tulux ZEN3 luminaires that has been evaluated during this doctoral thesis is the use of the ECGs' "Touch Dim" function. This function makes it possible to switch and dim the light sources without the use of an additional DALI control unit (such as the DALI Easy II). Figure 5.7 shows the wiring diagram for this solution in our specific test office setting.

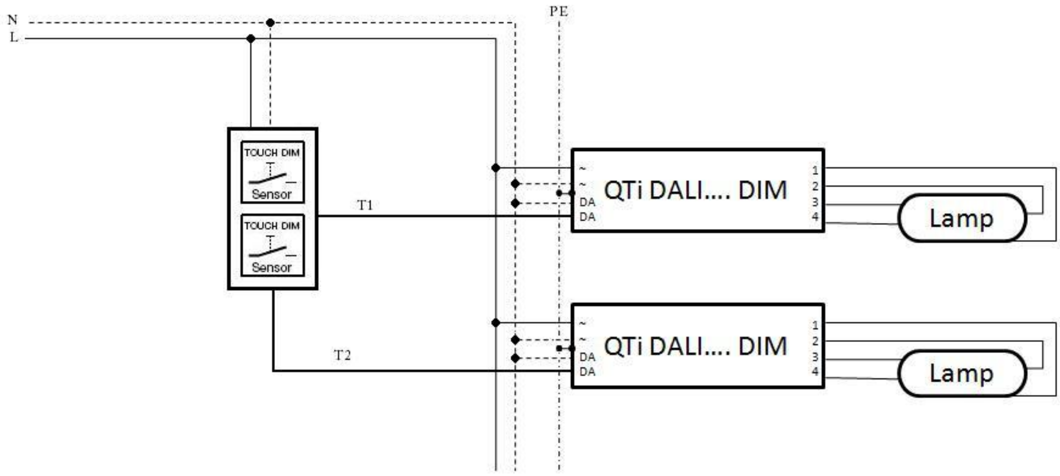


Figure 5.7: Touch Dim lighting control - Wiring diagram. - The figure shows the wiring diagram of the test office's lighting installation for Touch Dim lighting control.

Simple hand switches or electric push buttons (see Figure 5.8) can be used as "Touch Dim Sensors". The ECGs, as well as the sensors, are connected to the 240 V power supply. One of each ECG's DALI inputs is connected to the neutral conductor of the 240 V power supply, the other one is connected to one of the "Touch Dim Sensors" (via the T1 or T2 lines, respectively). The T1 and T2 lines are connected to the phase once the "Touch Dim Sensors" are pushed. Short pushing (i.e. less than 1s) causes switching (on or off) and long pushing (i.e. longer 1s) causes dimming (alternatively dimming towards higher or lower light flux).

The major advantages of this technical solution is that no additional DALI control unit is needed and that the handling of the switches and the associated actions on the luminaires are extremely straight-forward. One possible drawback of the solution is the fact that the switches are not necessarily located within easy reach of the office occupants. However, this might not be a problem since the existing light switches within the LESO building are all installed next to the doors (i.e. out of reach for most occupants). This fact is, nevertheless, not causing major annoyances to the occupants (see Chapters 2 and 3).

For the test office room. it was therefore opted for the simple, straight-forward and

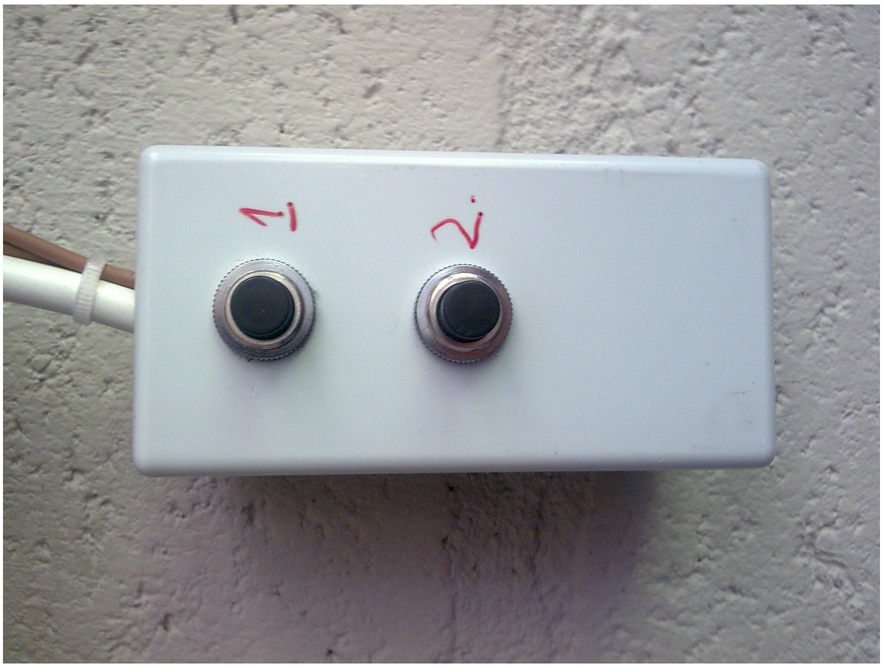


Figure 5.8: Touch Dim push button couplers. - The figure shows the two push button couplers associated with the Touch Dim lighting control.

cost-effective "Touch Dim Sensor"-solution using the two push buttons illustrated in Figure 5.8.

5.3 Installation of the task lighting system

Within the framework of this doctoral thesis, two LED light bulbs were tested in a task lighting application: the PHILIPS Master LED Bulb "Cold white" (showing a luminous efficacy of 32.9 lm/W) and the PHILIPS Master LED Bulb "Warm White" (showing a luminous efficacy of 22.1 lm/W)(78). The latter is shown in Figure 5.9.

For both lamps, a lifetime of 45'000 hours is announced by the manufacturer. A comparable CFL produced by the same manufacturer (PHILIPS Genie WW 827) comes with a luminous efficacy of 54.5 lm/W and a lifetime of 8000 hours. If we assume a market price of approximately 100 CHF for the LED light bulbs and a market price of approximately 10 CHF for the CFL lamps (corresponding offers can be found on the Internet), this yields an installation cost of 2.22 CHF/1000 operating hours for the LED bulbs and 1.25 CHF/1000 operating hours for the CFL. In terms of luminous

Figure 5.9: MASTER LED bulb by Philips. - The figure shows the PHILIPS Master LED Bulb "Warm White" with a luminous efficacy of 22.1 lm/W.

efficacy and cost, these white LED bulbs are therefore not yet competitive compared to CFLs. They have, however, one important advantage in terms of ergonomic handling compared to the latter and have therefore been chosen as complementary task lighting solution in our test office room. This advantage will be discussed in the next Section.

5.4 Lighting Performance Assessment

Once the setup of the complementary electric lighting system described in the two previous Sections had been completed, a detailed lighting performance assessment of the system was carried out. First of all, the average illuminance on the test office's workplane, created by the two ZEN3 luminaires was measured. For this purpose, a handheld luxmeter (Pocket Lux 2, LMT, Berlin (D), maximal relative measuring error of ±7%) was used to determine 21 distinct illuminance values equally distributed across one half of the workplane (i.e. across one office desk). The results of these measurements are given in Table 5.1.

These measurement results yield an average illuminance of 352 Lux ±24 Lux (SD),

	1	2	3	4	5	6	7
A	364 ±25	334 ±23	316 ±22	317 ±22	331 ±23	332 ±23	332 ±23
B	391 ±27	358 ±25	340 ±24	342 ±24	359 ±25	355 ±25	324 ±23
C	409 ±29	376 ±26	359 ±25	359 ±25	375 ±26	371 ±26	342 ±24

Table 5.1: Workplane illuminances - new scenario. - Measured workplane illuminances [Lux] for the new lighting scenario on a 3 x 7 measurement matrix.

which corresponds to an illuminance uniformity g_1 of 0.9. This value is 66% higher than the simulated value given in Chapter 4. Due to this surprising (but yet very nice) result, the average workplane illuminance for the "Best Practice" lighting scenario was equally measured with the same method (see measurement results in Table 5.2). An average illuminance value of 232 Lux ±35 Lux (SD) (uniformity g_1 of 0.79) was found. This is approximately 35% more than the simulated value given in Chapter 4.

	1	2	3	4	5	6	7
A	273 ±19	249 ±17	228 ±16	212 ±15	199 ±14	189 ±13	182 ±13
B	291 ±20	264 ±18	243 ±17	227 ±16	212 ±15	200 ±14	193 ±14
C	303 ±21	277 ±19	256 ±18	235 ±16	220 ±15	207 ±14	199 ±14

Table 5.2: Workplane illuminances - "Best Practice" lighting scenario. - Measured workplane illuminances [Lux] for the "Best Practice" lighting scenario on a 3 x 7 measurement matrix.

Figure 5.10 displays the real illuminance values under the assumption that the *light distributions* obtained through the simulations were correct. This allows to calculate the average values for the remaining four reference planes via linear extrapolations.

It was found that the low illuminance values obtained with the RELUX Vision model used for the simulations presented in Chapter 4 were due to the fact that an empty room (i.e. no furniture) was used. Simply adding four office desks to the model already yields much better results (see Figures 5.11 and 5.12).

The optimized model still largely underestimates the average illuminance values in both cases; this is however not necessarily a disadvantage because, in the particular case of office lighting simulations, it is better to carry out "worst case"-simulations than simulations that overestimate the workplane illuminances.

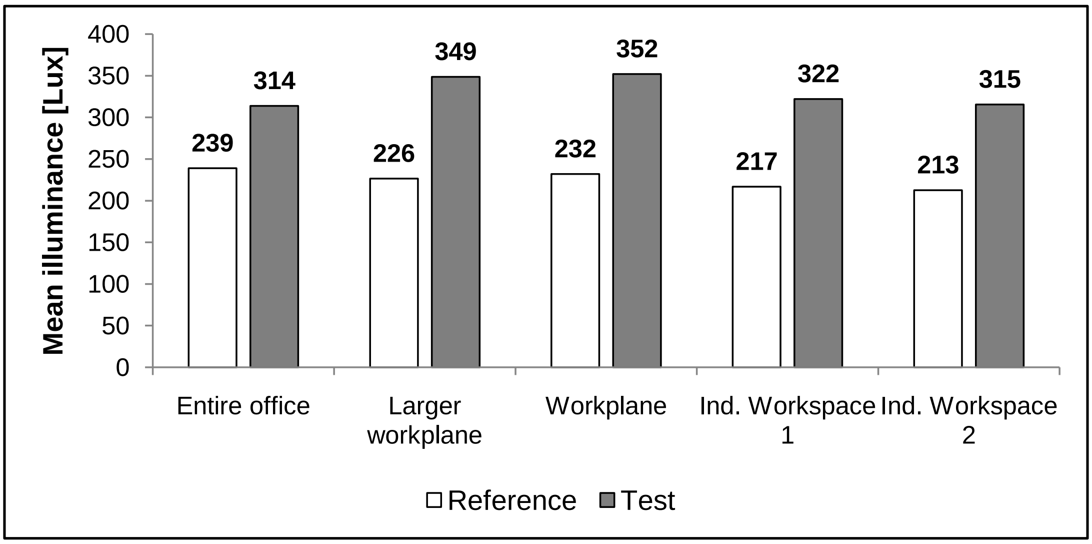


Figure 5.10: Real workplane illuminances. - The figure shows the real illuminance values (partly extrapolated) under the assumption that the *light distributions* obtained through the simulations were correct.

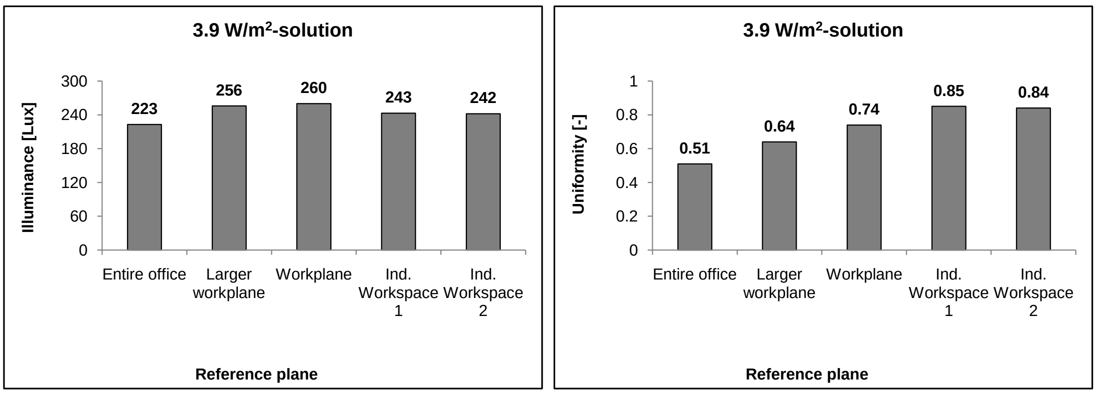


Figure 5.11: Average illuminances and uniformities obtained with an optimized RELUX Vision model - New lighting scenario. -

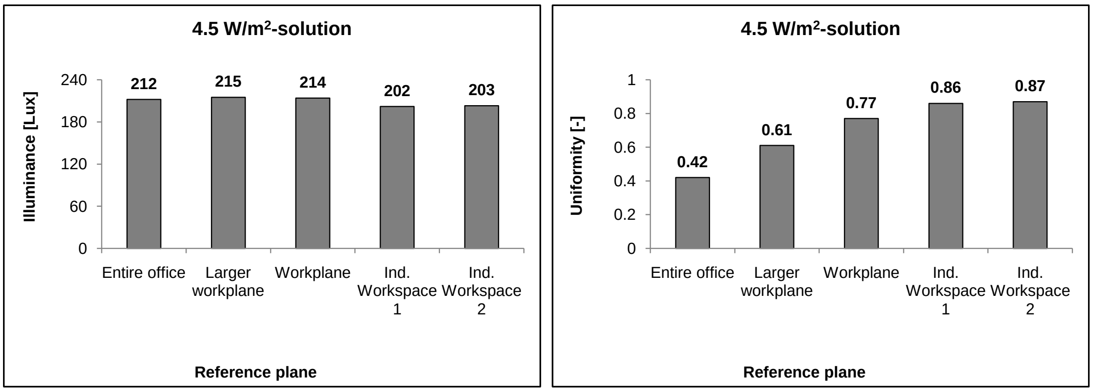


Figure 5.12: Average illuminances and uniformities obtained with an optimized RELUX Vision model - "Best Practice" lighting scenario. -

Figure 5.13 shows a measured dimming curve for the new ambient lighting system in the test office room. The latter was determined by placing a luxmeter on one of the office room's individual workspaces (see Figure 4.6) and by then gradually dimming the light from a power consumption of 100% (corresponding to 62 W) down to 0% while making continuous luxmeter readings.

It can be seen from the resulting "Illuminance vs. Power"-plot that the decrease in illuminance is quasi-linear from 62 W down to approximately 15 W. It is also interesting to note that the illuminance curve does not intersect with the x-axis at 0 W. This shows that the ECGs consume electricity even when the lamps are switched off. This standby-power was measured: it is equal to 1.25 W for both ECGs.

Figure 5.14 shows the monitored relative workplane illuminance obtained over time with the desk lamp shown in Figure 3.13 for the cases where the latter is either equipped with one of the PHILIPS LED bulbs (see Figure 5.9), with a PHILIPS Genie CFL or with a low-budget CFL from IKEA (46).

It is evident that both CFLs need significantly more time for reaching their maximum light output than the two LED bulbs due to the necessary warming up of the plasma in the CFL tube. The LEDs immediately reach their maximum light flux, the 10s time delay being due to the sampling rate chosen for this experiment. Figure 5.15 gives the time delay required by the four different lamps to reach at least 95% of their maximum light flux. It is interesting to note that the CFL from IKEA reached this

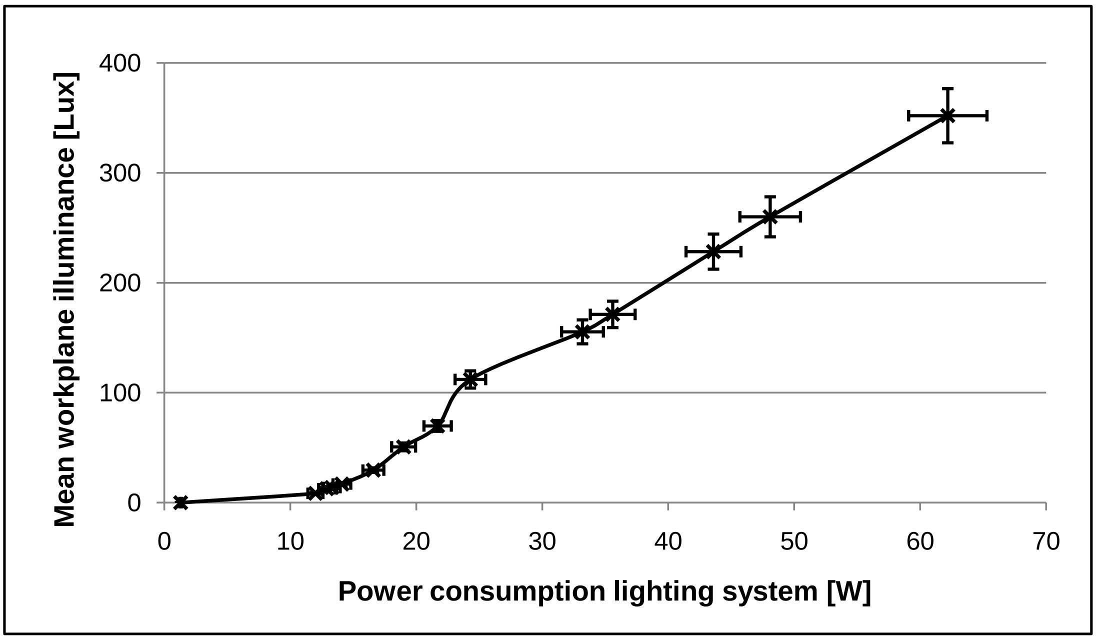


Figure 5.13: Dimming curve - ambient lighting.for new ambient lighting in the test office room. - The figure shows a measured dimming curve for the new ambient lighting system in the test office room.

threshold much quicker than the PHILIPS Genie CFL. It is also interesting to note that the workplane illuminance decreased slightly with time for the Philips Master LEDs (see Figure 5.14); a decrease of more than 5% over the first 5 minutes having been observed. This effect can be explained by the heating up of the LED and an associated deterioration of its semiconducting properties.

5.5 Conclusion

The new complementary electric lighting system installed in the test office room of the LESO building offers higher illuminances, better illuminance uniformities on the workplanes and more flexibility (the two luminaires can be switched and dimmed separately) than the "Best Practice" lighting scenario described in Chapter 3. At the same time, it reduces the LPD in the office room. For temporary task lighting, the CFL in the test office rooms desk lamp was replaced by an LED light bulb. This can be expected to further improve the comfort for the office's occupants, since the LED light bulb reaches its maximum luminous flux immediately after switch-on (whereas CFL typically take

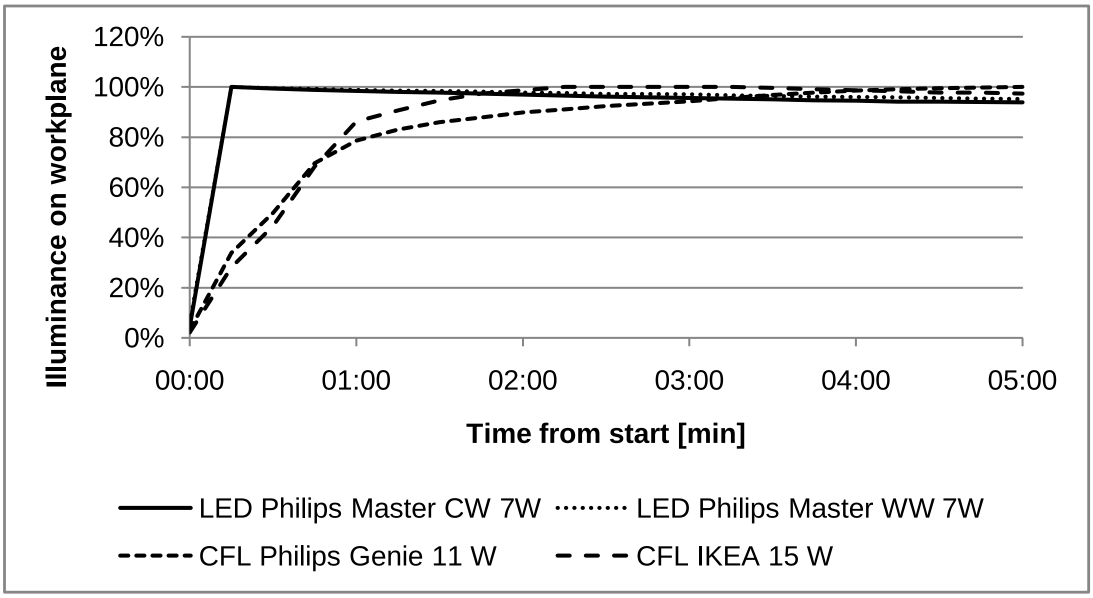


Figure 5.14: LED task lighting - Workspace illuminance vs. time. - The figure shows the monitored relative workplane illuminance obtained over time with the desk lamp shown in Figure 3.13 for the cases where the latter is either equipped with one of the PHILIPS LED bulbs (see Figure 5.9), with a PHILIPS Genie CFL or with a low-budget CFL from IKEA (46).

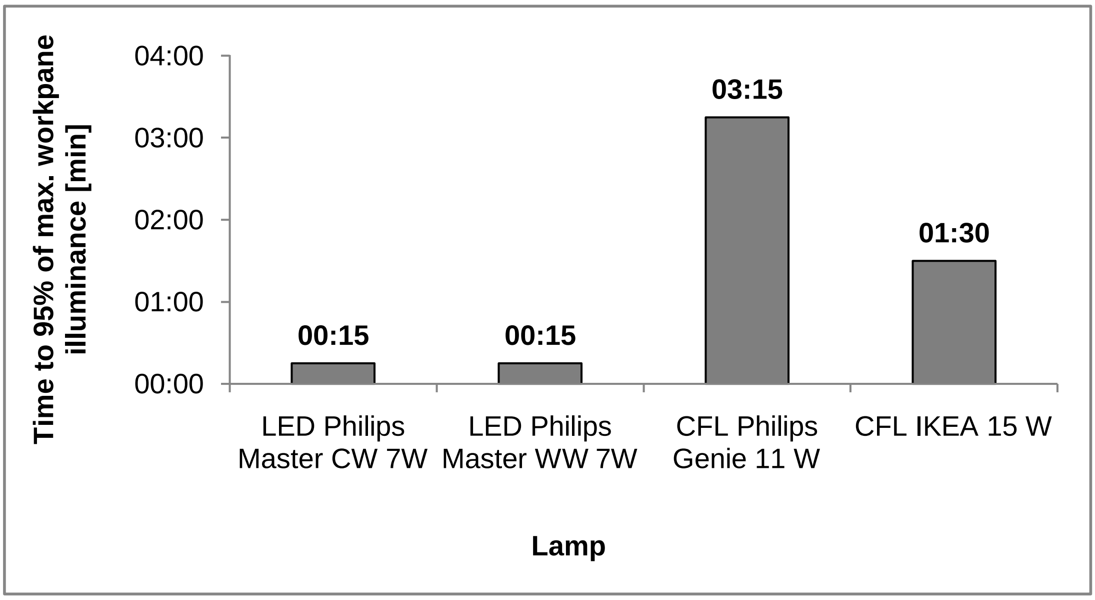


Figure 5.15: Start-up times for LEDs and CFLs. - The figure visualizes the start-up time for five different lamps.

considerably longer to warm up). In order to verify that this new lighting scenario is equally well accepted by the office occupants and that it does not have a negative impact on visual performance, a study with 20 human subjects was carried out in the test office room within the framework of this doctoral thesis. This is explained in detail in Chapter 6.

6

Visual Comfort & Performance Assessment

6.1 Introduction

In the previous Chapters, possibilities to minimize the LPD in the test office room of the LESO building were discussed in detail. Chapter 4 has presented different options based on fluorescent- and LED-technology. The installation of a highly flexible, complementary electric lighting system with an LPD of only 3.9 W/m^2 for the ambient lighting in the test office office room was documented in Chapter 5. However, in order to make sure that this new system performs as well as the "Best Practice" lighting solution in terms of occupant comfort and visual performance, it was seen necessary to carry out a POE satisfaction assessment with test persons during which the two lighting scenarios were going to be compared.

From April to May 2008, the "Best Practice" lighting scenario (referred to as "Reference") was thus compared with the newly installed lighting scenario of the test office room (referred to as "Test") during a POE experiment. For this purpose, objective visual performance tests (computer-based and paper-based) and subjective visual comfort assessmnets with 20 human subjects were carried out. The main hypothesis of this study was that the 20 human subjects would not perform worse under the more energy-efficient "Test" -lighting scenario than under the "Reference"-lighting scenario (which is extremely well accepted by the buidling's occupants (68)). Furthermore, it was expected to find a positive impact of the "Test"-lighting on the study participants visual performance during the paper-based task, compared to the "Reference"-lighting (based on prior experience in the LESO solar experimental building).

6.2 Detailed Experiment Description

The performance and visual comfort tests took part in evenings, because this is when the electric lighting systems in the ADS-equipped office rooms of the LESO building are typically used (see Chapter 2). For each subject, the experiment was scheduled in such a way that he or she arrived at the laboratory around sunset. The subjects were young and healthy males and females (10 males, 10 females) with an academic background. Their average age was 23.7 ±3.5 years.

6.2.1 Experimental Setup

The workplace used during the visual comfort and performance assessment is shown in Figure 6.1.

In the first lighting scenario, it was illuminated with the two ceiling-mounted "Lip" luminaires by Regent (84). In the second lighting scenario, it was illuminated with the two "ZEN3" luminaires by Tulux (104), which were positioned above the workplane by means of the ceiling-mounted rail system (see Chapter 5). Table 1 summarizes the characteristics of the two different lighting scenarios (see previous Chapters for details).

Figure 6.2 shows photographs of the two different lighting scenarios, taken with an HDR camera trough a fish eye objective.

In terms of glare risk, the two scenarios are comparable: the "Lip" luminaires lead to a UGR of 13.84 versus a UGR of 14.75 in the case of the "ZEN3" luminaires. The UGR values have been computed using the software EVALGLARE (116). The two lighting scenarios are thus comparable in terms of glare risk, the latter being however slightly higher in the case where the "ZEN3" luminaires are used.

6.2.2 Methods

6.2.2.1 Alertness Monitoring

During the entire duration of each experiment, the test persons' alertness was monitored using the Karolinska Sleepiness Scale (KSS). It is a subjective rating during which the persons have to state their actual alertness level on a 9-stage scale going from "extremely

Figure 6.1: The Workplace. - Workplace used during the described study in the test office room.

Value	**"Reference"-scenario**	**"Test"-scenario**
luminaire type	2 x "Lip" (Regent)	2 x "Zen3" (Tulux)
luminaire optical efficiency	0.69	0.96
lamp type	one T8 fluorescent tube per luminaire (36W)	one T5 fluorescent tube per luminaire (28W)
LPD	4.5 W/m^2	3.9 W/m^2
average horizontal illuminance	232 Lux	352 Lux
horizontal uniformity g1	0.79	0.90
UGR	13.84	14.75

Table 6.1: The two low-LPD scenarios. - Overview of the two tested low-LPD lighting scenarios.

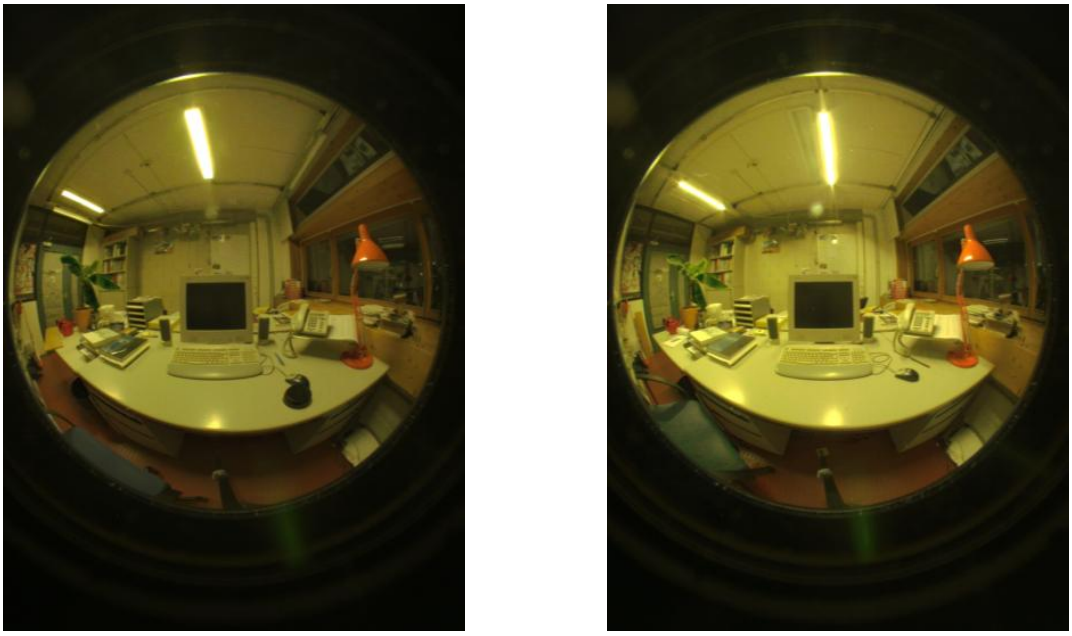


Figure 6.2: Comparison of the two lighting scenarios - Discomfort glare from luminaires. - Photographs of the two different lighting scenarios, taken with an HDR camera and a fish eye objective. These photos were used to calculate the UGR-values with EVALGLARE (116).

alert" (= 1) to "very sleepy, great effort to keep awake, fighting sleep" (= 9). The KSS was validated against EEG data by Åkerstedt and Gillberg in 1990 (3). Table 6.2 gives an overview of the corresponding scale, the original ratings, as well as the translated French ratings used during this study.

6.2.2.2 Performance at Computer-based Task

One main objective of the study was to test the influence of the two different lighting scenarios "Reference" and "Test" on the subjects' performance during a computer-based visual performance task. For this purpose, the "Freiburg Visual Acuity & Contrast Test" (FrACT) (10) has been used. It allows to determine a person's visual acuity and contrast threshold through correct recognition of Landolt-rings on a PC screen. The computerized test can be downloaded free of charge on www.michaelbach.de/fract. Two different methods were used to assess the occupants' visual performance for each of the two lighting conditions. The first method consisted of showing the subject a sequence of 36 Landolt rings of different size and orientation (see Figure 6.3). The participant had to determine the orientation of the ring and give the appropriate answer via the PC's keyboard as quickly as possible. Each participant repeated this "acuity" test three times under each lighting condition. After each sequence (36 Landolt rings), the participant took a short break which was used to store the results of the test (e.g. correct answers, response time per ring) in an Excel spreadsheet. For each sequence of 36 rings, a performance indicator η_{perf} was determined as follows:

$$\eta_{perf} = \frac{n_{correct}}{\tau_{sequence}} \tag{6.1}$$

where $n_{correct}$ stands for the total number of correctly identified Landolt rings per sequence and $\tau_{sequence}$ stands for the total duration of the sequence.

Using the FrACT to determine a person's contrast threshold is another possible way to assess visual performance. Instead of looking at Landolt rings of different size, the contrast between the ring and the screen background is modified during the test. Yet again, each subject performed three sequences of this "contrast" test of 36 Landolt rings for each of the two lighting scenarios.

The entire FrACT is illustrated in Figure 6.3.

Value	English rating	French rating
1	extremely alert	extrêmement alerte
2	very alert	très alerte
3	alert	alerte
4	rather alert	assez alerte
5	neither alert nor sleepy	ni alerte, ni somnolent
6	some signs of sleepiness	signes de somnolence
7	sleepy, no effort to stay awake	somnolent, mais reste éveillé sans effort
8	sleepy, some effort to stay awake	somnolent, efforts pour rester éveillé
9	very sleepy, great effort to keep awake, fighting sleep	très somnolent, gros efforts pour rester éveillé, lutte contre le sommeil

Table 6.2: The Karolinska Sleepiness Scale - Overview of the Karolinska Sleepiness Scale (KSS).

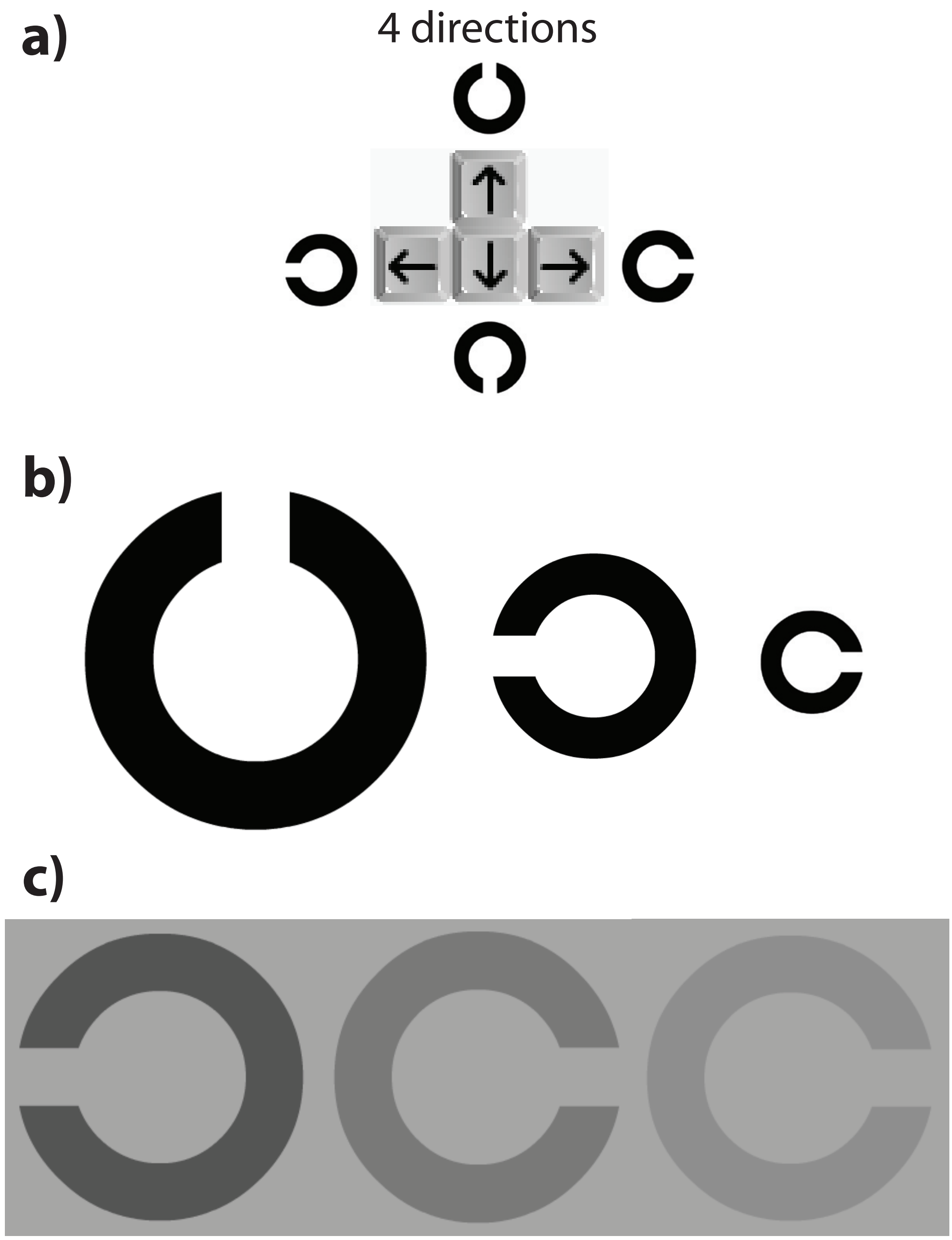


Figure 6.3: The Freiburg Acuity and Contrast Test. - Overview of the computer-based FrACT test used during the study.

6.2.2.3 Performance at Paper-based Task

Another main objective of this study was to test the influence of the two different lighting scenarios on the subjects' performance during a paper-based task. For this purpose, a test suggested by Courret (18) in 1999 was used. Yet again, Landolt rings are used during this test: the study participants receive a piece of white paper on which 96 Landolt rings are printed in clear grey. They are asked to determine, as quickly as possible and without writing on the paper, the correct orientations of the 96 rings by writing down the number of counted rings for all four possible orientations (open on top, open on bottom, open left, open right). The contrast between the paper and the grey color of the rings is very weak which makes this quite a difficult task. The test is shown in Figure 6.4.

Two different versions of this visual performance test (i.e. with different ring orientations) were used in order to avoid any bias from people who remember the number of rings previously counted during the first lighting scenario while they were doing the test under the second lighting scenario.

6.2.2.4 Subjective Visual Comfort Assessment

The subjective visual comfort of the study participants was assessed using a further optimized version of the OLS (see Chapter 2). The different statements and questions used in this OLS are shown in Figure 6.9 (see "Results"-Section of this Chapter).

6.2.3 Study Procedure

After arriving at the laboratory at the scheduled appointment time (i.e. sunset of the particular day), each participant was offered a quick tour around the laboratory: this typically took between 5 and 10 minutes. Then, a quick introduction concerning the study was given, questions were answered and study participants were offered to use the bathroom. After that, the visual performance tests began. Each subject was tested once under the "Reference"-condition and once under the "Test"-condition. Half of the participants started under one condition, the second half under the other condition (cross-over design). Figure 6.5 shows the detailed study schedule.

In the beginning of each session, the participants filled out a KSS-test. Then, they performed a computer-based acuity-test and a computer-based contrast-test (determin-

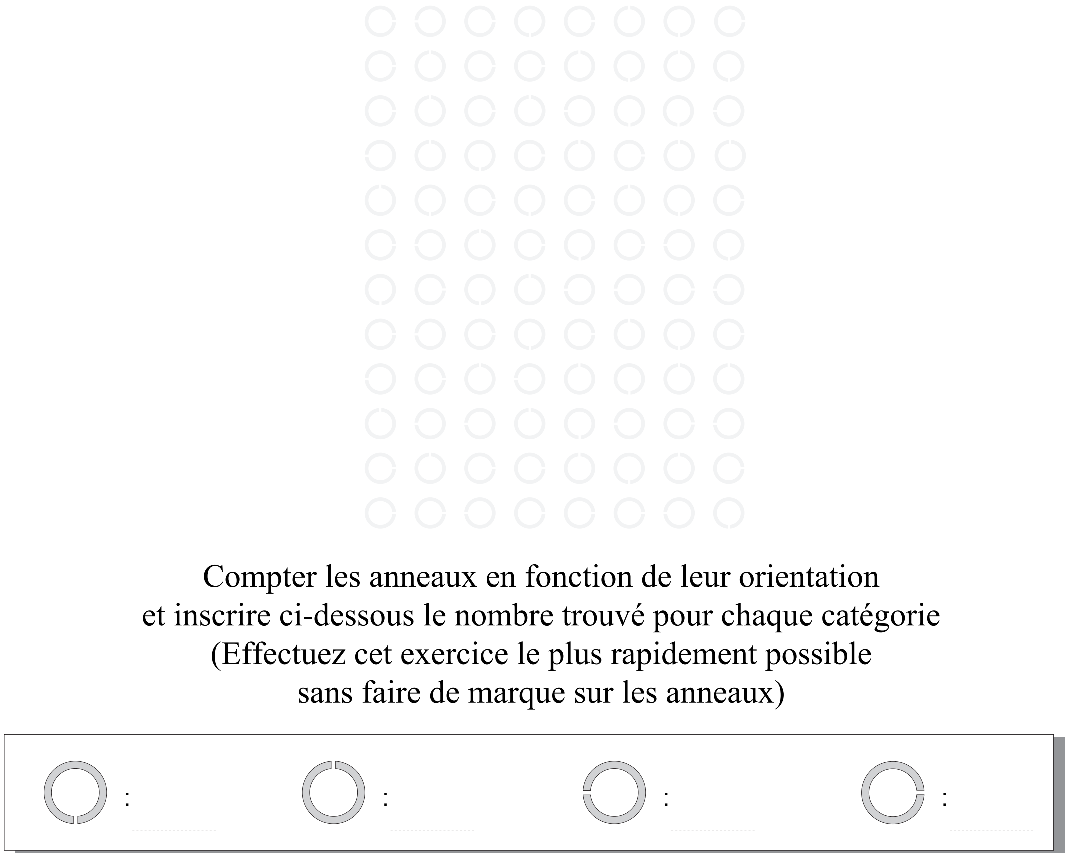


Figure 6.4: Paper-based Landolt ring task. - Paper-based Landolt ring task as suggested by Courret (18). The study participants are asked to count the number of rings for every orientation as quickly as possible and without marking the rings.

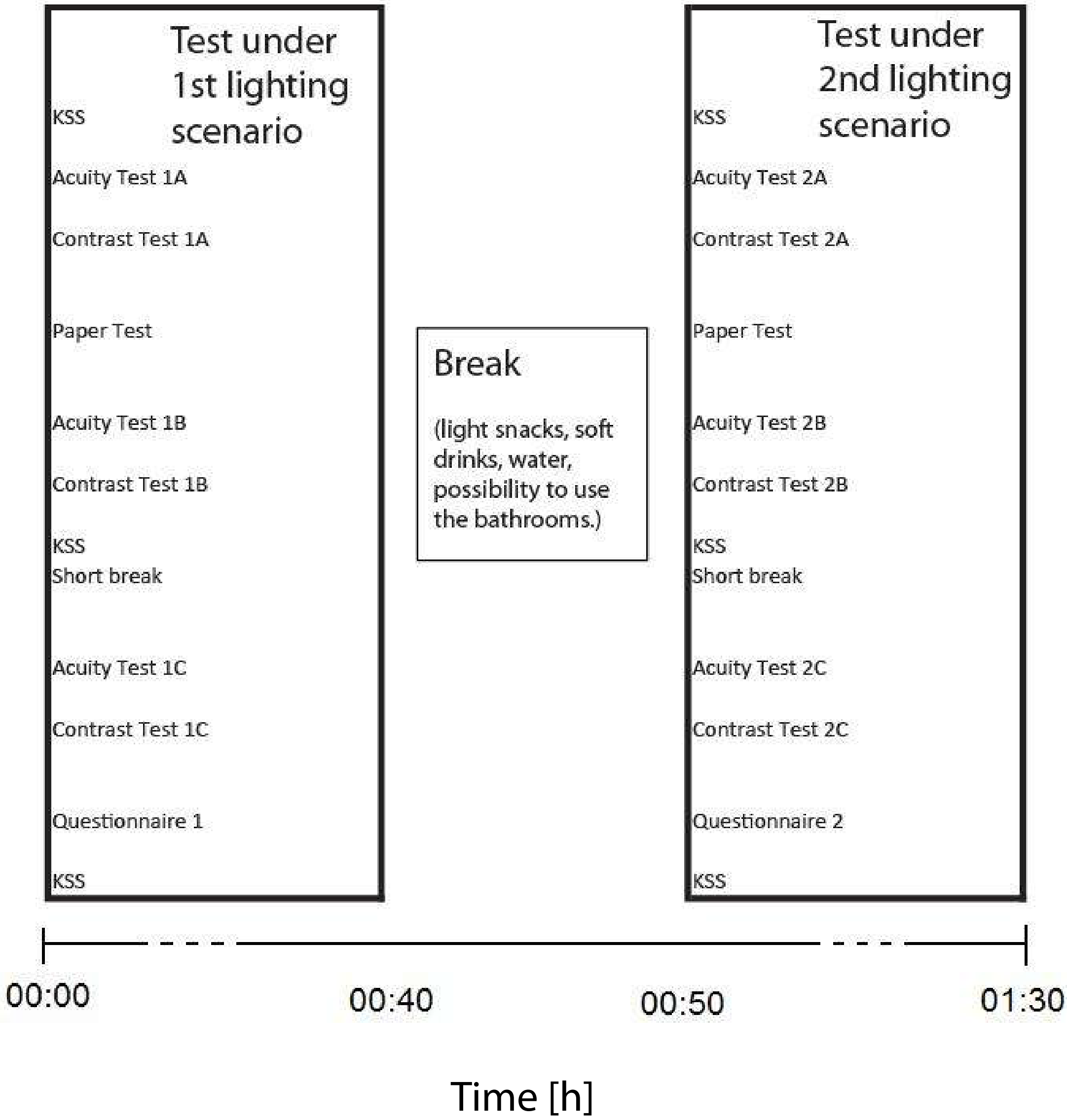


Figure 6.5: Study Schedule. - The Figure shows the detailed schedule of our study.

ing the correct direction of 36 Landolt-rings in both cases). After that, the paper-based task (see Figure 6.4) was carried out. The latter was followed by another sequence of acuity- and contrast-tests, a KSS-test and a short break during which participants were shown a humorous video clip (for relaxing reasons). Participants then took a third sequence of acuity- and contrast-tests and filled out the OLS. Each session ended with a third KSS-test. One such session took approximately 40 minutes. Between the two sessions, the lighting scenario inside the office room had to be modified. Meanwhile, the occupants took a break of approximately 10 minutes during which they were offered light snacks, soft drinks and water. They were also allowed to use the bathrooms. Then, the second session started. The only difference between the two sessions was the fact that the questionnaires for subjective visual comfort assessment filled out by the participants at the end of each session were slightly different: while the first OLS only contained 16 lighting-related questions, the second one had an additional section with general questions (e.g. age).

6.3 Results

6.3.1 Alertness

Figure 6.6 shows the participants' alertness monitored by means of the KSS throughout the experiment. Figure 6.6 a) shows the evolution of the participants' average alertness over the duration of the entire experiment (i.e. 90 minutes), based on six KSS-tests. The observed differences could not be shown to be statistically significant (2-sample dependent t-Test between the first and the last rating yields p-value of 0.77). The average alertness evolution during the session where the "Reference"-solution was tested is plotted in Figure 6.6 b), the alertness evolution during the "Test"-solution session in Figure 6.6 c). The observed differences were not statistically significant either (2-sample dependent t-Tests between the first and the last rating yield p-values of 0.24 for the "Reference"-solution and 0.79 for the "Test"-solution.)

6.3.2 Computer-based Task

Figure 6.7 gives an overview of the results obtained during the computer-based tasks. The average performance indicator η_{perf} of all "acuity" tests is shown in Figure 6.7 (left) for the two different lighting conditions. For both of them, the average performance

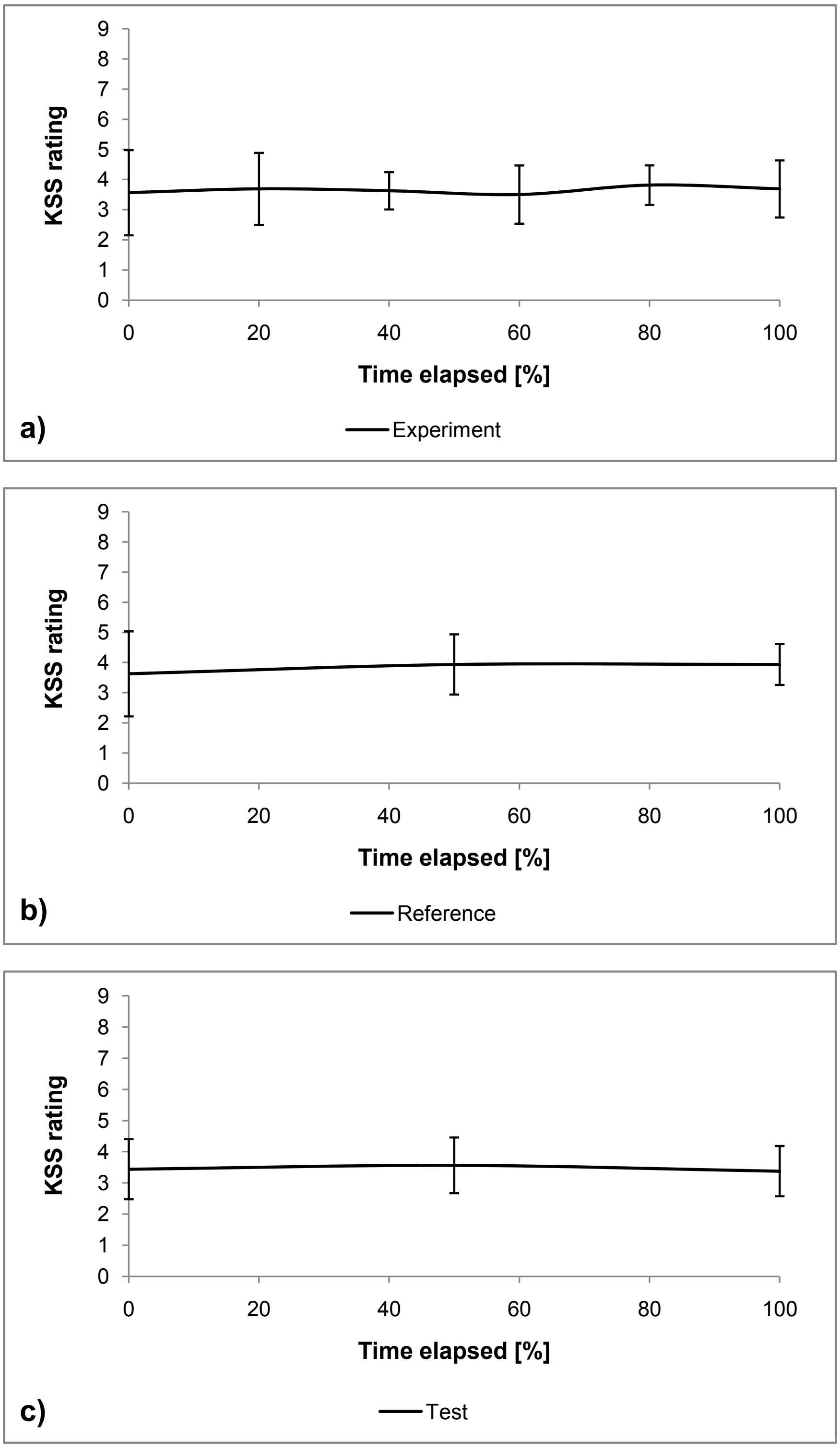


Figure 6.6: Karolinska Sleepiness Scale (KSS) ratings. - Evolution of the subjects' average KSS ratings over the duration of the entire experiment (panel a)), over the duration of only the "Reference"-part of the experiment (panel b)) and over only the duration of the "Test"-part of the experiment (panel c)).

indicator is close to 0.9 correct decisions per second. There was no significant difference between the two lighting scenarios (t-Test yields p = 0.161 > 0.05). Figure 6.7 (right) shows a comparison of the average contrast thresholds obtained during the "contrast" tests for the two lighting scenarios. Values of 0.37% for the "Reference"-scenario and 0.36% for the "Test"-scenario were measured. Yet again, the small difference was not statistically significant (t-Test yields p =0.158 > 0.05).

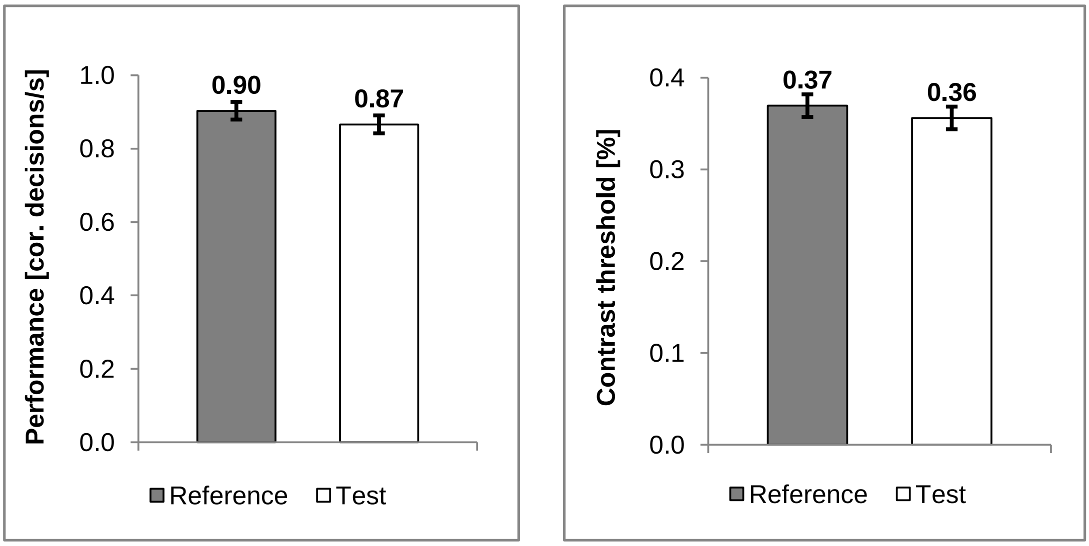


Figure 6.7: Results of the FrACT. - Avereage results of the "acuity"-test (left) and the "contrast"-test (right) obtained during the computer-based tasks. SEMs = ±0.024, ±0.024, ±0.012, ±0.012.

6.3.3 Paper-based Task

Figure 6.8 shows the results of the paper-based task for the two different lighting conditions.

The average number of mistakes per ring orientation is shown in Figure 6.8 (left). One can observe that the subjects made in average more mistakes under the "Reference"-lighting than under the "Test"-lighting. The differences between the average number of mistakes for each orientation that are displayed in Figure 6.8 (left) could, however, not be shown to be statistically significant (t-Tests yield p > 0.05). In Figure 6.8 (right), the difference between the "Reference"- and the "Test"-scenario becomes more evident. This Figure shows the average (over 20 participants) number of mistakes for the sum

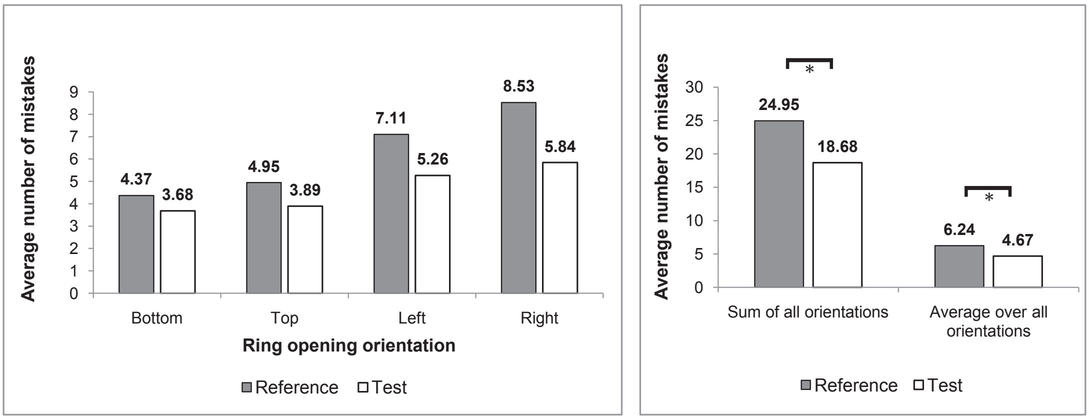


Figure 6.8: Results of the paper-based task. - Results of the paper-based task for the two different lighting conditions. *=p<0.05.

of all Landolt-ring orientations. Under the "Reference"-lighting, the participants got in average 24.95 out of 96 Landolt-ring orientations wrong while they made only an average of 18.68 mistakes under the "Test"-lighting, the difference being statistically significant ($p = 0.032 < 0.05$). The Figure also shows that the average study participant made an average of 6.24 mistakes per ring orientation under the "Reference"-lighting and only an average of 4.67 mistakes per ring orientation under the "Test"-lighting. This difference is also statistically significant ($p = 0.009 < 0.05$).

6.3.4 Visual Comfort Assessment

Figure 6.9 now shows the results of the subjective visual comfort assessment. Nineteen out of 20 study participants have properly filled out the corresponding questionnaires. Only the differences in statements S4 ("This office seems too dim.") and statement S10 ("The ceiling-mounted luminaires are too bright.") were statistically significant (t-Tests performed on test data yielded p-values of 0.036 and 0.011, respectively).

Figure 6.10 shows the differences between the "reference"- and the "test"-lighting for the statements S1 to S14. A negative value means that the "Test"-lighting performs worse than the "Reference"-lighting in this specific regard, a positive value corresponds to an enhancement.

Figure 6.11 shows an additional result of the subjective visual comfort assessment. In addition to the 14 statements listed above, the study participants were asked to state

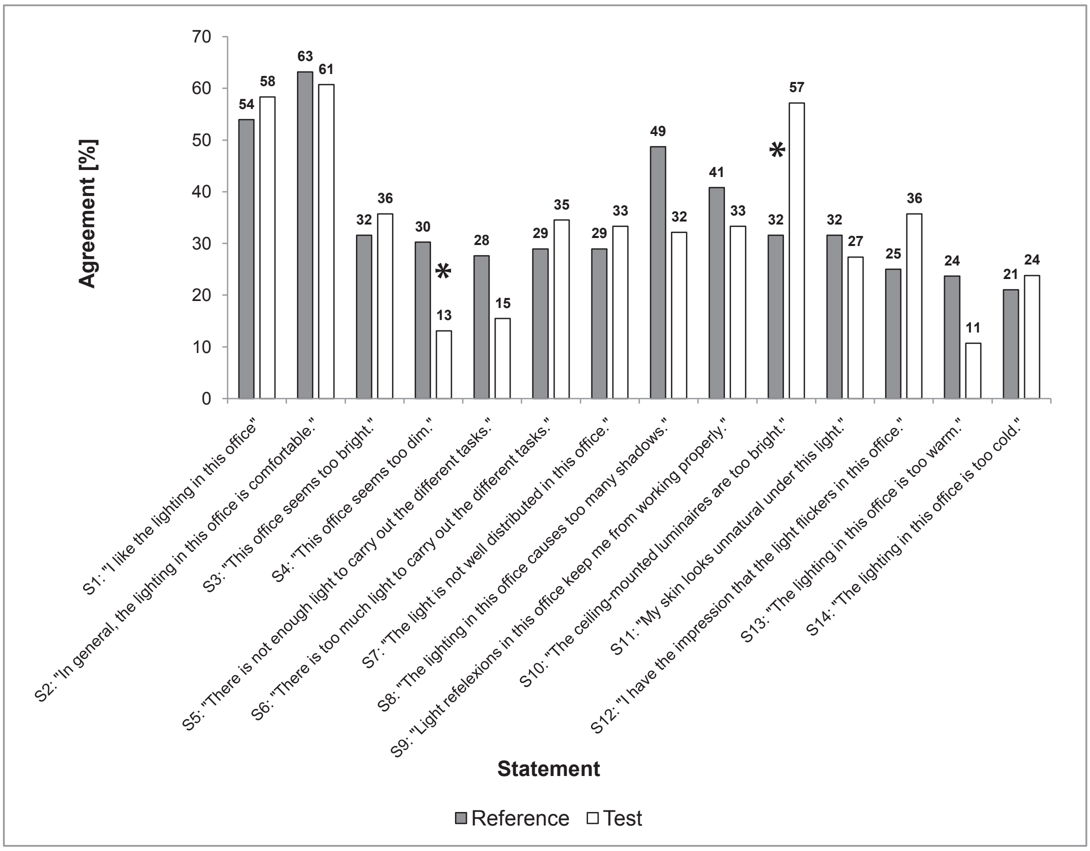


Figure 6.9: Subjective Visual Comfort. - Results of the subjective visual comfort assessment. *=p≤0.05.

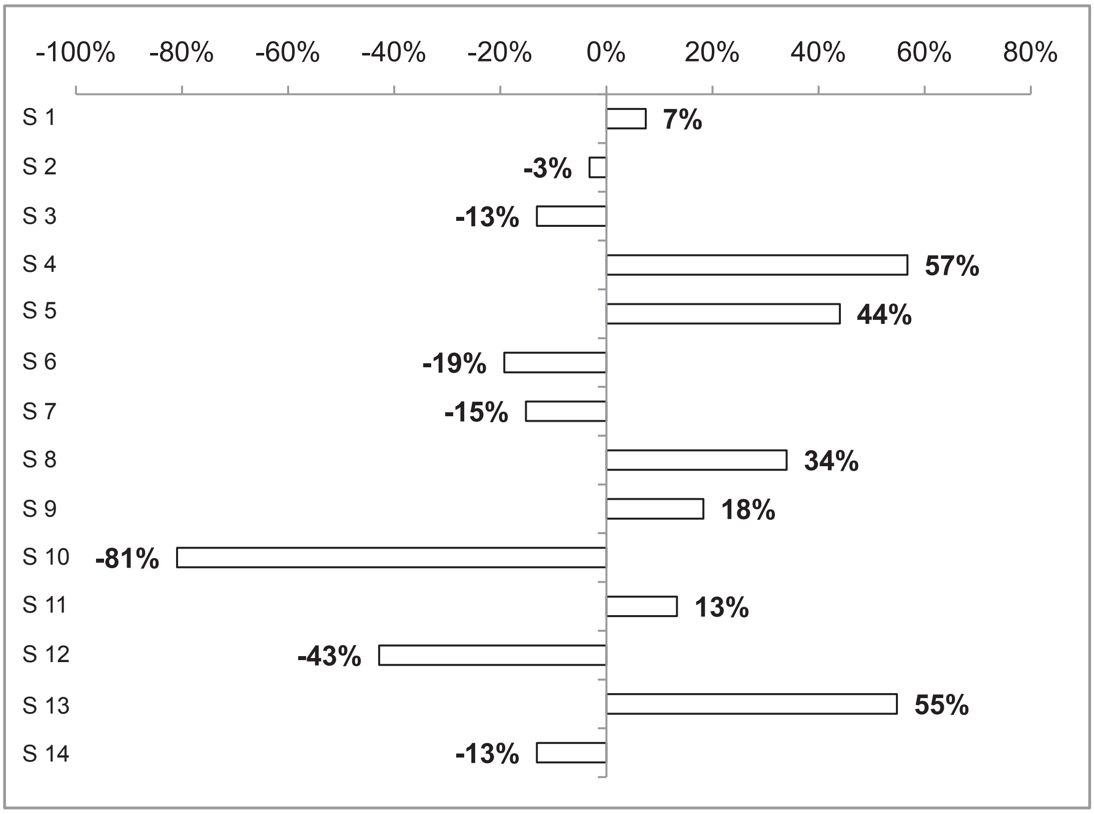


Figure 6.10: Subjective Visual Comfort - Differences. - Differences between the "Reference"- and the "Test"-lighting for the statements S1 to S14. A negative value means that the "Test"-lighting performs worse than the "Reference"-lighting in this specific regard, a positive value corresponds to an enhancement.

the maximum amount of time per day during which they could imagine themselves working under the given lighting condition.

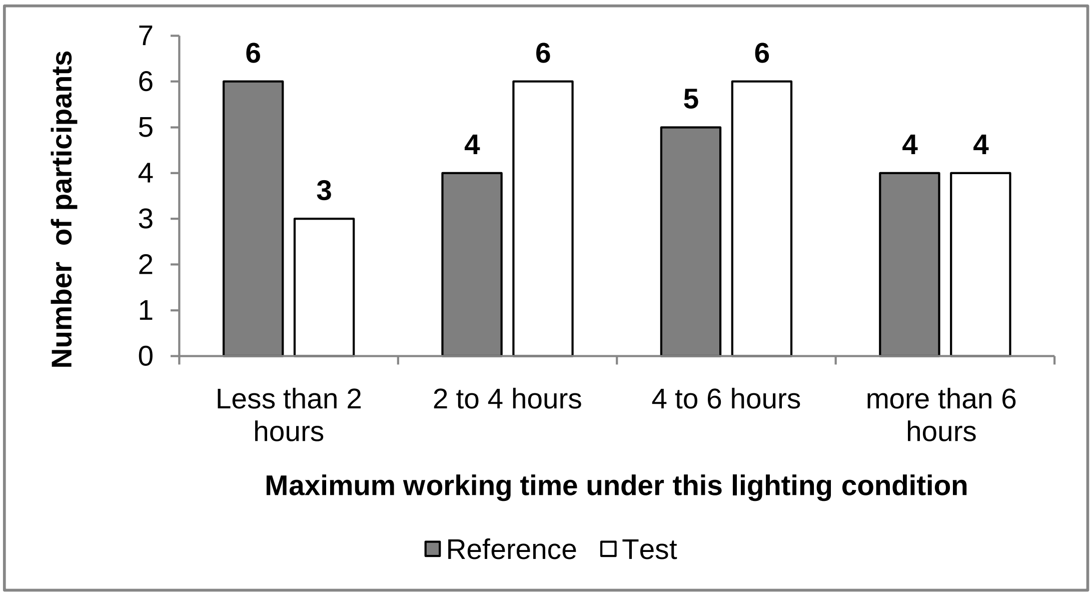


Figure 6.11: Maximum working time. - Maximum working time under each lighting scenario as indicated by the subjects.

At the end of the experiment, each participant was asked whether he or she preferred the "Reference"-condition or the "Test"-condition. Figure 6.12 shows the participants' answers to this question.

6.4 Discussion

Overall, the study participants preferred the "Test"-scenario over the "Reference"-scenario. Their performance in the paper-based task was significantly better under the "Test"-lighting than under the "Reference"-lighting. No significant differences in the computer-based tasks under the two different lighting scenarios were found. There was no significant decrease in the participants' alertness, neither over the entire duration of the experiment, nor in one of the two different sessions (i.e. "Reference"- or "Test"-session).

Figure 6.6 shows that the average alertness was indeed always situated between "rather alert" and "alert". Nevertheless, one could get the impression that a slight

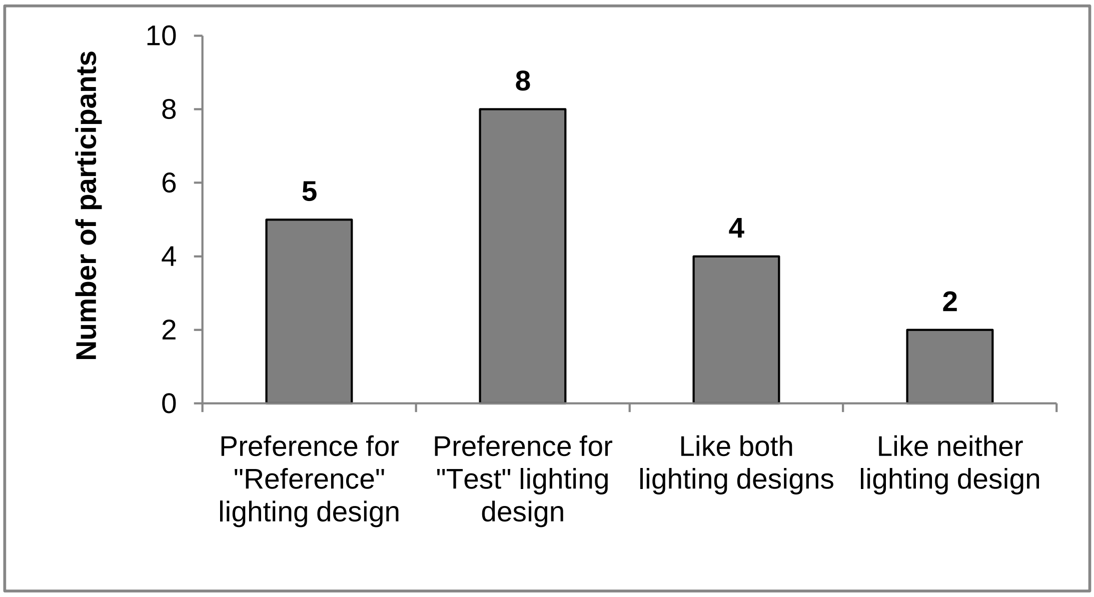


Figure 6.12: Participants' preferences. - Study participants' subjective preferences for one or the other low-LPD lighting scenario.

decrease in alertness occurred (i.e. an increase of the average KSS rating) during the "Reference"-sessions and a very slight increase of alertness (i.e. a decrease of the average KSS rating) during the "test"-sessions. These small differences are, however, not statistically significant. The small KSS rating variations over the entire experiment are also not statistically significant. This means that there is a considerable probability that the variations observed in Figure 6.6 have occurred by chance. It therefore makes sense to assume that the participants' alertness did not change throughout the study and that it is not possible to distinguish the two lighting scenarios regarding the participants' alertness.

Since the (very small) differences between the "Reference"- and the "Test"-scenario displayed in Figure 6.7 were not statistically significant, it can be concluded that there was no measurable influence of the lighting scenario on the study participants' performance during the computer-based tasks. In other words: the participants did not perform better or worse in the computer task under one or the other lighting scenario. This could of course indicate that the FrACT used during the study was inappropriate in this particular context; it might, for example, not be sensitive enough for such a test. However, another possibility is that the results rather illustrate the fact that the differences between the two lighting scenarios were not strong enough to have a measurable influence on the participants' performance during a computer-based task. This would implicate that it is possible to reduce the LPD in such office rooms from 4.5 W/m^2 to 3.9 W/m^2 without having a negative influence on the performance in computer-based tasks.

The fact that the differences between the "Reference"- and the "Test"-scenario in terms of performance in the paper-based task displayed in Figure 6.8 (left) could not be shown to be statistically significant but that the results become significant in Figure 6.8 (right) (where the calculations are based on the sum of all Landolt rings) might be a hint that the apparent insignificance in Figure 6.8 (left) is rather due to the small amount of samples than to the actual absence of an effect. In summary, the analysis of the paper-based task shows that the subjects performed on average better under the new "Test"-condition than under the old "Reference"-condition. The better performance is most likely due to higher workplane illuminance and a brighter room achieved under the "Test"-scenario. This leads us to the conclusion that, when working under artificial lighting conditions during a limited amount of time in the evening hours, the positive effects of elevated workplane illuminances are stronger than the negative effects of discomfort glare from luminaires. Passing from "Best Practice" to the new 3.9 W/m^2 lighting design will therefore not only minimize the electricity consumption but can also be expected to have a positive influence on the office occupants' performance on paper-based tasks.

During the subjective visual comfort assessment, the statement "In general, the lighting in this office is comfortable." scored agreement values of 63% for the "Reference"-condition and 61% for the "Test"-condition (difference not significant). For both conditions, these values are slightly lower than the typical values described by Akashi and Boyce (69%)(2). This is not surprising at all because the experiments described here took place during external darkness whereas the values described by Akashi and Boyce are most likely to describe agreements tested during normal office hours (with at least some daylight and its associated positive effects). In addition to that, Akashi and Boyce have only used a 2-stage scale (yes/no), whereas here, a 4-stage scale (yes/rather yes/rather no/no) was used. If we transform the 4-stage scale into a 2-stage scale (i.e. "rather yes" becomes "yes" and "rather no" becomes "no"), we find agreement values of 65% and 70% for the "Reference"- and the "Test"-solution, respectively. One can therefore assume that the two tested lighting scenarios are comparable to lighting conditions in other office rooms. It might seem surprising that the "Test"-lighting scores better agreement values in statement S1 ("I like the lighting in this office.") than the "Reference"-lighting and that this trend is inversed in statement S2 ("In general, the lighting in this office is comfortable."). However, the small differences in the average agreements to these two questions are not statistically relevant. As a matter of fact, only the differences in statements S4 ("This office seems too dim.") and statement S10 ("The ceiling-mounted luminaires are too bright.") are statistically significant (see Figure 6.9). Nevertheless, it seems somewhat surprising that a significant difference between the two lighting designs for statement S4 ("This office seems too dim.") and none for statement S5 ("There is not enough light to carry out the different tasks.") was found. It is possible that the absence of significance is in many cases the result of the small number of study participants rather than the result of an absence of a difference. It therefore makes sense to take a closer look at various statements where a large difference between the two lighting designs has occurred, even if some are not statistically significant.

If we take into account only those statements where a difference of at least ±20% is observed, we find an enhancement for the statements S4, S5, S8 and S13 and a deterioration for the statements S10 and S12 (see Figure 6.10). The facts that the new "Test"-condition creates higher illuminances on the workplane (S5) and makes the room in general appear brighter and less gloomy (S4, S8 and S13) are perceived positively, whereas the aggressiveness (S12) and especially the increased luminance of the luminaires (S10) are perceived negatively.

The results displayed in Figure 6.11 suggest a maximum working time that is higher for the "Test"-condition than for the "Reference"-condition.

In Figure 6.12, one can observe that five (out of 19) participants had a preference for the "Reference" lighting design, whereas eight participants preferred the "Test"-condition; four participants liked both solutions equally well. Only two participants felt that neither of the two environments was comfortable enough.

The results of the subjective visual comfort assessment outlined in Figures 6.9 to 6.12 can be interpreted as follows: despite the higher luminaire luminance and the more "aggressive" lighting style, the participants slightly preferred the new "Test" - lighting design over the old "Reference" - lighting design. It is moreover possible to say that occupant satisfaction under the "Test"-condition is not significantly worse than under the "Reference"-condition. It is thus possible to reduce the LPD in such office rooms from 4.5 W/m^2 to 3.9 W/m^2 without creating a negative impact on the office occupants' visual comfort.

6.5 Conclusion

The results of the described tests on visual performance and subjective visual comfort under two different low-LPD lighting scenarios lead to several interesting conclusions. First of all, the results show that the two tested low-LPD lighting scenarios are comparable to usual lighting scenarios in other office rooms in terms of subjective visual comfort. Overall, the study participants preferred the "Test"-scenario (LPD of 3.9 W/m^2) over the "Reference"-scenario (LPD of 4.5 W/m^2). In addition to that, their performance in the paper-based task was significantly better under the "Test"-lighting than under the "Reference"-lighting. This leads to the conclusion that, when working under artificial lighting conditions during a limited amount of time in the evening hours, the positive effects of elevated workplane illuminances are stronger than the negative effects of discomfort glare from luminaires. Another interesting finding of this experiment is the fact that no significant differences in the computer-based tasks under the two different lighting scenarios where found. This visualizes to what extent the lighting environment has a much smaller influence on the performance during computer work than on the performance during paper work. In general, it is concluded that energy-efficient lighting with LPDs of less than 5 W/m^2 is already achievable in today's office rooms without jeopardizing visual comfort and performance. Less powerfull electric lighting systems do not necessarily mean a decrease in visual comfort and performance; the results even show that *better visual comfort* and *better visual performance* can be achieved with *less connected lighting power*.

Further work could look at the long-term effects of different low-LPD lighting scenarios on performance and visual comfort of office workers. Another interesting question is whether the light exposure during the normal working day influences performance and visual comfort in the evening. Recent research in the field of chronobiology indicates that, amongst other factors, light history should be taken into consideration during office lighting design (112). In this regard, it is also very important to get a sound insight into typical ocular light exposures in office buildings. The next Chapter describes how such an effort was made within the framework of this doctoral thesis.

7

Chronobiological Assessment

7.1 Introduction

Chapter 2 of this Thesis has shown that the ADS installed in the south-facing office rooms of the LESO Building are able to offer comfortable daylighting conditions that are highly appreciated by office occupants. They can supply sufficiently high workplane illuminances during large parts of normal working days; thus, artificial lighting becomes mainly complementary in such office rooms. Chapters 3 to 6 have outlined how, based on ADS, highly energy-efficient lighting scenarios with LPDs of less than 5 W/m^2 can be achieved.

Besides the visual comfort in ADS-equipped office rooms and their potential for energy-efficient office lighting, it is not well understood to which extend the change in room (day-)lighting conditions during daytime has an impact on the circadian rhythms and neurobehavioral performance of office occupants. Considering that many people spend a fair amount of their time inside office rooms, this is a topic that should be taken more into consideration when designing lighting scenarios for office buildings (105; 112).

Recent research has revealed that the impact of lighting conditions on human circadian rhythms is strongly dependent not only on light intensity and timing of light exposure but also on spectral properties of the visible light. In particular, it has been shown that in humans, the circadian peak sensitivity to light as assessed by nocturnal melatonin suppression is in the blue range of visible light between 457-464 nm (13; 101).

During this doctoral thesis, a close look on typical ocular daylight exposures in ADS-equipped office rooms was taken. These daylight exposures were then compared to an artificial blue-enriched light source. Results from a recent study by Viola et al. have demonstrated that the use of the same light source positively influenced subjective wellbeing and sleep quality in office workers (111). As light in the blue range of the electromagnetic spectrum is most effective to influence circadian rhythms in humans, particular attention was given to the blue part of the measured ocular irradiance values, especially on its time course across a working day. As a last step, the measured irradiance levels were weighted with the circadian function c(λ), which represents the circadian efficiency-curve based on data from human melatonin suppression by light (45).

7.2 Methods

A portable digital spectroradiometer (Specbos 1201, JETI Technische Instrumente GmbH, Jena, Germany, see detailed in Appendix A) was fixed on a tripod at the approximate eye level of an office occupant (height 115 cm from the floor). Spectroradiometer and tripod were installed in the ADS-equipped test office room in the LESO solar experimental building. The setup is shown in Figure 7.1.

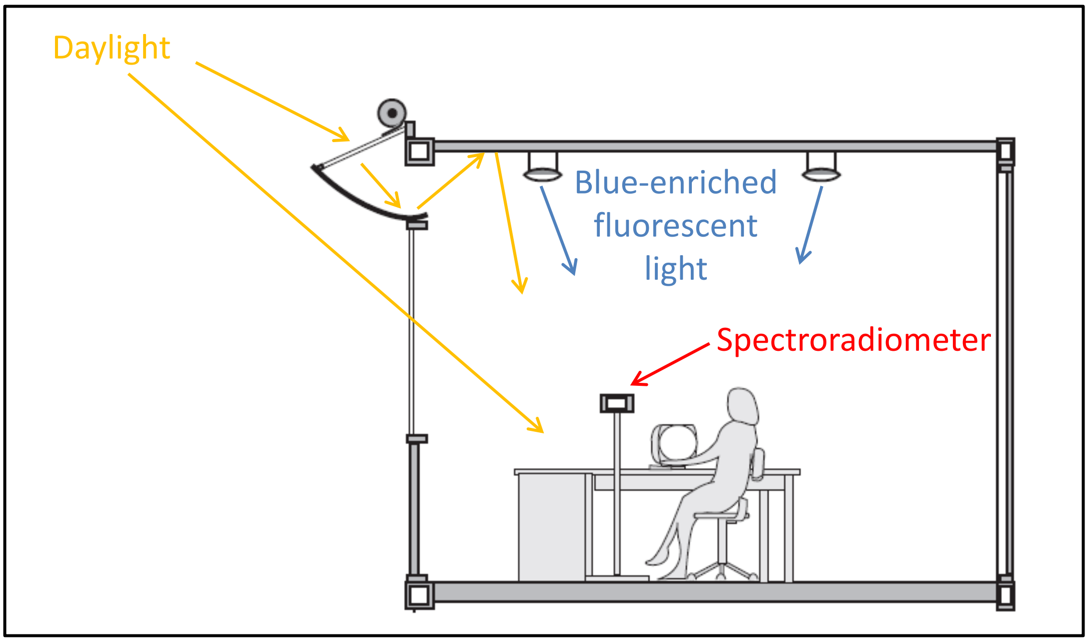


Figure 7.1: Setup of the Chronobiological Assessment. - This Figure shows the setup of the spectroradiometer installed in the ADS-equipped test office room.

Daytime irradiance values were recorded for several weeks from April-May 2009. The device was programmed to perform a complete spectral irradiance scan between 380 and 780 nm (with resolution of 1 nm) every 5 minutes. It was connected to a PC and the measured values were continuously stored after each scan.

In order to classify the weather on the recorded days, meteorological data of the same period was obtained from a local weather station (Meteosuisse (73), Pully, VD, Switzerland), which is located at the approximate distance of 7.7 km from the LESO building. This information was used to assign one of three different sky categories to all of our recorded days: Either an "overcast" (0 to 25% of sunshine / working day), "intermediate" (25 to 75% of sunshine / working day) or "clear" (75 to 100% of sunshine / working day) sky was assigned.

For the recordings of the artificial lighting, two "Zen 3" luminaires by Tulux (104), fixed on the test office room's ceiling-mounted rail system, were used. These luminaires were each equipped with one 58 W blue-enriched polychromatic fluorescent tubes (17'000 K, Activiva active, Philips), which had also been chosen during the study of Viola et al. (111). This electrical lighting installation was used to supply the necessary ocular daylight irradiances, to which were then compared out daylight measurements. Figure 7.2 shows a photograph of the blue-enriched Activiva active tube (right) and a warm-white fluorescent tube (left). The color difference is obvious.

The resulting average horizontal workplane illuminance (measured with a Luxmeter during nighttime) reached with this installation was 468 Lux ±39 Lux (SD), the average vertical illuminance at eye level (i.e. the value measured through the cosine-corrected spectroradiometer lens) was 252 Lux ± 2 Lux (SD).

For the analysis of the spectral irradiance values in the blue range of the visible light, the data obtained at 465 nm was collapsed into 2h bins from 09:00 to 17:00, resulting in 4 bins averaged over the days for the same sky condition.

The c(λ)-corrected irradiance values E_{ec} were calculated from the measured spectral irradiances $E_{e\lambda}$ by using the 'circadian action function curve' c(λ). This inverted-U shaped curve c(λ) is based on experimental findings in humans from the action spectra for light induced nocturnal melatonin suppression established by Brainard (13) and Thapan (101). By means of this circadian action function, the c(λ)-corrected irradiance E_{ec} can be calculated as follows:

Figure 7.2: Warm white light and blue-enriched white light. - This Figure visualizes the difference between a warm white fluorescent tube and a blue-enriched fluorescent tube as used during the study by Viola et al. (111).

$$E_{ec} = \int E_{e\lambda} c(\lambda) d\lambda \quad (7.1)$$

The circadian action function curve which is already implemented as selectable function in the spectroradiometer was used. The entire visible light spectrum between 380-780nm was taken into account.

7.3 Results

7.3.1 Ocular irradiances

Eighteen complete working days (i.e. from 09:00 to 17:00) between March and April 2009 were recorded. By means of the previously explained classification method, two days with a mainly overcast sky, nine days with intermediate skies and seven days with mainly clear skies were obtained. Table 7.1 gives an overview of the recorded days and the corresponding classification.

For visual illustration of the time course across the visible light spectrum between 380 and 780 nm, the irradiance levels at five different times of day were plotted for each sky condition (Figures 7.3 to 7.5). Plots correspond to averaged values of the corresponding days at 09:00, 11:00, 13:00, 15:00 and 17:00. The spectral irradiances obtained under artificial lighting are equally plotted on each graph for comparative reasons.

7.3.2 Ocular "Blue Light"

In order to investigate only the blue range of visible light, the averaged irradiances values at 465 nm ("Blue Light") are plotted in four time bins across the working day for the three sky types separate (Figure 7.6). For comparative reasons, the resulting blue light at 465 nm obtained under artificial lighting at nighttime is also shown. A Mann Whitney U-test revealed significant differences between the clear and the overcast sky during all times ($p<0.05$) except for the morning hours (09:00-11:00). There was no significant difference between days with intermediate and clear skies. On overcast days, blue light irradiance at 465 nm was lower in the later afternoon when compared to the intermediate sky condition. The time course on days with clear and intermediate skies exhibited higher values between 11:00 and 15:00 than in the morning or later afternoon

Date	Sunshine/Working Day [%]	Classification
30.03.09	0	overcast
09.04.09	100	clear
15.04.09	69	intermediate
16.04.09	0	overcast
17.04.09	54	intermediate
18.04.09	100	clear
19.04.09	29	intermediate
21.04.09	74	intermediate
22.04.09	100	clear
23.04.09	100	clear
24.04.09	80	clear
25.04.09	87	clear
28.04.09	30	intermediate
29.04.09	28	intermediate
30.04.09	35	intermediate
01.05.09	100	clear
02.05.09	56	intermediate
03.05.09	68	intermediate

Table 7.1: Sky type classifications. - Overview of the days recorded during our study, the respective fractions of sunshine per working day and the corresponding sky type classifications.

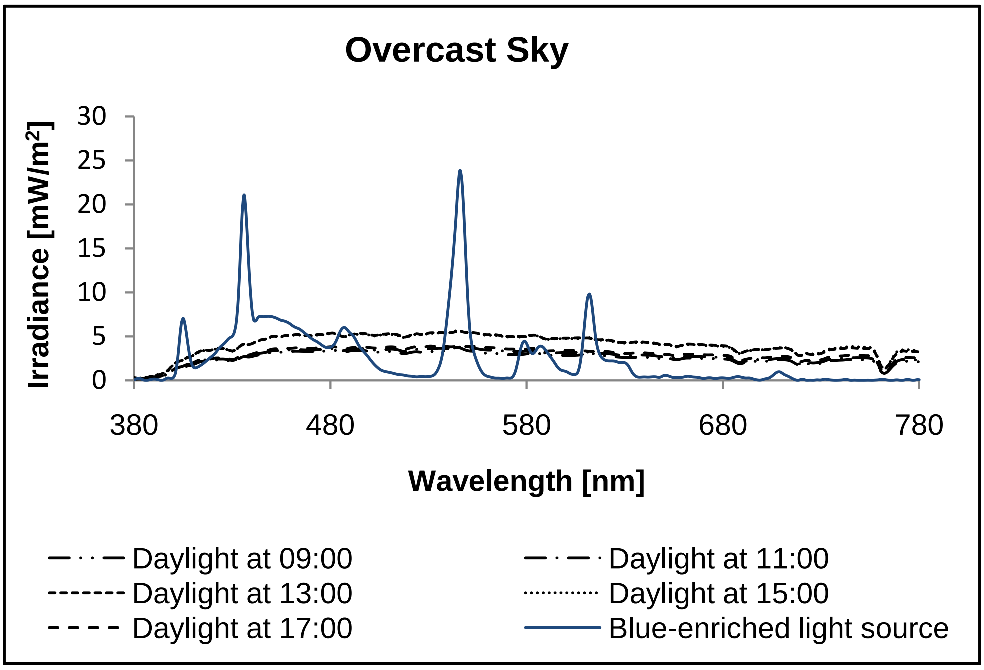


Figure 7.3: Spectral irradiances - Overcast. - Spectral irradiances measured in the test office room on an average overcast day.

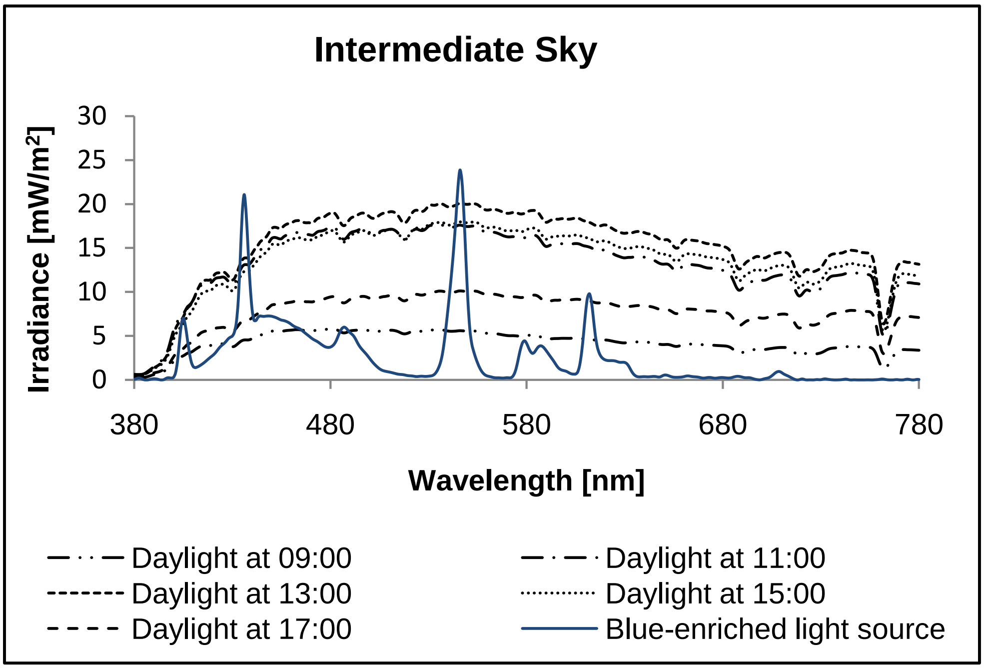


Figure 7.4: Spectral irradiances - Intermediate. - Spectral irradiances measured in the test office room on an average intermediate day.

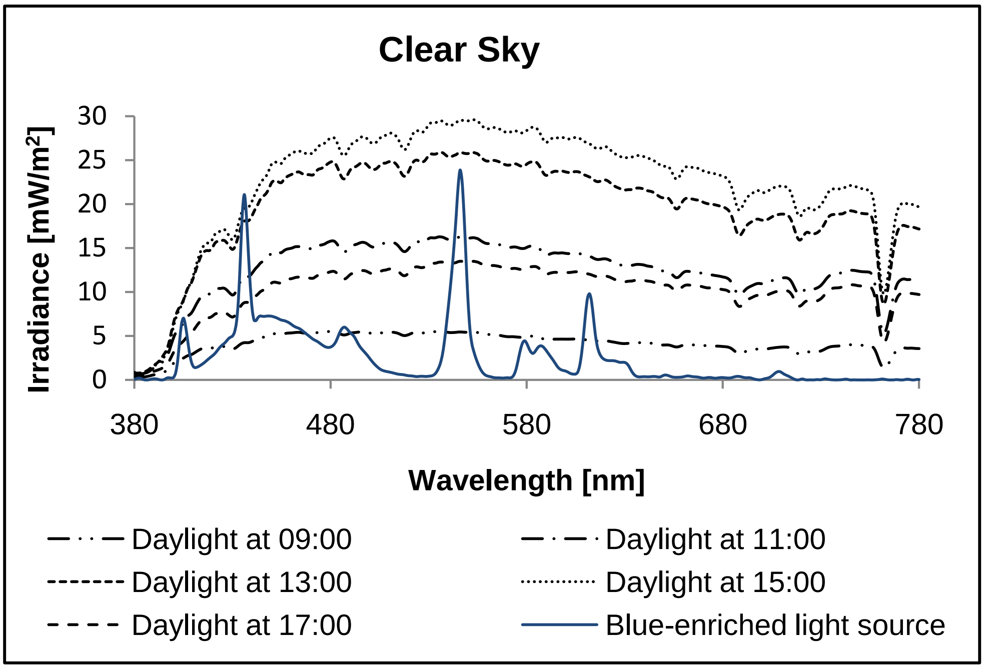


Figure 7.5: Spectral irradiances - Clear. - Spectral irradiances measured in the test office room on an average clear day.

($p<0.05$; Friedmann-Anova). For the overcast sky there was no significant change in the irradiance level across the day.

7.3.3 Ocular c(λ)-corrected irradiances

The c(λ)-corrected irradiances E_{ec} for overcast, intermediate and clear sky conditions are shown in Figures 7.7 to 7.9. The c(λ)-corrected irradiance obtained from the artificial blue-enriched light source was 0.492 W/m^2 $\pm$ 0.005 W/m^2 Lux (SD) and is indicated in Figures 7.7 to 7.9 as a vertical line.

For intermediate and clear days, the c(λ)-corrected irradiance levels were significantly higher during large parts of the working day than the artificial lighting ($p<0.05$; t-test), except in the morning hours before 10:00 and in the afternoon after 16:00. However, for overcast sky conditions, the c(λ)-corrected irradiance levels are close to those with artificial lighting conditions ($p>0.1$). When the different sky conditions were compared , significantly higher c(λ)-corrected irradiances were found on clear days, between 14:00 and 16:30 in the afternoon than during overcast days and slightly higher

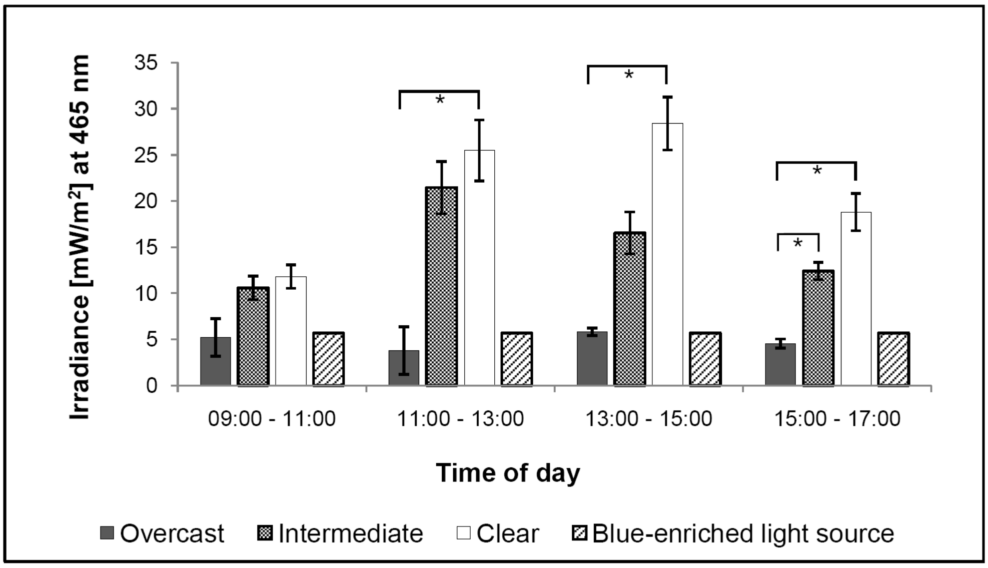


Figure 7.6: Daylight irradiances at 465nm ("Blue Light"). - Averaged irradiances values at 465 nm ("Blue Light") plotted in four time bins across the working day for the three sky types.

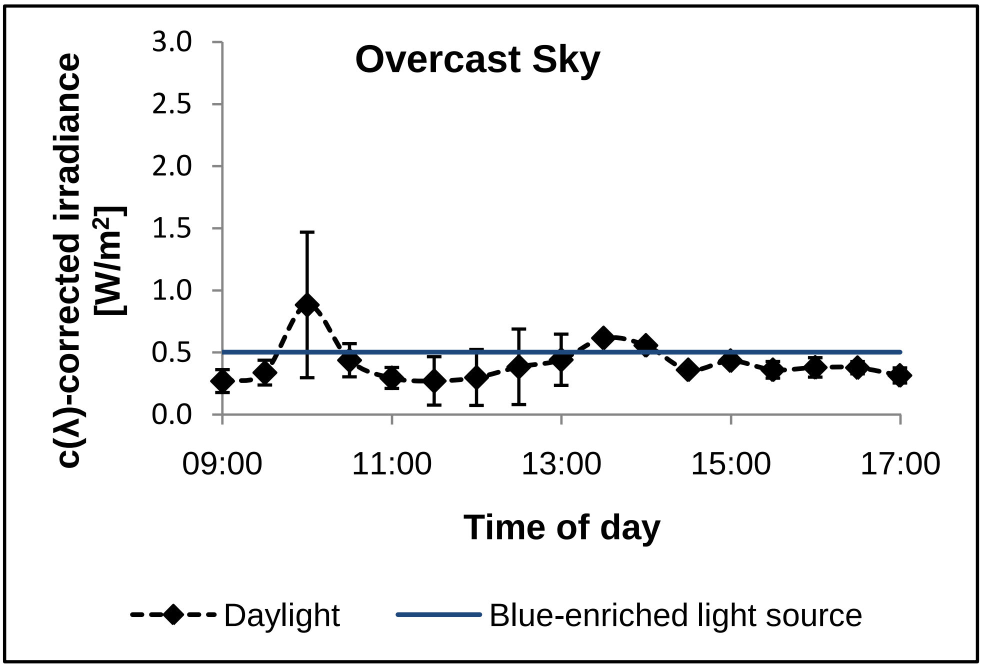


Figure 7.7: C(λ)-corrected irradiances - Overcast. - The Figure shows the c(λ)-corrected irradiances on an average overcast day.

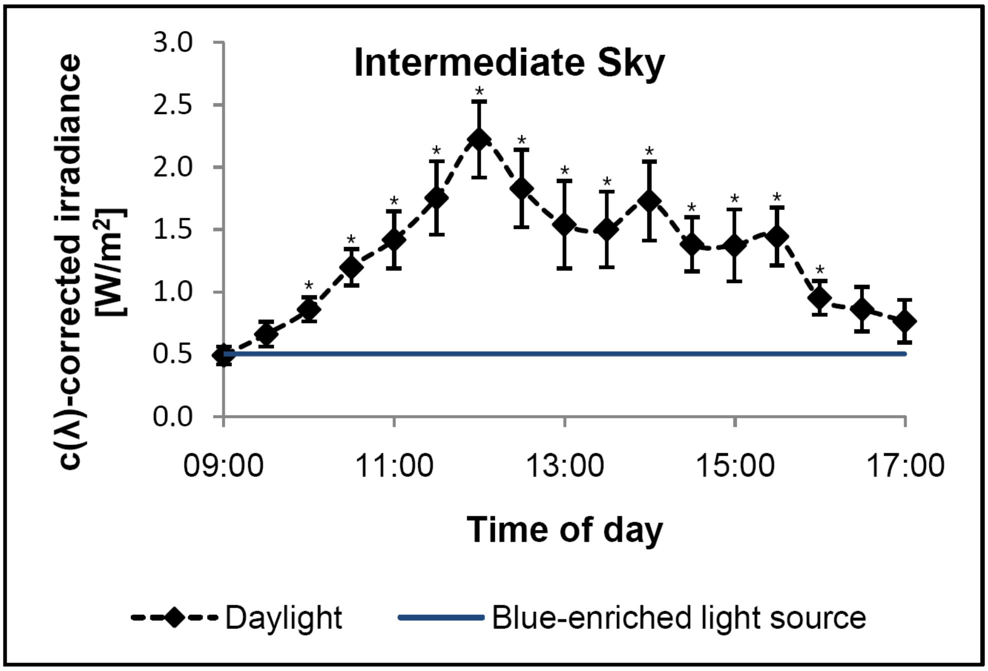


Figure 7.8: C(λ)-corrected irradiances - Intermediate. - The Figure shows the c(λ)-corrected irradiances on an average intermediate day.

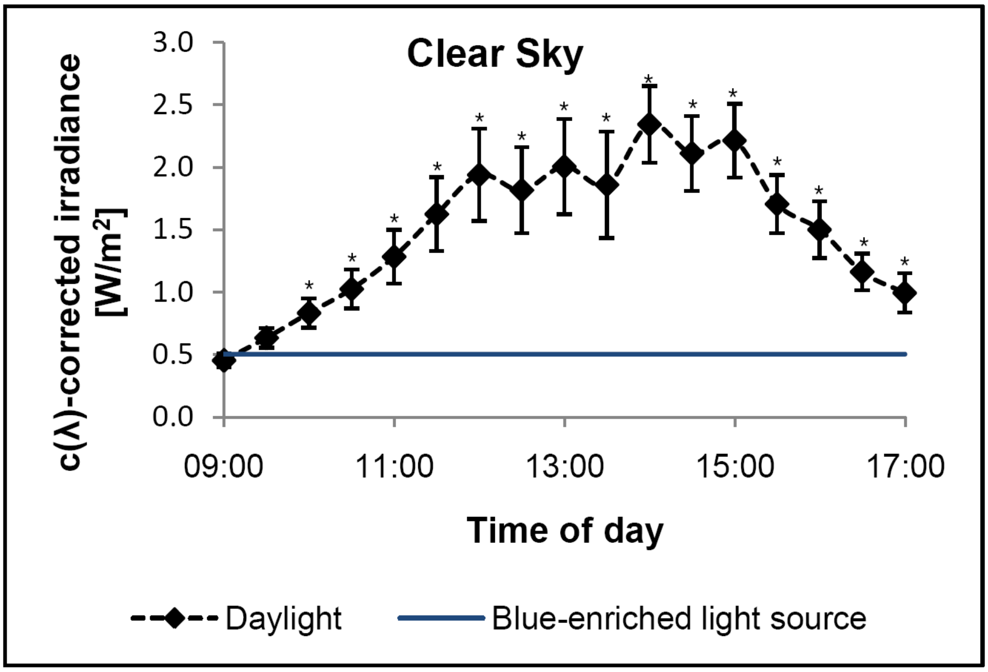


Figure 7.9: C(λ)-corrected irradiances - Clear. - The Figure shows the c(λ)-corrected irradiances on an average clear day.

between 11:00 and 13:00 ($p<0.1$). Irradiances on clear days were also higher at 16:00 compared to intermediate sky conditions ($p<0.05$). On overcast mornings between 10:30 and 12:00 the $c(\lambda)$-corrected irradiance levels were slightly lower than those with intermediate sky conditions between 10:30 and 12:00 ($p<0.05$).

7.4 Discussion

As expected, significant differences of daylight irradiances between the three sky types were found (Figures 7.3 to 7.5). The results also show the variability of irradiances and the spectral composition across working hours between 09:00 and 17:00. Irradiance values for overcast skies are in general much lower than those of intermediate and clear skies, especially between 11:00 and 15:00. Yet higher irradiance values are obtained on clear days, especially between 13:00 and 15:00. The same effects are visible in Figure 7.6 where only the spectral irradiance at 465 nm ("Blue Light") was analyzed.

These initial findings visualize the fact that the daylight exposures of occupants in those ADS-equipped office rooms are increasing when the weather outside is improving (i.e. the sky is clear). In other words, the occupants can benefit from nice weather, even while working inside. One could of course argue that glare might occur and visual comfort might decrease when ocular irradiances increase. However, it can be assumed from this and earlier work that good visual comfort was generally achieved during our experiments (5; 67; 68; 91). The occupants usually "ease" temporarily occurring glare by using the installed window blinds. Glare typically occurs on clear days when there is a high risk of direct sunlight reaching the office. Furthermore, such situations typically occur in the mornings and afternoons when sun elevations are comparably low. As a matter of fact, the irradiance differences that are apparent in Figure 7.4 and 7.5 between 11:00, 13:00 and 15:00 are more important under clear sky conditions than under intermediate sky conditions. Those differences could be the result of closed window blinds on the mornings of clear days.

Interestingly, around 09:00 the irradiance levels are similar under all three sky conditions. If our objective would be to add artificial light on overcast days in order to make the ocular irradiances comparable to those occurring on clear days, this would be most easily achievable in the early mornings.

Furthermore, the graphs for intermediate and clear skies in Figures 7.3 to 7.5 visualize the fundamental differences between artificial fluorescent light and daylight: Whilst the fluorescent light spectrum is mainly composed of several distinct peaks (centered on the emitting wavelengths of the applied fluorescence substances) the daylight spectrum is much more continuous and complete: virtually no wavelengths are "missing".

The comparably low spectral irradiance in the blue range achieved under the artificial blue-enriched light source (Figure 7.6) might seem surprising at first sight. This can partly be explained by the fact that the "blue peak" of the artificial lamp is at approximately at 436 nm (see 7.3 to 7.5), which had of course no influence on the irradiance levels at 465 nm.

After their experiments in a UK office building, Viola et al. concluded that the lighting situation created by the newly installed blue enriched lighting design was sufficient to improve alertness, performance and mood as well as subjective sleep quality in office workers. The average horizontal work plane illuminance during their experiments was found to be 310 lx. The lighting design in our test office room led to an average work plane illuminance of 468 lx. Thus, the two lighting designs are not only comparable, but the installation in the LESO building's test office room supplies even more blue-enriched light (and therefore higher $c(\lambda)$-corrected irradiances) than the installation used by Viola et al. Whether the same positive effects might be found in our office occupants in terms of alertness, performance, mood and sleep quality, needs to be tested.

We may assume that any other light source which performs at least as well as the two blue-enriched light sources in terms $c(\lambda)$-corrected irradiance E_{ec} could also induce those positive effects. Therefore, on working days with intermediate and clear skies, no additional blue-enriched artificial light would be needed in our ADS-equipped office rooms during very large parts of the working day: daylight almost always creates sufficiently high E_{ec} levels (see Figures 7.7 to 7.9). However, these plots of the $c(\lambda)$-corrected irradiances suggest that additional artificial lighting with blue-enriched polychromatic fluorescent tubes such as "Activiva active" might be useful on overcast days and even before 09:00 on days with intermediate and clear skies, in order to improve the building occupants' wellbeing, alertness, performance and mood.

7.5 Conclusion

These results show to which extent external sky conditions influence light exposure of office workers in an ADS-equipped office room for different sky types. It was found that the considered ADS was able to supply natural blue light irradiance levels during large parts of days with intermediate and clear skies, which were much higher than those created by the artificial lighting installation based on two blue-enriched fluorescent lamps. The same is true for the corresponding c(λ)-corrected irradiances E_{ec}. It seems admissible to assume that, within this tested ADS-equipped office room at the LESO solar experimental building, complementary artificial lighting with blue-enriched polychromatic fluorescent tubes might be useful on days with predominantly overcast skies and before 09:00 and after 16:30 on all days. The results suggest that in all other cases, the available daylight is sufficient during this time of year.

It has to be mentioned that the use of the circadian action function c(λ) has of course several limitations because it does, for example, not account for the length of light exposure and is based on nocturnal melatonin suppression only. However, since more appropriate objective quantifications of the human non-visual response to light of different wavelengths are currently not available, using the c(λ)-curve is a reasonable choice for the moment.

Further research will reveal whether daylight and ADS are sufficient to obtain the described positive effects (111) without artificial lighting and to also influence objective variables. In particular, it is necessary to quantify how much artificial lighting is required to complement insufficient natural light conditions, especially in the blue range of visible light, in order to optimize circadian biological and behavioral functions of office workers and other populations.

Last but not least, ways to supply the desired c(λ)-corrected irradiances with a minimum of electricity consumption have to be discussed. Using blue LEDs for energy-efficient "Blue Lighting" might be an interesting option for the future. This topic is adressed in the next Chapter of this Thesis.

8

An LED-luminaire for energy-efficient "Blue Lighting"

8.1 Introduction

As explained in the previous Chapter, the ADS installed in the test office room at the LESO solar experimental building is able to provide ocular irradiance levels (and in particular c(λ)-corrected irradiance levels) that are comparable to or higher than the irradiance levels described by Viola et al. (111). Only on overcast days, in the mornings and eventually in the evenings, artificial light sources are necessary to keep the c(λ)-corrected irradiance levels in the regions for which Viola et al. have recently described their positive effects on alertness performance and sleep-quality. The blue-enriched fluorescent tubes used by Viola et al. could also be used in the case of the test office room in the LESO building. However, they are not very energy-efficient: The lighting scenario with two "Activiva active" fluorescent tubes mounted in two ZEN3 luminaires (as described in Chapter 7) leads to a connected lighting power P_{con} of 116 W which corresponds to an LPD of 7.25 W/m^2. From an energetic point of view, it would make much more sense to combine the "Test" lighting scenario or the "Reference" lighting scenario described in Chapter 6 with an additional lamp installation that could be used to increase the c(λ)-corrected irradiance levels in a more energy-efficient manner when needed. Such a lamp installation could, for example, be based on LED technology. As a matter of fact, colored LEDs potentially offer interesting possibilities for such additional lighting installations since they produce quasi-monochromatic light while achieving good luminous efficacies (93). Ferguson et al. have presented a tunable LED device that could be used for chronobiological applications in 2008 (27) and have shown its potential for melatonin suppression in rats.

In order to get an idea of how much additional artificial light would be needed for this purpose, various spectral irradiance measurements (using the Specbos 1201 in the same way as explained in Chapter 7 and as illustrated in Figure 7.1) were carried out in the test office room at nighttime (i.e. no daylight). Figure 8.1 gives an overview of these spectral measurements.

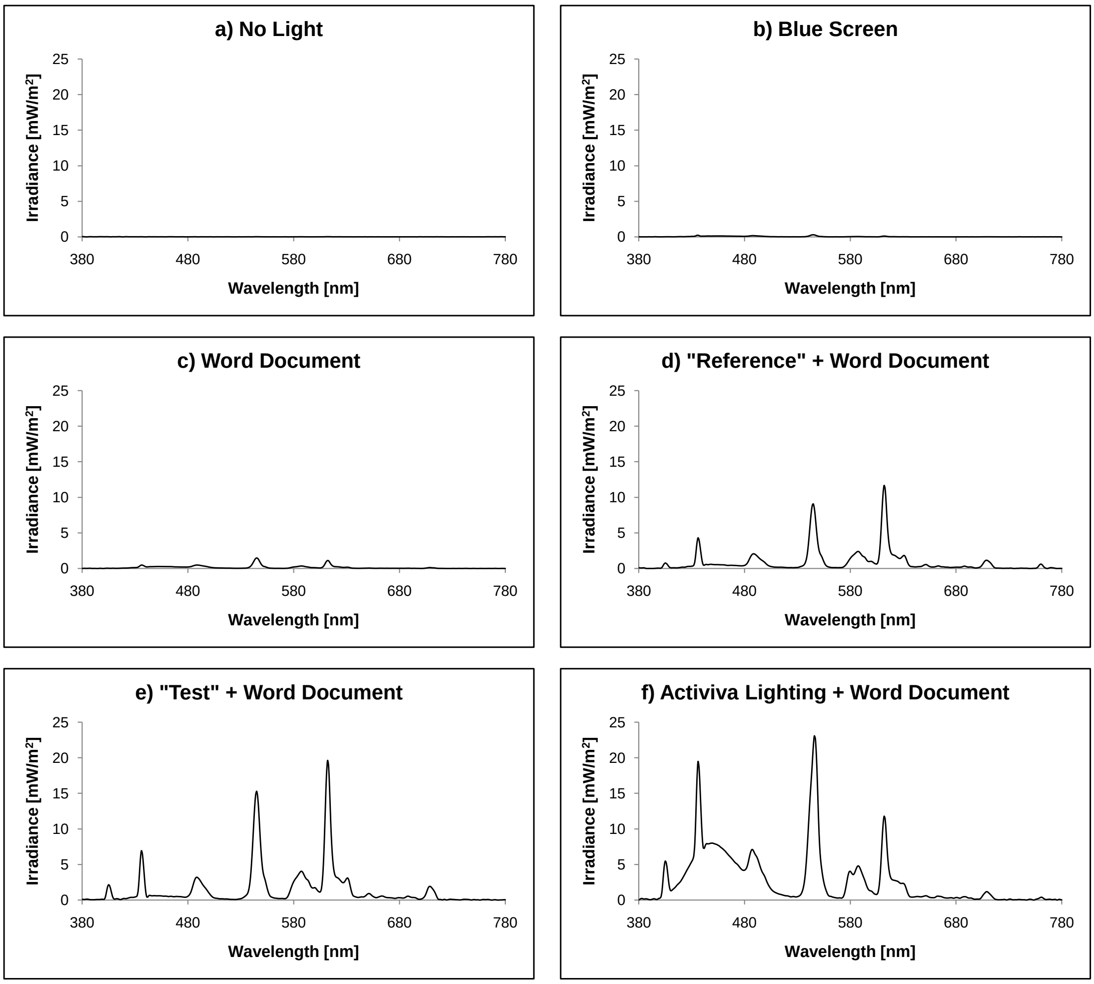


Figure 8.1: Irradiance measurements in test office room - Nighttime. - This Figure shows different spectral irradiance measurements carried out in the test office room at night time. The spectroradiometer was placed at the approximate eye level of an office worker.

These results show that the light emitted from a blue computer screen (e.g. Windows standard screen) can be neglected but that an open Word document already has a stronger effect on the detected irradiances at eye level (see panels a) to c) of Figure 8.1). The measured irradiances for the previously introduced "Reference" and "Test" lighting scenarios (see Chapter 6) can be observed in panels d) and e). For both measurements, the Word document was left open on the computer screen in order to simulate realistic office work. Panel f) shows the situation achieved by the "Activiva active" lighting scenario. Figure 8.2 shows the c(λ)-corrected irradiance levels for the six spectral light distributions displayed in Figure 8.1. It is obvious that neither the "Reference" nor the "Test" scenario can compete with the Activiva-lighting and that the computer screen has almost no influence on the measured ocular c(λ)-corrected irradiance levels.

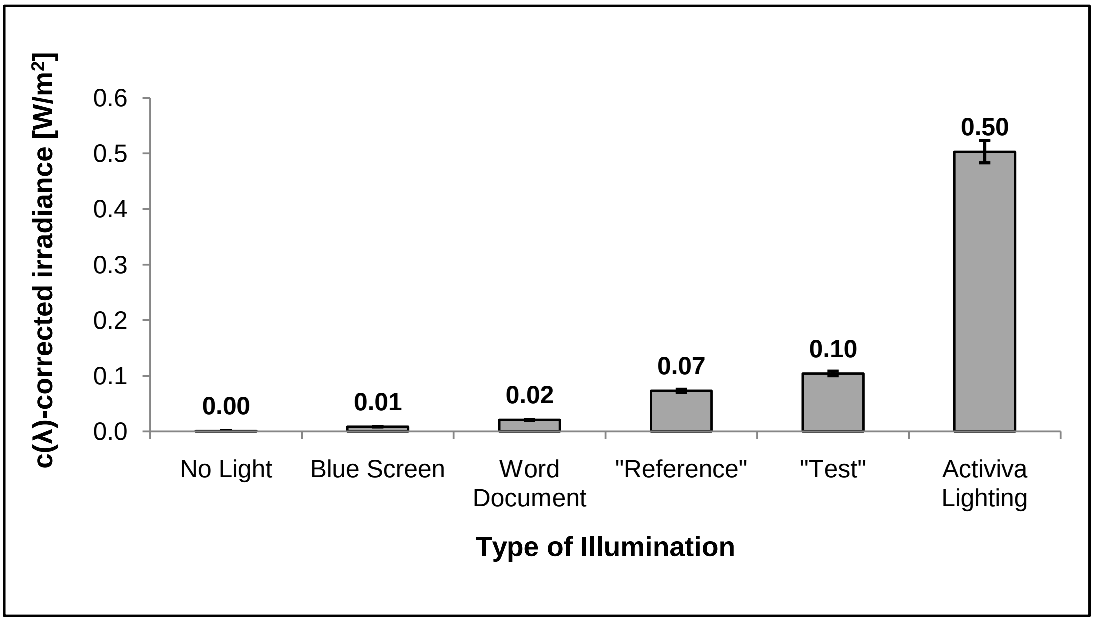


Figure 8.2: C(λ)-corrected irradiance levels - Nighttime. - This Figure shows the c(λ)-corrected irradiance levels for the six spectral light distributions displayed in Figure 8.1.

8.2 Using Blue LEDs instead of Blue-Enriched Fluorescent Tubes?

Placing several blue LEDs directly in the visual field of an office worker could be a very simple way to increase the c(λ)-corrected irradiance levels while consuming only a minimum of electricity. Figure 8.3 shows a small device containing three blue LEDs ("Dragon Puck" by OSRAM (77)). The device has a power consumption of 3.6 W and creates quasi-monochromatic blue light centered at a wavelength of 468 nm. This small device has simply been fixed to the top of the test office's computer screen and the result was then measured with the spectroradiometer. When the blue LED device was the only light source in the test office room, a c(λ)-corrected irradiance level of 3.21 W/m^2 was measured at eye level. This value is more than seven times higher than the c(λ)-corrected irradiance level created by the Activiva-lighting. There is, however, one serious disadvantage: the blue light beam issued from the device points directly towards the office occupant and creates unbearable discomfort glare.

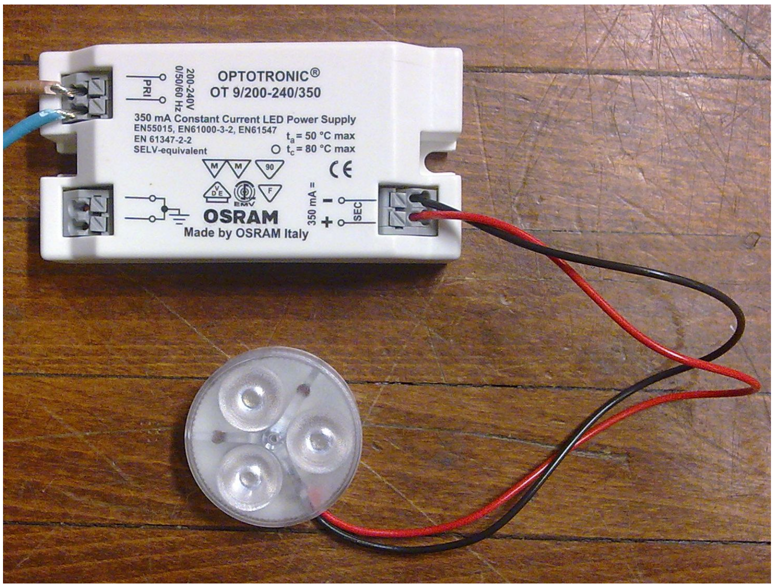


Figure 8.3: "Dragon Puck" by OSRAM (77). - This Figure shows a small device containing three blue LEDs ("Dragon Puck" by OSRAM (77)). The device has a power consumption of 3.6 W and creates quasi-monochromatic blue light centered at a wavelength of 468 nm.

Figure 8.4 shows a comparison between the initial workplace (left) and the workplace with the blue LED device attached to the computer screen (right). Both pictures were taken on an extremely overcast day, with the "Test"-scenario in operation for complementary electric lighting. The photographs show that even when switched on during daytime, the lighting scenario with the blue "Dragon Puck" device attached to the computer screen is highly uncomfortable.

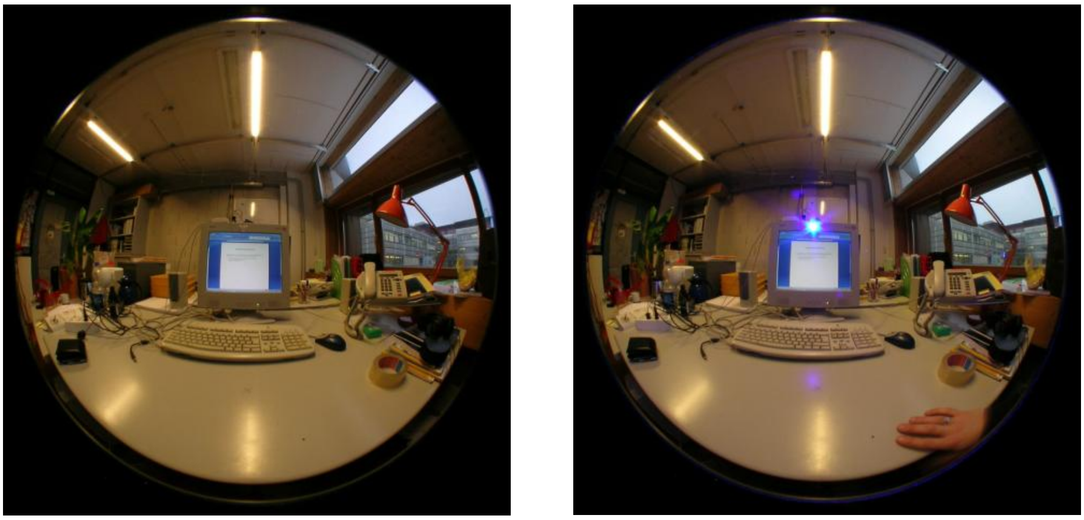


Figure 8.4: Workplace view with and without blue LED. - The Figure shows a comparison between the initial workplace (left) and the workplace with the blue LED device attached to the computer screen (right).

Even if simply installing the blue LED device in the center of the office occupant's visual field led to unacceptable discomfort glare, the measured c(λ)-corrected irradiance level of 3.21 W/m^2 underlines the extremely large potential of blue LEDs for energy-efficient "Blue Lighting".

8.3 Design and Test of the Luminaire

One way to reduce the discomfort glare induced by the blue LED device shown in Figure 8.3 could be to integrate it into a specially conceived luminaire which would be able to better distribute the light flux issued from the device. A first prototype of such a luminaire was designed within the framework of this doctoral thesis. Figure 8.5 gives an overview of the luminaire and its dimensions.

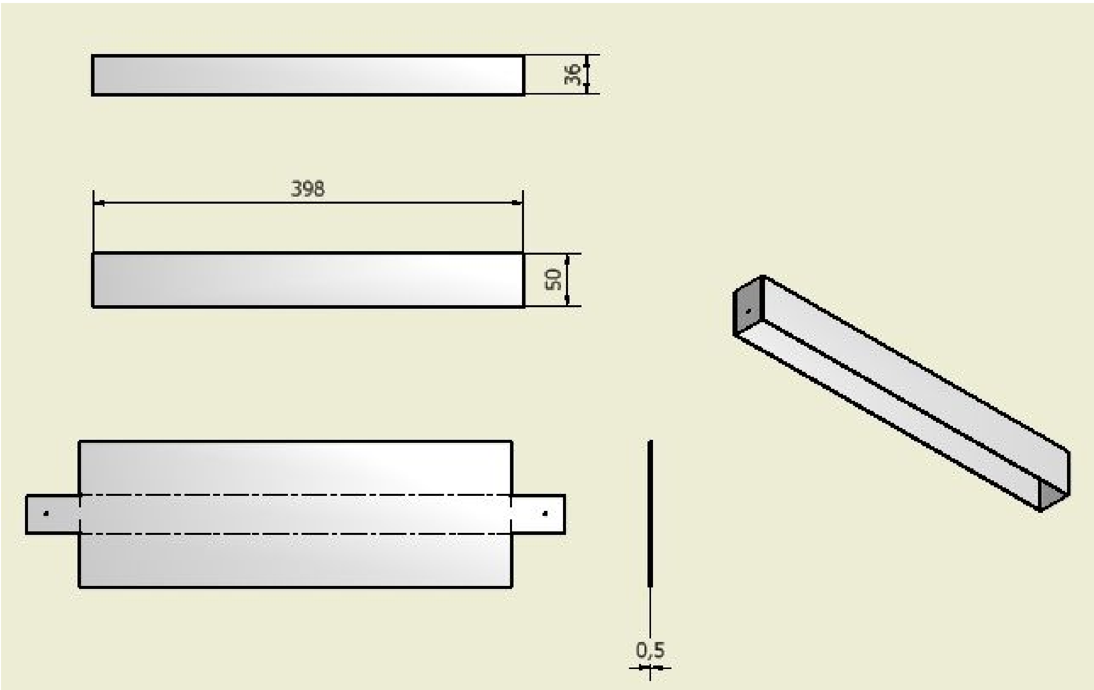


Figure 8.5: The luminaire. - This Figure gives an overview of the luminaire for the blue LED and its dimensions.

A highly reflective aluminum foil with a thickness of 0.5 mm was bended as indicated in Figure 8.5 to obtain the luminaire. As mentioned in Chapter 3, the long-term use of LEDs requires an appropriate heat management in order to avoid a decrease in light output flux. A luminaire made up of a bended aluminum foil is not only comparably easy to manufacture and extremely light, it can also serve as a heat sink for the LED device due to the advantageous thermal capacities of aluminum (e.g. thermal conductivity of 220 W/mK (57). The blue LED device was attached to the left side of the luminaire with an M3 metal screw. A luminaire screen was fabricated from semi-translucent white paper. Figure 8.6 shows photographs of the luminaire and the mounted blue LED device (top) and the luminaire covered by the paper screen switched on (bottom). In the following, this luminaire for "Blue Lighting" based on LED-technology will be referred to as "BlueLum".

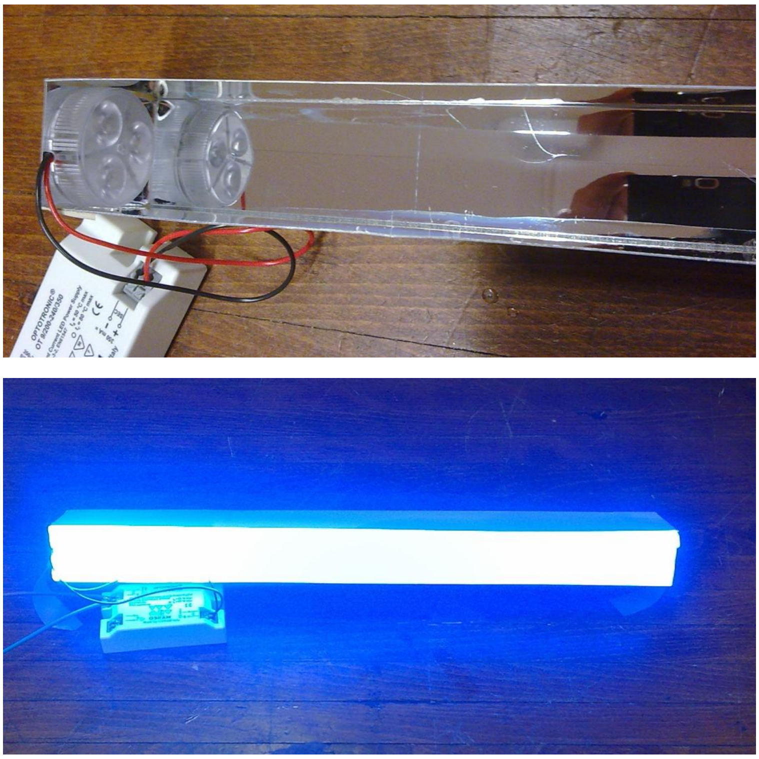


Figure 8.6: The BlueLum prototype. - The Figure shows photographs of the luminaire and the mounted blue LED device (top) and the luminaire covered by the paper screen switched on (bottom).

Due to its light weight and its compact dimensions, the BlueLum can easily be mounted on top of a computer screen. This particular application is shown in Figure 8.7. The resulting lighting scenario is much more comfortable than the "blue LED"-scenario presented within the previous Section and can be supposed to be much better accepted by office occupants.

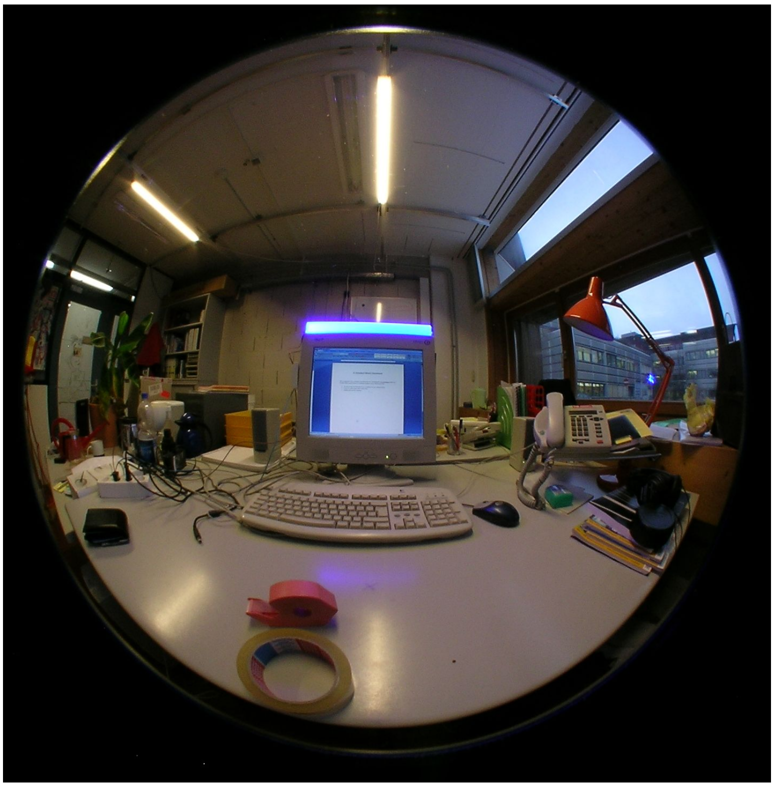


Figure 8.7: BlueLum fixed on computer screen. - This Figure shows the BlueLum fixed to the test office room's computer screen.

Figure 8.8 shows the measured ocular irradiance distributions when the BlueLum is mounted on top of the test office room's computer screen. The spectral irradiance distribution when only the BlueLum is switched on in the dark test office room (Word document open on computer screen) is shown in panel b). Panels c) and d) show the resulting spectral irradiance distributions for the cases where the BlueLum is combined with the "Reference"- and the "Test"-lighting, respectively. For comparative reasons, the Activiva-lighting is shown in in panel a) of the Figure.

The resulting c(λ)-corrected irradiance levels are shown in Figure 8.9. One can observe that the combinations of "Reference"- or "Test"-lighting together with the

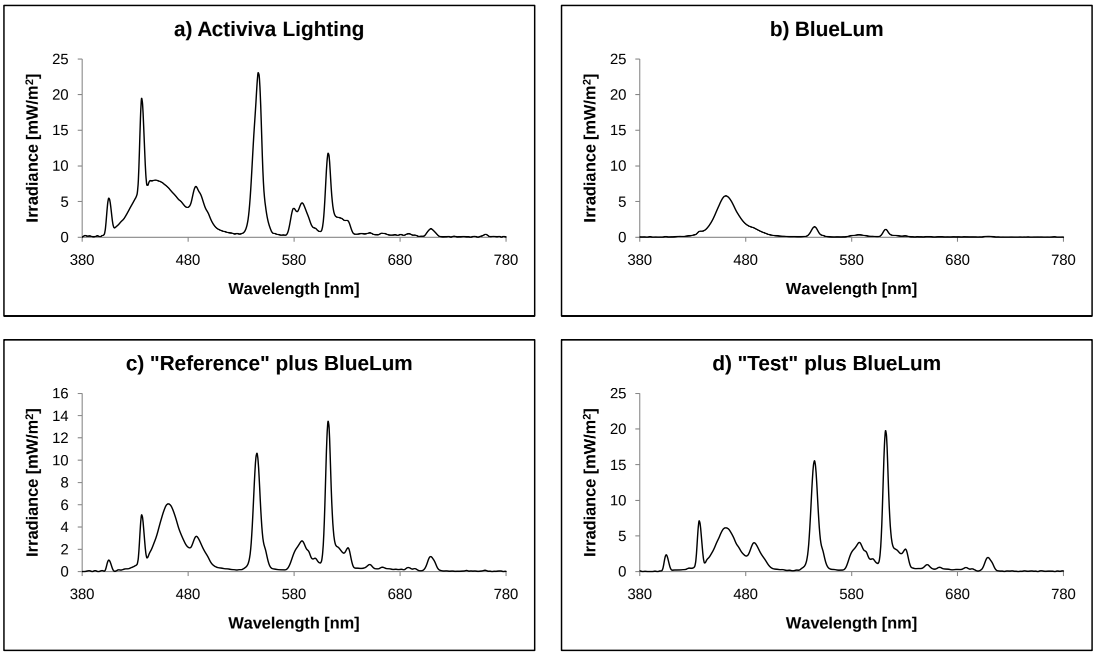


Figure 8.8: Ocular irradiance distributions - One BlueLum. - This Figure shows the measured ocular irradiance distributions when the BlueLum is mounted on top of the test office room's computer screen.

BlueLum do not reach the same c(λ)-corrected irradiance levels at eye level as the Activiva-lighting.

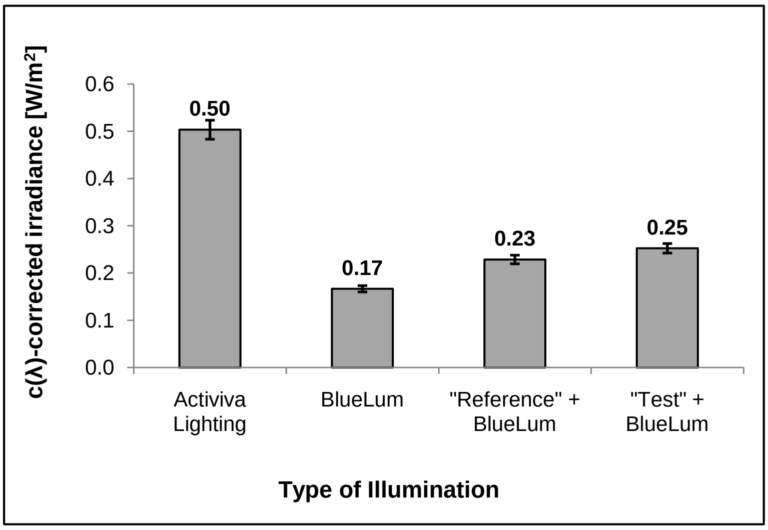


Figure 8.9: C(λ)-corrected irradiance levels - One BlueLum. - This Figure shows the resulting c(λ)-corrected irradiance levels for one BlueLum device.

However, due to the low weight of the BlueLum, the latter doesn't necessarily have to placed *on top* of the computer screen. It is in fact also possible to place it *laterally*, i.e. on the left or the right side of the computer screen. In such a way, three BlueLums can be fixed on one computer screen. Figure 8.10 shows the resulting spectral irradiance distributions for the case where three BlueLums are mounted on the computer screen in the test office room. The resulting combinations of the three BlueLums and the "Reference"- and "Test"-scenarios are now comparable to the Activiva-lighting in terms of spectral irradiance distribution.

Figure 8.11 confirms that the c(λ)-corrected irradiance levels at eye level are now very much comparable to the Activiva-lighting for the combinations of three BlueLums and the "Reference"- or "Test"-scenarios.

Figure 8.12 now gives an overview of the power consumptions for these last types of office illumination. The combination of "Test"-lighting and three BlueLum-devices leads to a connected power of 68 W, whereas the Activiva-lighting has a maximum power consumption of 116 W. This corresponds to a reduction of more than 40% and can therefore lead to substantial electricity savings.

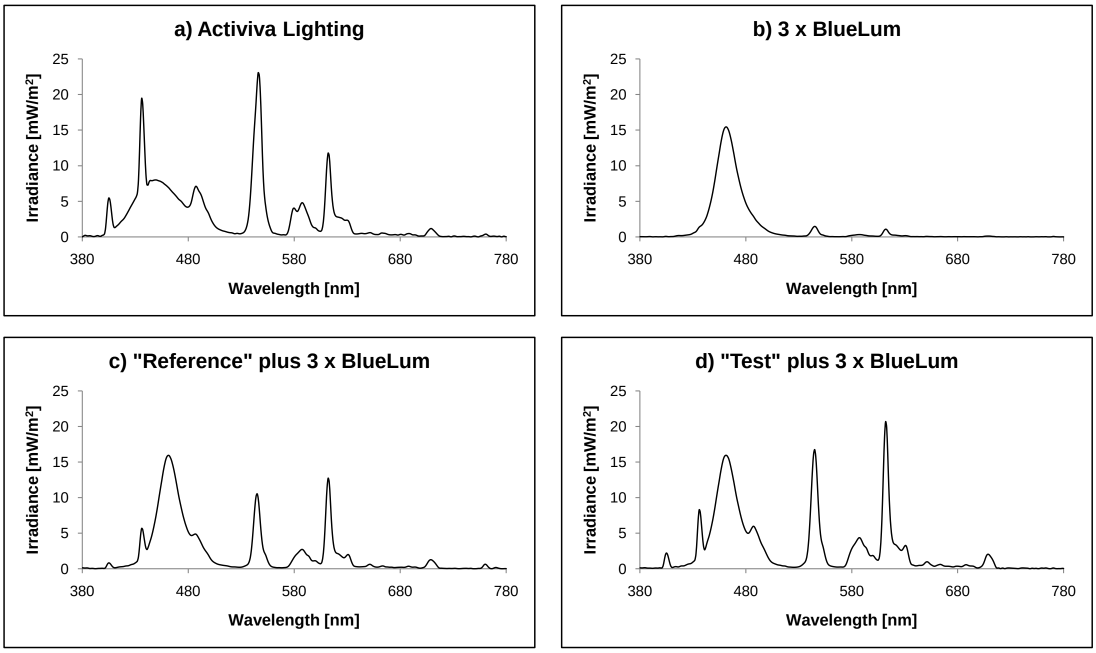


Figure 8.10: Ocular irradiance distributions - Three BlueLums. - This Figure shows the measured ocular irradiance distributions when three BlueLums are mounted on top of the test office room's computer screen.

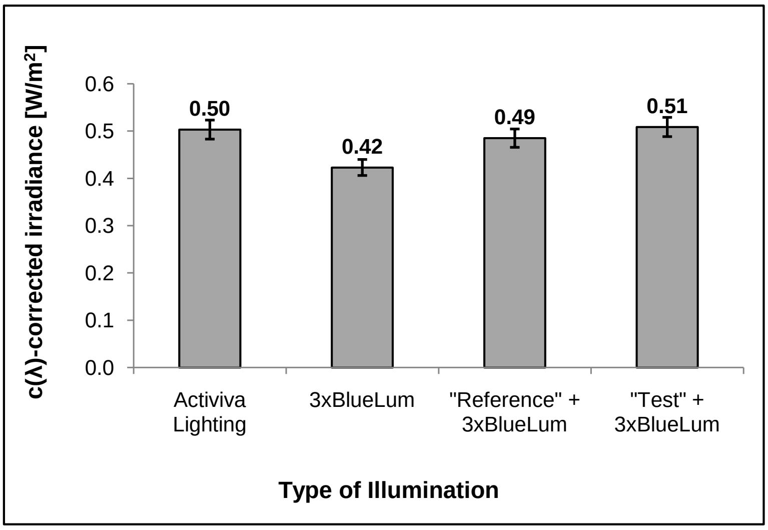


Figure 8.11: C(λ)-corrected irradiance levels - Three BlueLums. - This Figure shows the resulting c(λ)-corrected irradiance levels for three BlueLum devices.

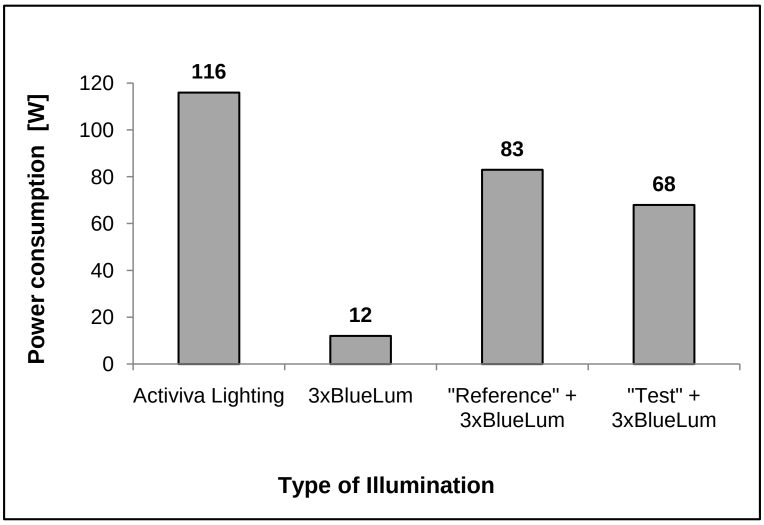


Figure 8.12: Power consumption - BlueLum vs. Activiva. - This Figure gives an overview of the power consumptions for the lighting solutions with three BlueLums and the Activiva lighting.

8.4 "Blue Lighting" plus "Red Lighting"?

In addition to the recent findings on the positive effects of blue light on human alertness, performance and well-being, there is also evidence that light of other wavelengths has specific influences (physiological and psychological) on the human body. Hill and Barton for example have shown a positive influence of red sports dress on the probability of winning in contests in 2005 (40). On the other hand, Elliot et al. have shown in 2007 that the brief perception of red prior to an important test can impair performance in humans (26). Very recently, Figueira et al. have put forward preliminary evidence that both blue and red light can induce alertness at night and have contemplated that this induction might not necessarily only imply reactions of the circadian system (28).

At the end of this doctoral thesis, the BlueLum device was transformed into a "BlueRedLum" - a device that can supply both blue and red light as well as any mixed spectral composition. This has been achieved by simply mounting a red "Dragon Puck" device in addition to the blue one on the opposite end of the aluminum BlueLum-luminaire.

This new device could be of great use during applied chronobiological studies in office environments in the future.

8.5 Conclusion

The above discussions and measurement results show that LEDs have not only a large potential for general lighting applications in office rooms (typically with white LEDs), but might also be interesting for special lighting applications, such as "Blue Lighting" (i.e. lighting that can influence for example alertness, performance, mood or well-being in office workers via the human circadian system). The BlueLum device developed during this doctoral thesis enables office lighting solutions that can be expected to create the same positive effects as the ones described by Viola et al. (111), but that will show a significantly lower electricity consumption. It also has to be emphasized that the BlueLum presented in this Chapter is a first prototype. There is still huge scope for optimizing the device, for example by using the non-imaging optics theory (113). This theory could help to minimize the light reflections inside the BlueLum and to make the device yet more energy-efficient. It shall also be mentioned that various LED-based color lighting applications are already commercially available (e.g AmbiLight™by PHILIPS (78)). However, the advantage of the BlueLum developed during this doctoral work is that its performance in terms of c(λ)-corrected irradiances has been thoroughly assessed and compared to values which had been shown to have positive effects on office workers (111). An interesting possibility to verify the potential of the BlueLum in this regard might be to use it for an animal study comparable to the one described by Ferguson et al. (27).

In any case, the BlueLum device and the BlueRedLum device (which cannot only supply controllable flux of blue light but also of red light to office occupants) open a wide range for future chronobiological studies at the LESO-PB. Acceptance studies with office workers using the BlueLum and the BlueRedlum are also an interesting option for future work.

9

A First Applied Study on Chronobiological Lighting Aspects in Office Rooms at LESO-PB

9.1 Introduction

The previous Chapters have already given an insight into non-visual aspects of office lighting. There are many *clinical studies* that have shown the influence of light of different intensity and spectral composition on humans, for example in terms of sleepiness and psychomotor vigilance performance (79), working memory (107), alertness (14), melatonin suppression (13; 101) or yet brain activity (58).

As described in Chapters 7 and 8, Viola et al. have recently carried out an *applied chronobiological study* in a real office environment and have managed to show positive effects associated with blue-enriched fluorescent tubes. Hoffmann et al. have attempted to show the influence of variable lighting intensities on melatonin secretion and subjective mood in an experimental office workplace (42). There is still important scope for further applied chronobiological studies in office environments in order to test which of the chronobiological findings from clinical studies are relevant to office work.

This Chapter describes how a first applied study on chronobiological lighting aspects in office rooms was prepared within the framework of the doctoral thesis and discusses some preliminary results.

9.2 Setup of a Controlled Lighting Conditions Exposure Room

In order to test the light-dependent chronobiological functions in humans under realistic office lighting conditions, a special light exposure room in the LESO Solar Experimental Building has been installed within the framework of this doctoral thesis. Such a room should make it possible to expose human study participants to a large variety of controlled lighting conditions. In particular, the comfortable exposure to natural light and the comfortable and flexible exposure to artificial light of different intensity, distribution and spectral composition was seen as desirable.

Due to the positive experiences with the ADS installed in the south-facing office rooms of the LESO building, it was decided to transform the building's south-facing, ADS-equipped seminar room into a Controlled Lighting Conditions Exposure Room (CLC Exposure Room). The room has a surface area of approximately 35 m^2 and is located on the second floor of the building. It is fitted with two separate ADS, each equipped with the associated external and internal blinds for glare protection (see detailed explanations in Chapter 2). Figure 9.1 (left) shows the location of the seminar room inside the LESO building; an inside view of the room's two ADS is shown in Figure 9.1 (right).

Before having been transformed into a CLC Exposure Room, the LESO building's seminar room was only equipped with two free-standing luminaires for indirect lighting like the one shown in Figure 3.12. It was impossible to create a large variety of artificial lighting scenarios with only these two free-standing luminaires. Therefore, a DALI-controlled lighting system composed of eight "Lip" luminaires by Regent (84) (see Figure 3.15) was installed in the room. The chosen luminaires were each equipped with one 58 W fluorescent tube by PHILIPS (4000 K, 5200 lm). Figure 9.2 gives an overview of the electric lighting installation in the CLC Exposure Room. The eight luminaires were organized in four groups of two luminaires. Each of these groups can be addressed via one separate DALI-channel. In particular, the switching and the continuously variable dimming of each group is possible via the remote control and the IR receiver connected to the DALI controller. In addition to the lighting management

Figure 9.1: Controlled Lighting Conditions Exposure Room - The photograph on the left shows the location of the CLC Exposure room on the second floor of the LESO building in Lausanne. An inside view of the room's two ADS is shown in the photograph on the right.

by the remote control and the IR receiver, it is also possible to switch and dim all eight luminaires simultaneously via the installed push button coupler. Furthermore, it is possible to operate the DALI controller from a computer via the PC interface.

The precise positions of the eight DALI-controlled "Lip" luminaires are indicated in Figure 9.3. This Figure shows the results of a RELUX Vision (85) simulation carried out during the design process of the CLC Exposure Room. For this simulation, all eight luminaires are switched on. The simulated average illuminance on the workplane is 615 Lux with a uniformity g_1 of 0.66 and a maximum of 715 Lux. Due to the fact that the CLC Exposure Room was simulated without furniture and is, in reality, equipped with grayish tables, the actually achieved average illuminance can be expected to be somewhat higher (see Chapter 5). Indeed, a maximum of 793 Lux ($\pm$7%) on the workplane was measured after the installation of the electric lighting system was finished.

The results of a RELUX Vision simulation during which only one luminaire group is switched on are shown in Figure 9.4.

Figure 9.5 shows a simulated lighting scenario were one group is completely switched on (i.e. 100% of its maximum light flux) and a second group is dimmed down to only 50% of its maximum light flux. Figures 9.4 and Figure 9.5 clearly visualize the

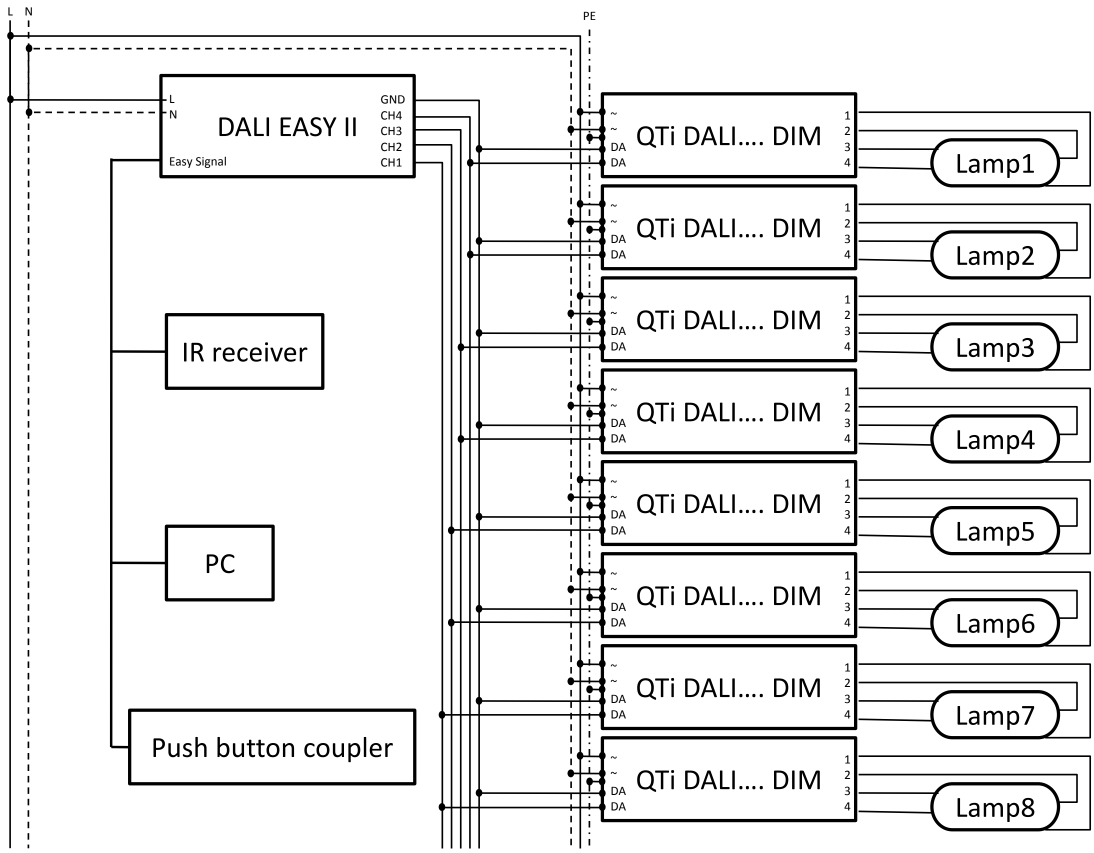


Figure 9.2: Electric Lighting System of the CLC Exposure Room - This Figure gives an overview of the electric lighting installation designed for the CLC Exposure Room during this doctoral project. The control unit "DALI EASY II" controls the eight ceiling-mounted lamps via four separate output channels. A push button coupler, a computer interface and an IR receiver with an associated remote control are in place and can be used to program different lighting scenarios via the "DALI EASY II".

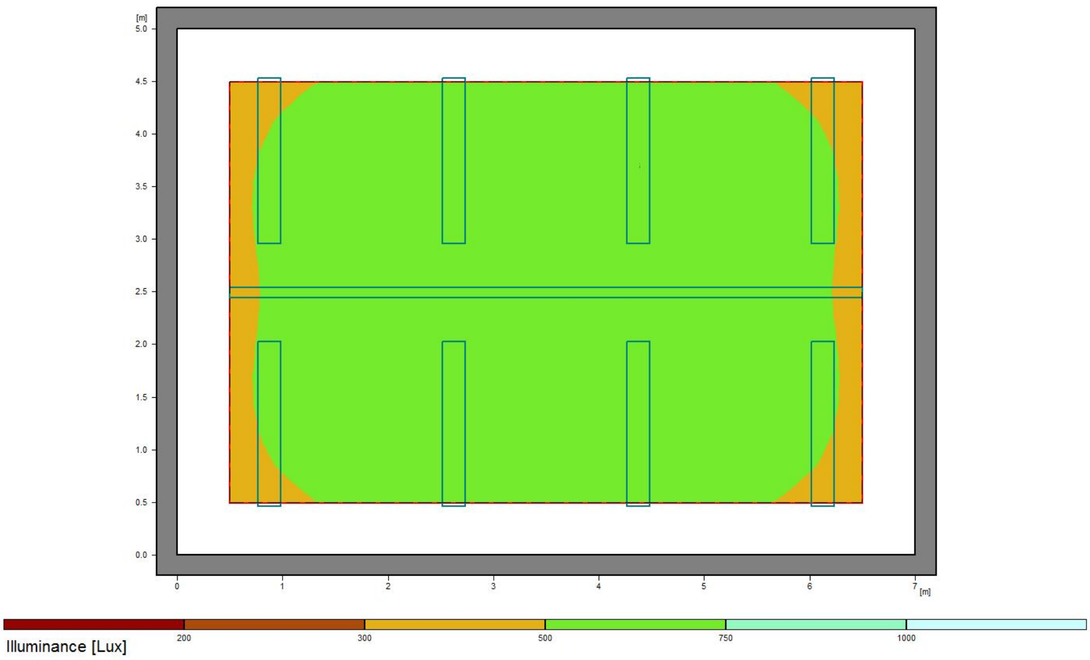


Figure 9.3: All lamps on in the CLC Exposure Room - The Figure shows the resulting illuminance distribution on the CLC Exposure Room's workplane when all ceiling-mounted lamps are switched on at 100%.

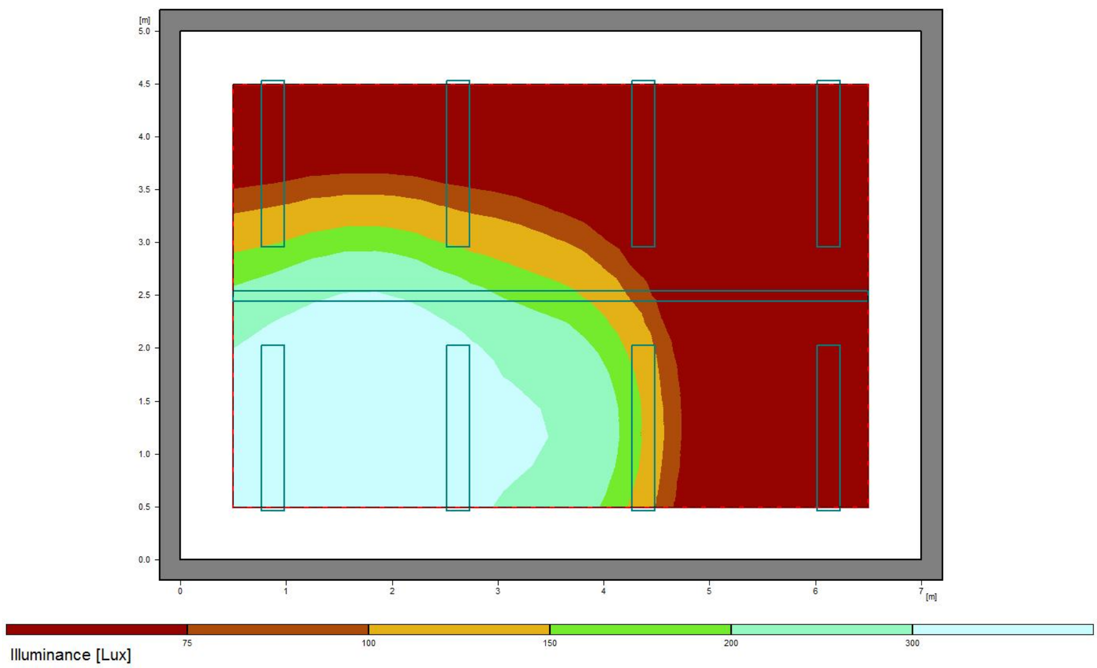


Figure 9.4: Only one lamp group on in the CLC Exposure Room - This Figure shows the resulting illuminance distribution on the CLC Exposure Room's workplane when only one lamp group is switched on at 100%.

important flexibility of this DALI-controlled electric lighting installation in the CLC Exposure Room: in addition to the three particular lighting scenarios shown here, a large variety of different lighting scenarios can be achieved.

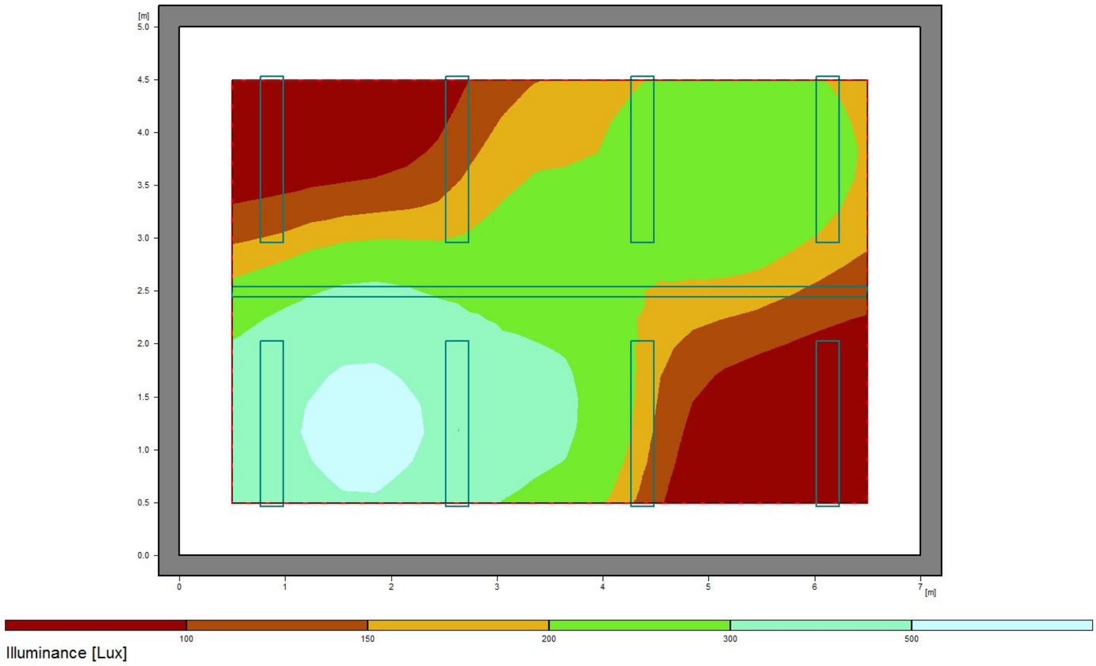


Figure 9.5: Advanced dim lighting scenario in the CLC Exposure Room - This Figure shows the resulting illuminance distribution on the CLC Exposure Room's workplane when one lamp group is switched on at 100% and a second one at 50%.

9.3 Test of Two Different Office Lighting Conditions on Evening Performance, Visual Comfort and Hormonal Secretion

9.3.1 Introduction

Towards the end of this doctoral thesis, a first chronobiological study that makes use of the CLC Exposure Room was prepared. The study has started in October 2009 and is on the way to be extended. The objective of this study is to investigate acute time-delayed influences of different lighting scenarios on subjective alertness, mood, performance and hormonal secretion in human subjects. The study participants are exposed to higher (DL) on one day and to artificial light (AL) on the other day in a balanced cross-over design. Light exposures last from 12:00 to 18:00. From 18:00 to 20:00, all subjects carry out repeated performance tasks under dim light conditions ($<$ 5 Lux). The hypothesis of the study is that exposure to daylight (with the typically associated high illuminances, the spectral continuity and the temporal variety) during the day has not only *immediate positive effects* on office occupants compared to static artificial lighting (with the typically associated lower illuminances, spectral discontinuity and missing temporal variation) but also *time-delayed positive effects* on alertness, mood, performance and hormonal secretion in the evening. It was decided to test this paradigm under realistic office lighting conditions during the winter season. The study was approved by the local Ethical Committee and is in accordance with the Declaration of Helsinki.

9.3.2 Screening Procedure

It was decided to carry out the pilot study with healthy male and female participants between 20 and 30 years of age. The study participants are being recruited via advertisements from the local campus at the EPFL and the University of Lausanne. In order to find out whether an interested person is suitable for the study or not, each potential participant must answer two questionnaires (see Appendices C.2 and C.3) and undergoes an interview with one of the study investigators.

Exclusion criteria for the study are:

- Medical or psychiatric illness
- Pregnancy
- Permanent medication (other than oral contraceptives)
- Alcohol abuse
- Drug abuse
- Smoking
- Extreme Chronotypes (Horne & Östberg Questionnaire, (43))
- Shiftwork in the last two months
- Travel over more than two time zones in the last two months

All study participants gave informed written consent prior to the study.

9.3.3 Study Design

During the week that precedes the beginning of the actual laboratory study and between study days, participants are asked to maintain a regular sleep-wake schedule at home, including approximately 8 h of bed rest, within a self selected target time of ±30 minutes. In order to test the subjects' compliance, each subject is wearing a wrist monitor (Daqtix®, Oetzen, Germany (19)) for seven days before the start of the study's laboratory part and completes sleep logs at home. Figure 9.6 shows a picture of the Daqtix®, worn like a watch at the wrist of the test person's non-dominant hand.

Figure 9.6: The Daqtix device. - Study participants wear the Daqtix®seven days prior to the study at their non-dominant wrist. The device records acceleration values and illuminances.

The Daqtix®records spatial acceleration values and stores them in an integrated flash memory. In addition to an acceleration sensor, the device also disposes of a light sensor which measures illuminances. The acceleration and illuminance values can be downloaded. The downloaded recordings make it possible to determine when the subjects went to bed and when they got up during the last seven days.

On study days, subjects are asked to abstain from caffeine and alcohol and to come to the laboratory at 12:00. On each study day, a maximum of two participants are scheduled. During six hours (approximately between 12:00 and 18:00), the participants are seated in the CLC Exposure Room. They are allowed to read and write during these six hours and to listen to music using earplugs. The use of portable computers is not authorized. Each participant disposes of an inclined reading/writing support. In this way, it is attempted to keep the participants' viewing direction as horizontal as possible in order to keep the ocular light exposure constant. The vertical irradiances and illuminances are monitored throughout the entire afternoon with the digital spectroradiometer (see Appendix A), installed at the approximate eye-level of the participants. Figure 9.7 shows a photograph of the two workplaces in our CLC Exposure Room, with the reading/writing supports, the digital spectroradiometer (and a laptop on which the monitoring data is continuously stored during the experiment) as well as a luxmeter that is used to continuously monitor the horizontal workplane illuminance in the center of the room.

Figure 9.7: Workplaces of the CLC Exposure Room. - Photograph of the two workplaces in our CLC Exposure Room, with the reading/writing supports, the digital spectroradiometer as well as a luxmeter that is used to continuously monitor the horizontal workplane illuminance in the center of the room

For the DL conditions, vertical illuminances between 1000 and 2000 Lux are aimed at and illuminance levels are controlled every thirty minutes. If they exceed 2000 Lux, the blind installations are used to reduce the illuminances. Eventually occurring discomfort glare issues are equally resolved on the spot through appropriate blind setting. If the spectroradiometer detects records vertical illuminances lower than 1000 Lux, the electric lighting installations are used to manually add complementary artificial light to achieve vertical illuminances higher than 1000 Lux.

For the AL exposure, all eight Lip luminaires (see Figure 9.2) are switched on and evenly dimmed down as to achieve a horizontal workplane illuminance of 418 Lux (±7%) at the center of the CLC Exposure Room (measured with the luxmeter shown in Figure 9.7). This dimming configuration is stored in the DALI control unit as a scene via the remote control and the IR receiver (see Figure 9.2). Like this, it is possible to use exactly the same artificial lighting scenario for all study participants.

During the first six hours of the study, subjects receive two meals (sandwiches) and cold beverages. They are only allowed to leave their seat to use the bathroom. During this time, two questionnaires (Visual Analog Scale for Mood, Wellbeing and Temperature (VAS-MWT) and Karolinska Sleepiness Scale (KSS), see descriptions below) are given every thirty minutes and the Visual Comfort Scale (VCS, see below) is given hourly. The paper-based Landolt-ring test already described in Chapter 6 and an optimized OLS (OLS 1) is given once.

After six hours in the CLC Exposure Room, subjects are taken into a windowless test room with dim light (< 5 Lux on the workplane). In this test room, each subject carries out four n-back test sessions (see detailed descriptions below) per day. Each n-back session is composed of three 2-back and three 3-back tests. The (easier) 2-back tests are always presented before the 3-back tests. One session (thus consisting of three 2-back and three 3-back test) lasts approximately seven minutes and is repeated every thirty minutes. In addition to that, each subject performs three FrACT sessions, each one of which consists of one "acuity" and one "contrast" test. The participants' alertness, mood and wellbeing is simultaneously monitored through four VAS-MWT and four KSS every 30 minutes. Saliva samples for hormonal assessments are collected every 30 minutes approximately. After the participants have given their last saliva sample, the light is switched on, and the second version of the optimized OLS (OLS 2) is filled out.

Figures 9.8 and 9.9 visualize the study protocol for the light exposure in the CLC Exposure Room and the protocol for the test sessions in the windowless test room, respectively.

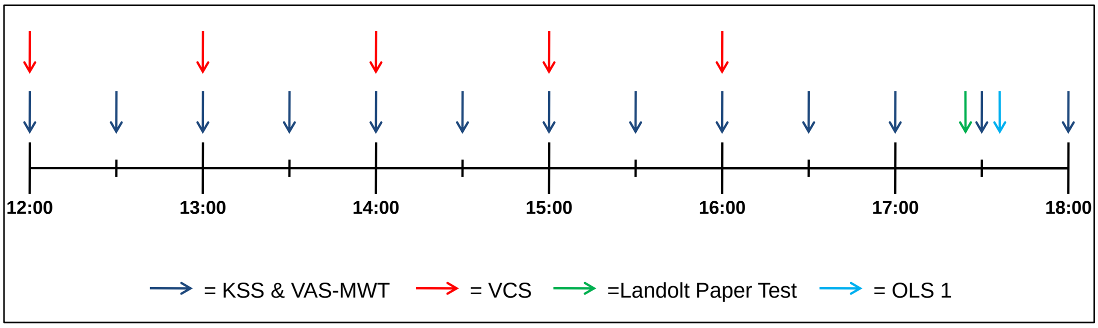


Figure 9.8: Protocol during light exposure. - This Figure gives an overview of the light exposure part of the study. The arrows indicate at what times which questionnaires are filled out by the occupants.

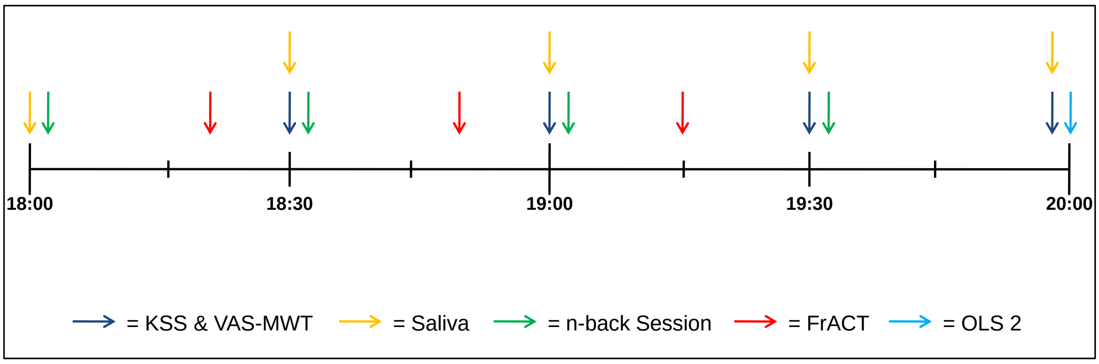


Figure 9.9: Protocol during test session. - This Figure gives an overview of the test session part of the study. The arrows indicate at what times which questionnaires are filled out and which tests are done by the occupants.

9.3.4 Questionnaires and Paper-based Tests

During the study, the following questionnaires to query subjective ratings from the study participants are used.

1. The **Karolinska Sleepiness Scale (KSS, French Version)** (3) (see detailed explanations in Chapter 6) is used to assess the participants' subjective alertness throughout the study (see Appendix C.4).

2. Furthermore, a French version of the **Visual Analogue Scale for Mood, Well-being and Temperature (VAS-MWT)** is used. A Visual Analogue Scale (VAS) allows continuous assessment of subjective variables between two extremes. Wewers and Lowe have provided an informative discussion of the benefits and shortcomings of different types of VAS (115). The VAS-MWT is given in Appendix C.5.

3. In order to assess in particular subjective visual comfort issues during the experiment, an optimized version of the amended **Office Lighting Survey (OLS)** (see Chapters 2 and 6) is used. The discrete four-stage scale used during our previous studies has been replaced by a VAS in order to measure the participants' responses on a continuous scale. Two slightly different versions of this optimized OLS are used at different moments during the chronobiological study (see Appendix C.6).

4. Additionally, a shortened version of the optimized OLS is also used during the study in order to keep track of eventual changes in visual comfort over the duration of the study. This questionnaire is being referred to as the **Visual Comfort Scale (VCS)** (see Appendix C.7).

In addition to these questionnaires, the paper-based Landolt-ring test already described in Chapter 6 is being employed during the study in order to see how different lighting scenarios influence the participants' visual performance in a paper-based task.

9.3.5 Computer Performance Tests

Two different computer-based tests are used in the chronobiological study. The first one is the **Freiburg Visual Acuity and Contrast Test (FrACT)** (10) (for a detailed description see Chapter 6). The "acuity" as well as the "contrast" part of the test is used. The test is run with four different ring orientations (testing with eight ring orientations is also possible with the FrACT). In addition to the FrACT, the so-called **n-back Test** is used. This validated neurobehavioral performance task tests working memory and executive functions in humans (49). The subject is presented a sequence of symbols and he or she has to decide whether the second last (2-back) or the third last (3-back) symbol was the same as the current presented symbol by pressing a button on the keyboard. For the study described here, a version with abstract symbols was used. All subjects have the opportunity to exercise the task before the first session in order to make sure they really understand what they are supposed to do. The order of the symbols is different for each test and between day 1 and day 2, but the difficulty levels are comparable. The test in its current form has been programmed using the software tool Eprime®(47) and validated by Jäggi and Buschkuehl (49).

9.3.6 Collection of Saliva Samples for Hormonal Analyses

The objective of collecting saliva samples is to assess dim light salivary melatonin and cortisol levels in the evening to assess circadian phase. It is envisaged to show differences in the onset of melatonine and the decline of cortisol in the evening between the two study conditions DL and AL. From each study participant, saliva is collected every thirty minutes, starting at 18:00. The subject has to spit into a small recipient which is then stored at 4 ℃ in a fridge. The first sample is taken while the subject is still in the CLC Exposure Room, the following ones in dim light conditions in the windowless test room. This results in ten saliva samples per subject (five per day).

9.4 Preliminary Results

As previously mentioned, the study is on the way to be extended. It has been decided to enroll approximately thirty participants in the study; at the time of writing, experiments with 21 subjects have been completed. Amongst these 21 subjects were twelve males and nine females. One of the female participants did not complete the study and was excluded from the analysis. In this Section, preliminary results for twenty study participants are therefore presented. In particular, an insight into the results of the 3-back tests and the KSS ratings is given. Additionally, some preliminary results from the FrACT will be discussed.

9.4.1 Vertical illuminances obtained during the study

It was often not possible to maintain the vertical illuminances during DL exposure between 1000 and 2000 Lux as initially intended. Under overcast sky conditions and in the evenings, it is sometimes not possible to achieve the lower threshold. One reason for this is that the lower blinds of the ADS are kept closed during the experiment in order to avoid any visual contact with the exterior of the building: outside view could have a positive psychological influence on the study participants and could bias the experiment since there is no outside view during AL exposure. The window blinds are also used to avoid discomfort glare: this is a second reason why the lower threshold of 1000 Lux was sometimes not achieved, even on days with clear or intermediate sky conditions. Illuminance drops after 16:00 in the afternoons could not be avoided: the reason for this is the fact that study took part in November and December when the days were getting progressively shorter. Also the higher threshold of 2000 Lux was sometimes overshot. This is typically the case when direct sunlight hits the spectroradiometer at certain times of the day. However, all subjects which completed the study so far were exposed to average vertical illuminances between 410 and 1949 Lux throughout the DL exposure. The detailed irradiance measurements during DL exposure for all subjects are given in Appendix D.

A constant vertical illuminance of 173 Lux ($\pm 2\%$) was measured with the digital spectroradiometer during AL exposure.

9.4.2 Analysis of KSS ratings

A 3-way repeated measurements analysis of variance (rANOVA) with all KSS ratings during the afternoon and the evening with the factors "Sample", "Order" and "Condition" revealed no significant differences between the different KSS-ratings (see Figure 9.10).

When looking only at the factors "Condition" and "Order" we find no significant differences between the mean KSS ratings were found. However, the differences in KSS ratings over the 17 different "Samples" are highly significant ($p < 0.005$).

However, a 1-way rANOVA for the main effect "Study day" (see Figure 9.11) shows that there was a significant difference in mean KSS ratings between the two days: On the second day of the study, the participants were in average more alert than on the first day of the study ($p < 0.05$).

No correlation between the mean vertical illuminances at eye level during exposure in the CLC Exposure Room and the mean KSS ratings were found.

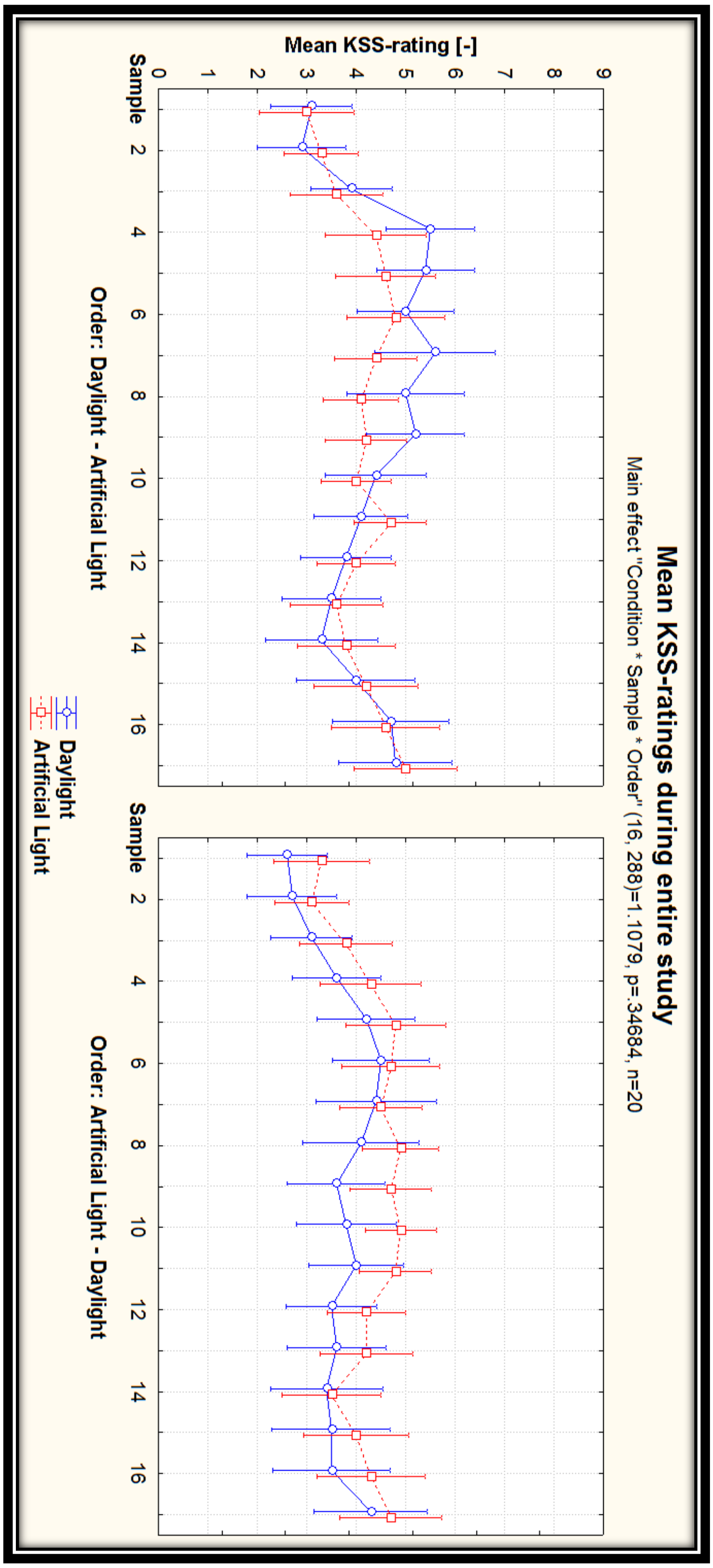


Figure 9.10: Mean KSS ratings for the entire study.

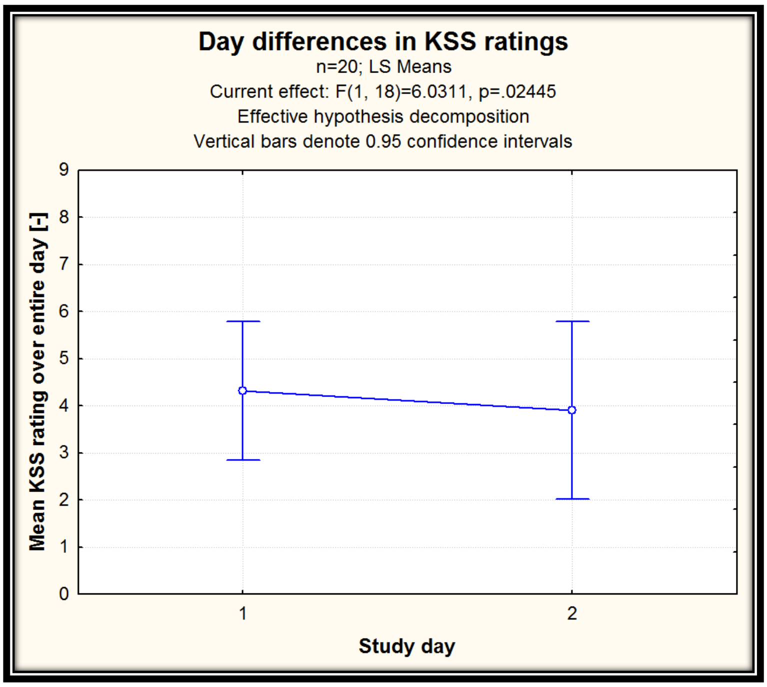


Figure 9.11: Day differences in KSS ratings. - This Figure shows that there was a significant difference in mean KSS ratings between the two days.

9.4.3 Analysis of 3-back test results

Because, according to the literature, the 3-back test is more sensitive than the 2-back test and less likely to show a ceiling effect (49), priority was given to the analysis of the results obtained during the 3-back test. Figure 9.12 gives an overview of the twenty participants' average performance in the 3-back test when exposed to DL (left) or AL (right) conditions during six hours preceding the tests. The performance is quantified via each test's accuracy mass pr and is calculated as follows:

$$pr = total_{hits} - total_{fa} \quad [-] \tag{9.1}$$

where $total_{hits}$ describes the number of times where the participant pushed the "A"-key when he or she *was supposed to push it* and $total_{fa}$ is the number of false alarms. The values of $total_{hits}$ and $total_{fa}$ are expressed as fractions between 0 and 1.

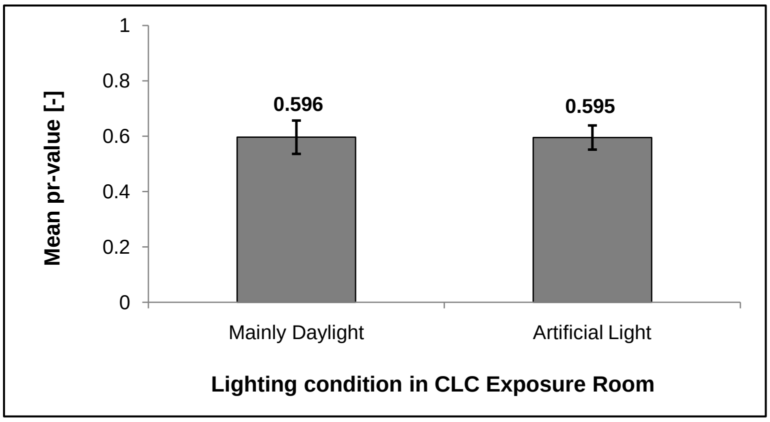


Figure 9.12: Mean performance 3-back test. - This Figure gives an overview of the twenty participants' average performance in the 3-back test when exposed to DL (left) or AL (right) conditions during six hours preceding the tests.

Figure 9.12 shows that the twenty participants scored a mean pr-value of 0.596 ± 0.060 (SE) after DL exposure and a mean pr-value of 0.595 ± 0.043 (SE) after AL exposure. Looking only at these two means over twenty participants and two days with different *orders of exposure* (as mentioned before, a cross-over design where ten participants started with DL exposure and ten participants started with AL exposure was used) might mask some underlying dynamics in the time course of the results. In order to analyze the data, different rANOVA were carried out (using the software tool STATISTICA, version 6.12, (96)) with the factors "Test" (3-back tests 1-24), "Condition" (DL vs. AL) and "Order" (begin with DL or AL).

Effect	SS	DF	MS	F	p
ORDER	5.323	1	5.323	6.08	**.024***
CONDITION	0	1	0	0	0.97
CONDITION*ORDER	2.351	1	2.351	23.66	.000*
TEST	1.054	11	0.096	2.67	**.003***
TEST*ORDER	0.459	11	0.042	1.16	0.316
CONDITION*TEST	0.261	11	0.024	0.55	0.864
CONDITION*TEST*ORDER	0.675	11	0.061	1.43	0.162

Table 9.1: Results of 3-way rANOVA for the 3-back tests.

The results displayed in Table 9.1 show that there was a significant difference in mean pr-values for the main effect "Order". This means that the group of participants who started with AL on the first day and who were exposed to DL on the second day scored in average better pr-values than the group who started with DL on the first day and who were exposed to AL on the second day. Figure 9.13 visualizes this finding.

Furthermore, the results in Table 9.1 indicate a significant difference in mean pr-values for the main effect "Test". This means that there were significant differences between the different 3-back tests. In particular, the mean pr-values were improving towards the end of the study. This fact is shown in Figure 9.14, where the mean pr-values were collapsed in four hourly time-bins. The pr-values scored during the first hour of the first day were significantly lower than those scored during the second hour of the second day.

Further analysis confirmed that on the first day, the mean pr-values for all study participants kept improving over the evening. On the second day, this practice effect that had occurred during the first day persisted (i.e. significantly higher mean-pr-values than on the first day), but there was no intra-day improvement. It makes thus sense to only look at the results of the second day, because in this way no practice effect has to be accounted for.

Figure 9.15 shows the mean pr-values obtained on the second day of the study, for DL and AL exposure. The apparent differences are, however, not statistically significant ($p = 0.31 > 0.05$).

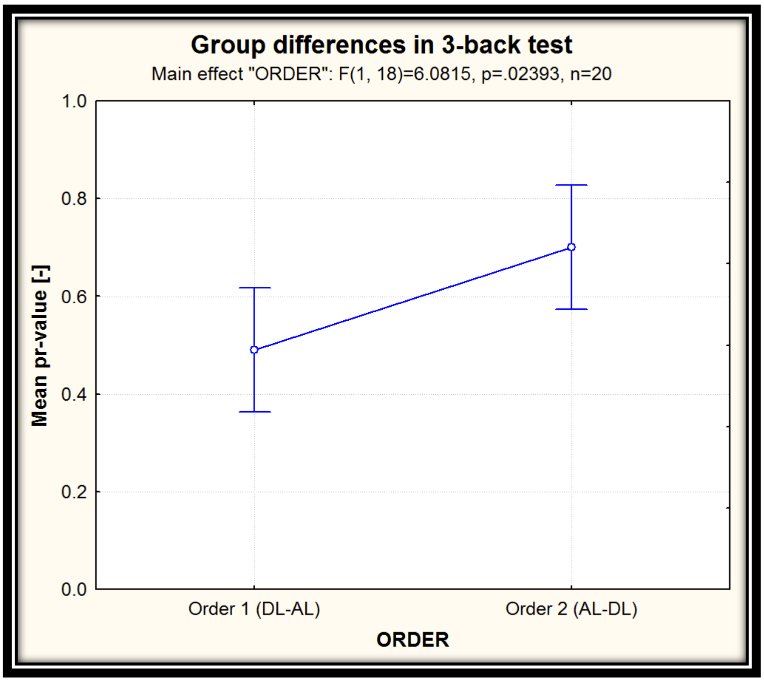


Figure 9.13: Group differences in pr-values. - This Figure visualizes the fact that there was a significant difference in mean pr-values for the main effect "Order".

Looking only at the main effect "Condition" on day 2 provides more power to the rANOVA; like this, the difference in mean pr-values between the conditions DL and AL becomes significant (see Figure 9.16).

In order to test if those subjects who performed better were less tired, a correlation analysis was carried out between averaged subjective alertness ratings and averaged performance in the 3-back tests. A significant negative correlation was found. Figure 9.17 visualizes this negative correlation between the participants' mean KSS ratings and their average performance in the 3-back test. In other words: The more alert they were, the better they performed.

9.4.4 Preliminary results for the FrACT

The average results of the FrACT's acuity-part for the two different lighting exposures are shown in Figure 9.18. There is no significant difference between the two means of the performance indicator.

Figure 9.19 displays the average results of the FrACT's contrast-part for the two

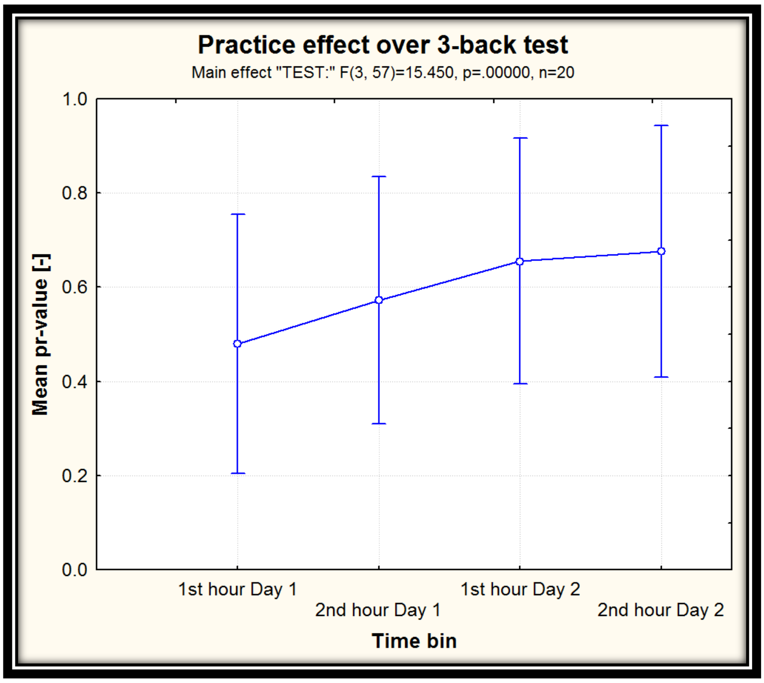


Figure 9.14: Practice effect over 3-back tests (binned). - This Figure visualizes the significant difference in mean pr-values for the main effect "Test". Occupants got ever better results with increasing repetitions.

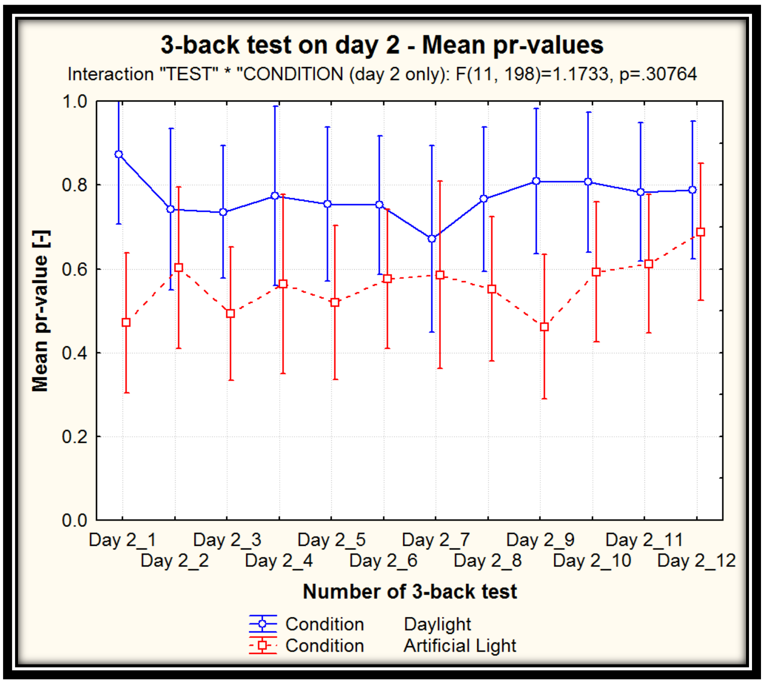


Figure 9.15: Mean pr-values for each 3-back test - Day 2. - This Figure shows the mean pr-values obtained on the second day of the study, for DL and AL exposure.

different lighting exposures. Yet again, the mean contrast thresholds do not differ significantly.

9.4.5 Discussion of preliminary results

First of all, these preliminary results of the chronobiological study visualize that, in this specific setting, the two different daytime lighting exposures "Daylight" (DL) and "Artificial Light" (AL) did not cause a significant difference in the participants' average performances in any of the computer tests. This is clearly shown in Figures 9.12, 9.18 and 9.19. Of course, this does not mean that prior light exposure has no influence whatsoever on computer-based tasks. However, it suggests that in practice, such an influence could be masked by various other factors. The insights into the mechanisms occurring during the 3-back test presented in Subsections 9.4.2 and 9.4.3 suggest that such other factors could be:

- **Practice effect.** Figure 9.14 visualizes the practice effect that occurred during the study. Especially during the first day, the participants scored better results

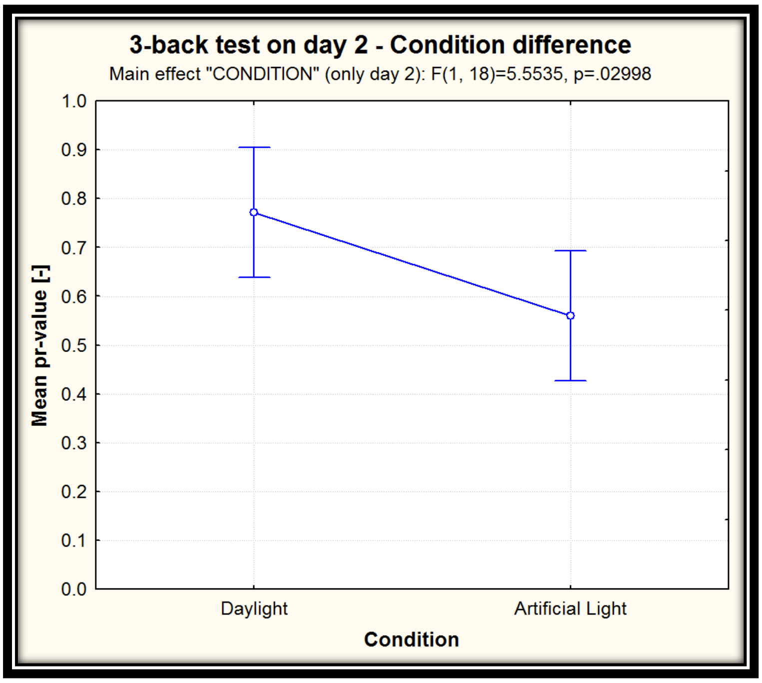


Figure 9.16: Mean pr-values for all 3-back tests - Day 2. - This Figure shows the difference in mean pr-values between the conditions DL and AL for all 3-back tests taken together.

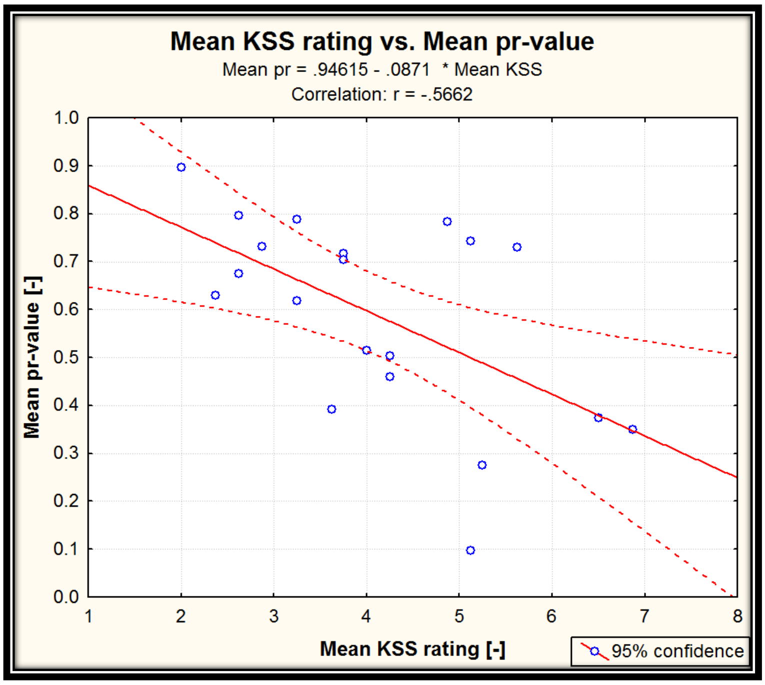


Figure 9.17: Mean KSS rating vs. Mean pr-value. - This Figure visualizes the negative correlation between the participants' mean KSS ratings and their average performance in the 3-back test.

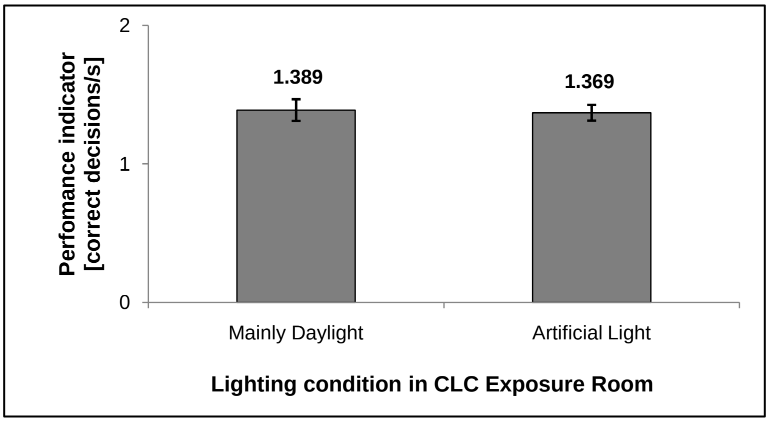


Figure 9.18: Mean performance FrACT - Acuity. - This Figure shows the average results of the FrACT's acuity-part for the two different lighting exposures DL and AL.

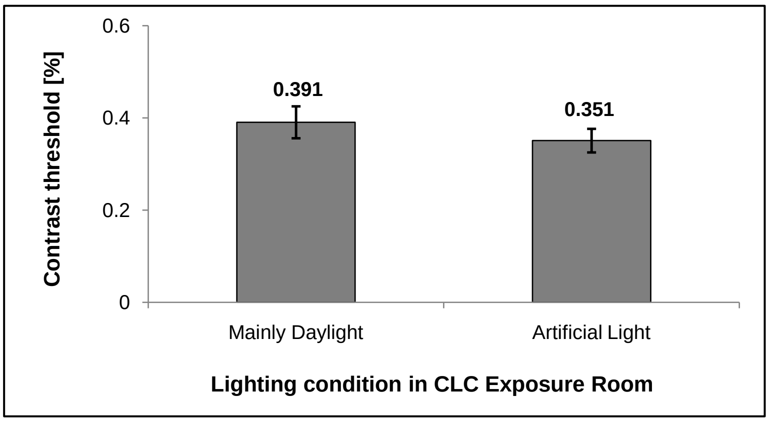


Figure 9.19: Mean performance FrACT - Contrast. - This Figure shows the average results of the FrACT's contrast-part for the two different lighting exposures DL and AL.

with an increasing number of repetitions. The practice effect persisted during the second day of the study: The participants were significantly better on the second day of the study than on the first day. However, there was no significant intra-day improvement on day 2.

- **Aptitude of study participants.** The results presented in Figure 9.13 show that those participants who were exposed to AL on the first day and to DL on the second day (Group 2) performed significantly better in the 3-back test then the participants with the inverse lighting exposure order (Group 1). One possible explanation for the fact that Group 2 (AL-DL) performed significantly better during the 3-back test than Group 1 (DL-AL) could be that there might have been a difference in alertness during the tests between the two groups. This was, however, not the case: no significant difference between the mean KSS-ratings of the two groups was found ($p = 0.525 > 0.05$). One could also imagine that the better performance of Group 2 is due to an intrinsically higher average aptitude of Group 2 for the 3-back test. If this is really the case, then this effect should more and more equal out the higher the number of subjects gets.

- **Alertness.** As visualized in Figure 9.17, the study participants performed in average better in the 3-back test the more alert they were. In addition to that, the participants were significantly more alert on the second day than on the first day (see Figure 9.11). This might be another reason (in addition to the practice effect) why the participants performed in average better on the second day.

Even if these three effects can be supposed to have masked the influence of the two different lighting scenarios in this particular setting, it is still possible that lighting exposure has played a role: For example, the better results of Group 2 in the 3-back test are not necessarily due to an intrinsically higher aptitude of the individuals for that particular computer-based test; they could, theoretically also be due to the fact that Group 2 had AL on the first day and DL on the second day (and not the inverse order). This possibility should be considered if the group difference does not equal out with a growing number of participants. In addition to that, clinical studies have clearly demonstrated that different lighting conditions can have a considerable effect on the alertness and brain functions of humans (79; 88; 107) . Even if we have found no inter-condition difference in the mean KSS ratings of the study participants, the influence of lighting conditions on alertness (and therefore on performance in the 3-back test in particular and on performance in general) must not be neglected.

9.5 Conclusion

The results in this Chapter show that the CLC Exposure Room, for which a highly flexible electric lighting system has been designed during this doctoral thesis, is a good basis for carrying out chronobiological studies at LESO-PB. A large variety of artificial lighting scenarios can be set up using the controlling and dimming capacities of the DALI control system. By changing the fluorescent tubes (e.g. from natural white to blue-enriched fluorescent lighting) different spectral compositions of artificial light can easily be achieved. In addition to that, the CLC Exposure Room will make it possible to run test sessions with one or more BlueLum devices, equally developed during this study (see Chapter 8). The results of the vertical illuminance measurements presented in 9.4.1 show that a large band of illuminances can be obtained in the CLC Exposure Room. However, keeping the vertical illuminances at eye level constantly between 1000 and 2000 Lux has proven to be somewhat difficult. This might be a certain disadvantage for certain chronobiological studies, but it definitely depicts the reality in ADS-equipped office rooms which can be considered an advantage for applied studies.

The analysis of the preliminary results presented in Section 9.4 has not revealed a difference in performance and alertness of study participants after DL or AL exposure. However, if day 2 was analyzed separately, it was found that the subjects performed better after DL exposure. This might be due to group differences (e.g. one group performed in general better than the other one), but it might also indicate a positive influence of daylight on the performance of office workers. Taking into account only day 2 might be justified, because there was no intra-day practice effect on day 2. A larger number of participants might yet lead to more detailed results. In addition to that, some data have not yet been analyzed. The analysis of the salivatory melatonin levels for example is still ongoing at the Centre Hospitalier Universitaire du Canton du Vaud (CHUV). This analysis might reveal a significant shift in evening melatonin onset between the two exposure conditions.

10

Enabling a widespread use of Sustainable Lighting Solutions - Two Case Studies

10.1 Introduction

Besides the ADS presented within the previous Chapters, other types of ADS have also been developed over the last few years. The Anidolic Integrated Ceiling (AIC), first presented by Courret in 1999 (18), is one of them. Figure 10.1 shows an overview of an AIC mounted on a test module located on the campus of the EPFL. The zenithal "Collector", covered by a double glazing, captures daylight from the sun and the sky vault. The two anidolic elements of the Collector redirect the daylight flux into the highly reflective "Duct" by which it is conducted to the "Distributor" element. The latter then distributes the light flux into the office room. Courret et al. have calculated an overall system efficiency of 32% (ratio of emerging light flux at the exit of the distributor and incoming light flux at the entry of the collector) (17).

Using the AIC, rather than the ADS installed at the LESO solar experimental building, opens up interesting lighting options for larger office spaces where the daylight flux has to be transported to areas situated deeper towards the building core. This Chapter presents two case studies concerning an AIC that have been carried out within the framework of this doctoral thesis. The first one explains how a highly energy-efficient integrated lighting system has been developed for an open plan office in Singapore, the

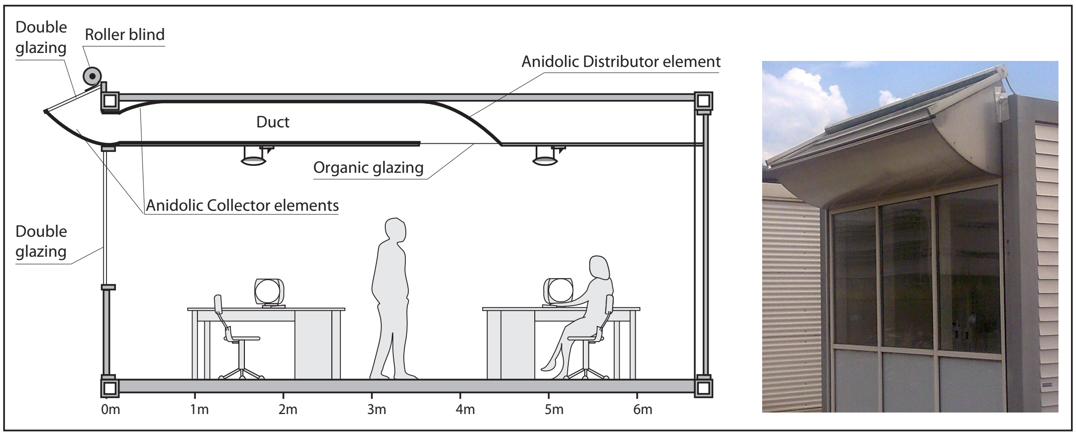


Figure 10.1: AIC and test module. - The figure shows an overview of an AIC mounted on a test module located on the campus of the EPFL.

second one discusses the use of highly reflective coating materials within an AIC.

10.2 Lighting Strategy for an Open Plan Office in Singapore

10.2.1 Introduction

Wittkopf et al. at the National University of Singapore (NUS) have recently shown that the AIC shown above can be expected to perform very well in tropical conditions (120; 121). According to their simulations, the fraction of the usual Singapore working day (08.00 until 18.00), during which the electric lighting system must be switched on due to insufficient daylight provision, is 75% for a reference office room in Singapore. The simulations also show that in the same office room equipped with an AIC, this fraction can be reduced down to 54%. Under the assumption that the electric lighting system is automatically switched off when enough daylight is available to supply the required workplane illuminances, this corresponds to electric alectricity savings of 21% compared to the reference office room. These interesting findings are an ideal starting point for applying some of the concepts discussed in the previous Chapters of this Thesis to office rooms in tropical climates. In order to benefit from the increased light flux within the office room created by the AIC and to achieve maximum electricity savings, the electric lighting system must be down-sized as much as possible. Because for the time being there is no knowledge on user satisfaction related to this type of ADS in Singapore (unlike the situation within the LESO solar experimental building in Switzerland), it makes sense to define a target lighting power density for Singapore that is slightly more conservative than the 3 W/m^2 adopted for Switzerland: a lighting power density of 5 W/m^2 is suggested as starting point. Once this system is installed in combination with the AIC, occupant satisfaction assessments, further simulations and in-situ measurements could be carried out in order to yield a proof-of-concept for this type of office room in Singapore.

10.2.2 Daylight performance of simulated office room

Wittkopf et al. considered a 6m x 6m Singapore office room with an AIC located 2.65m above floor level for their simulations. They have only taken into account diffuse skylight because this is typical for Singapore; obstructing surrounding buildings and their reflectance were also taken into account (121). The considered room is sidelit by a window (dimensions 5m x 1.85m) that is situated directly underneath the AIC, in the center of one of the four walls. The reflection / transmission properties for the different room components are summarized in Table 10.1.

Surface	Reflectance / Transmittance [%]	Photometric property
Floor	20	ideal diffuse
Walls	50	ideal diffuse
Ceiling	80	ideal diffuse
Glazing	80	clear glass

Table 10.1: Reflection and transmission properties of the simulated office room.

A corresponding computer model of this Singapore office room was built up using RELUX Vision within the framework of this doctoral thesis. Under the assumption that eight persons will occupy this office room, an appropriate energy-efficient electric lighting system has been designed. Figure 10.2 shows a 3D-view of the corresponding model (so far there is no electric lighting system in place).

Wittkopf et al. divided the 36 m^2 office room into three equal sections of 2m x 6m. The first one is situated near the window, the second one in the center of the room and the third one in the rear. The average daylight autonomy, defined as the percentage of

Figure 10.2: Singapore office room. - The figure shows a 3D-view of the RELUX Vision model for the Singapore office room (6 m depth, 6 m width, 2.65 m height.

time over a user set period of time during which the illuminance due to daylight flux at a certain point is high enough to make additional artificial light dispensable, was then calculated for each section under the assumption that the conditions are identical for every day of the year (121). For this particular situation, these authors considered a 300 Lux daylight illuminance threshold above which electric lighting is dispensable. Table 10.2 summarizes the corresponding simulation results; Figure 10.3 visualizes the three equal sections and the resulting daylight autonomies from window section to rear section of the office room (DA_W, DA_C and DA_R), the latter being equipped with side window and AIC.

Room section	DA [%] (only window)	DA [%] (window + AIC)
Window	74	63
Centre	1	11
Rear	0	64

Table 10.2: Daylight autonomies for the three different room sections.

Wittkopf et al. have predicted not only daylight autonomies for this type of office room in Singapore. In fact, it has also been shown that illuminance ratios (comparable to daylight factors, but defined for all sky types) for this office room can be expected to be comparably elevated. For the office's rear section for example, the author predicts an average illuminance ratio improvement factor of 2.2 compared to the same room without AIC. This improvement leads to illuminance ratios (or daylight factors) in the range of 6 to 7% in the rear section of the office room. These results clearly illustrate the excellent performance of AIC within this north-facing Singapore office. The installation of an AIC in this room has two advantages:

- The first one is that the room's window section is shaded because the AIC's external element is partly blocking the direct sunlight reaching the room; this leads to a reduced DA in this section (63% instead of 74%), but also to a reduced glare risk here.
- The second advantage (yet more evident) is the significant increase of the DAs in the center and the rear sections of the room.

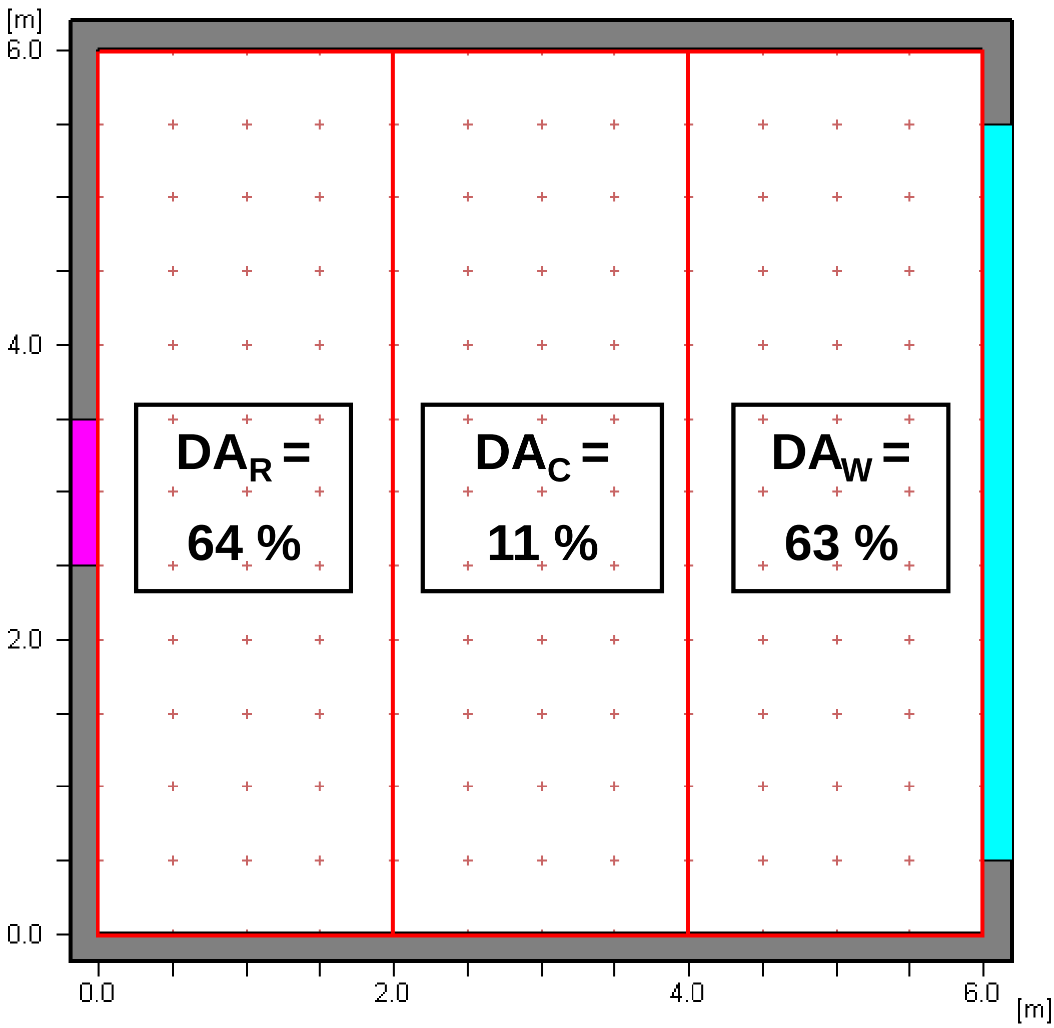


Figure 10.3: Singapore office room subdivision. - The figure shows the three equal sections and the resulting daylight autonomies from window section to rear section of the office room.

This means that the AIC of the described office room in Singapore will provide sufficient daylight fluxes within the window and the rear section of the room during more than 60% of a usual Singapore working day. During the rest of the day, an auxiliary electric lighting system must be switched on to produce an additional artificial light flux in order to guarantee the required minimum illuminances. As for the centre section of the room, auxiliary artificial light flux will be necessary during 90% of a usual Singapore working day. The office room thus requires an electric lighting system, which is able to supply an additional artificial light flux to the sections when there is not sufficient daylight available. In addition to that, the system has to be able to supply enough light for sporadic cases when persons wish to continue working later in the evening (or before sunrise).

10.2.3 Design and performance of an adequate electric lighting system

An adequate electric lighting system can be implemented using two "ZEN3"-luminaires equipped with a single 21 W high efficiency fluorescent tube each (luminaire connected power, including electronic control gear: 25 W) and four "Tulux Zen 3"-luminaires equipped with a single 28 W high efficiency fluorescent tube each (luminaire connected power, including electronic control gear: 32 W). A detailed luminaire description was given in Chapter 5 this Thesis. This installation leads to an LPD slightly lower than 5 W/m^2.

Figure 10.4 illustrates the integration of the six luminaires within the RELUX Vision computer model of the Singapore office room. The figure also shows 17 different reference planes, placed 0.75 m above floor level, which were chosen in order to assess the electric lighting system's performance; one main reference plane represents the entire office. A distance of 0.5 m was maintained between the walls of the room and this major reference plane. Four additional reference planes, called "workplane" in our model, were considered. These "workplanes" are placed directly on top of the eight office desks shown in Figure 10.2, each "workplane" covering simultaneously two desks. As it can be observed in Figure 10.4, a slightly larger reference plane, called "workplane surroundings", is placed around each workplane. In addition to that, every workplane comprises two 0.6 m x 0.6 m "individual workspaces", which coincide with the desks shown in Figure 10.2. These are the regions where special visual tasks (for example reading or writing) are normally carried out. The "individual workspaces" require

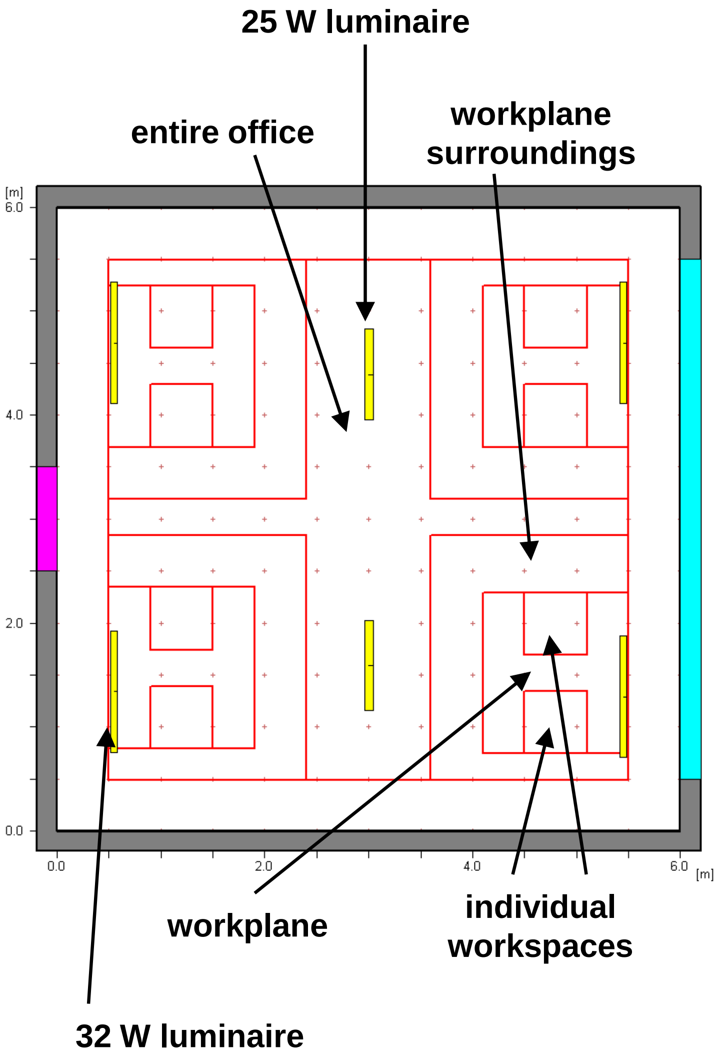


Figure 10.4: Electric lighting design for Singapore office room. - The Figure gives an overview of the electric lighting design developed for the Singapore office room.

higher illuminances and uniformities than the rest of the room. Table 10.3 gives an overview of the different reference plane types used in the computer model, as well as the corresponding required minimum average illuminances and uniformities.

Reference plane	E_{av} [Lux]	Uniformity g1 [-]
Individual workspaces	300-500	0.7
Workplanes	300	0.7
Workplane surroundings	200-300	0.6
Entire office	200	0.6

Table 10.3: Reference planes - Singapore office room.

Figure 10.5 (left) shows the simulation results in absence of daylight (only artificial light). One can observe the symmetric light distribution, as well as the fact that the illuminance maxima mostly coincide with the different workplanes and workspaces. All six luminaires are switched on.

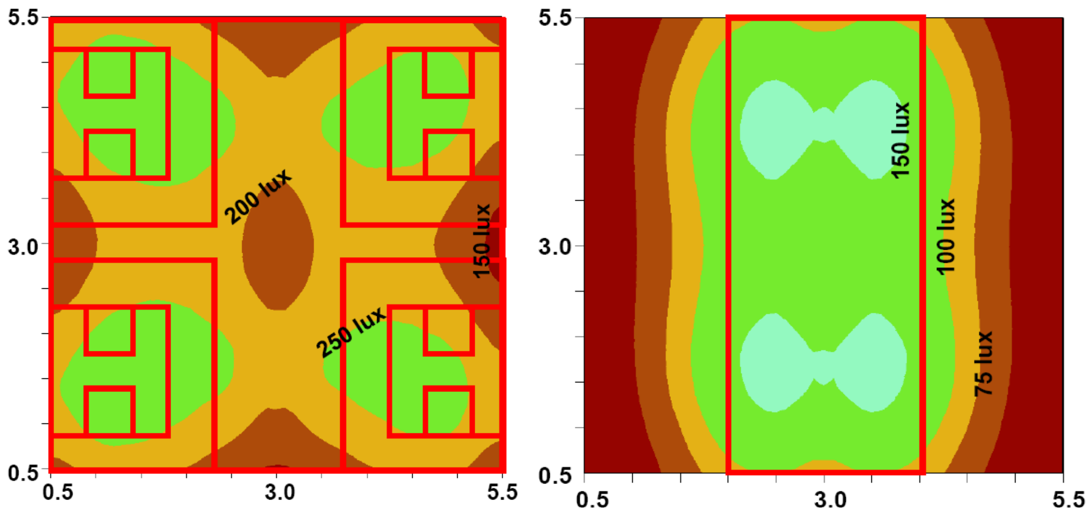


Figure 10.5: Simulation results for Singapore office room. - The left panel of this Figure shows the simulation results in absence of daylight for all luminaires switched on, the right panel the situation where only the two luminaires situated in the center of the room are switched on.

Figure 10.5 (right) shows the situation where only the two luminaires situated in the center of the room are switched on. It can be observed that they mainly illuminate the center of the room and still achieve a good uniformity. The resulting illuminances in the rear and window section of the room rapidly drop when leaving the center section. This situation will occur only when the daylight flux reaching the center section is not sufficient but the daylight flux reaching the rear and window section is appropriate. Table 10.4 shows the average illuminances E_{av} and the uniformities g_1 for the different reference planes illustrated in Figure 10.4. The values for the workplane surroundings, the workplanes and the individual workspaces correspond to the average obtained for each type of reference plane. Standard deviations are 7.9, 10.1 and 11.3 [Lux] for the illuminances and 0.03, 0.02 and 0.03 [-] for the uniformities.

Reference plane	E_{av} [Lux]	Uniformity g1 [-]
Individual workspaces	259 +/- 4.4%	0.85 +/- 3.0%
Workplanes	252 +/- 4.0%	0.7 +/- 3.3%
Workplane surroundings	234 +/- 3.4%	0.64 +/- 4.1%
Entire office	230	0.6

Table 10.4: Simulated illuminances and uniformities - Singapore office room.

When comparing these results with the target values given in Table 10.3, one can observe that the uniformity requirements are fully satisfied. In particular, the uniformities on the individual workspaces are extremely elevated. The average illuminances show appropriate values on the reference planes "entire office" and "workplane surroundings" only. However, it has to be kept in mind that the electric lighting system in this office room is intended to be complementary to daylight during usual Singapore office hours. This means that when the daylight flux that reaches the window and rear section of the room is large enough to create 50 Lux average illuminances on the workplanes and individual workspaces, the electric lighting system will be capable to raise the overall illuminances above the required values (specified in Table 10.3 on all reference planes). In addition to that, it can be assumed that even people occasionally working at night will be satisfied with this system: occupants of anidolic offices in Switzerland, who sometimes work at nighttime, accepted workplane illuminances that are significantly lower than the recommendations listed in Table 10.3. Furthermore, the discussions in Chapter 5 have shown that our RELUX Vision model of the test office room in the LESO building systematically underestimate the achieved workplane illuminances. This is likely to also be the case here.

The situation shown in Figure 10.5 (right) (only the two luminaires located in the room's center section switched on) leads to an average illuminance of 132 Lux and a uniformity of 0.68. If we keep yet again in mind that this situation only occurs when there is enough daylight flux to provide the required illuminance levels in the rear and window sections of the room, we can consider the complementary electric lighting system to be appropriate during this situation as well. If we consider that at every moment when the daylight flux in one of the room's sections is not sufficient (i.e. lower than 300 Lux) complementary electric lighting is automatically switched on in the corresponding section, then the average daily electricity demand for electric lighting within an office room during a usual Singapore working day can be found by applying the following equation:

$$E_{lighting} = \sum_{x=R,C,W} ((100\% - DA_x) * P_{con,x}) * 10h \tag{10.1}$$

In this equation, DA_x stands for a section's daylight autonomy whereas $P_{con,x}$ represents the installed lighting power within this section. With $P_{con,R} = P_{con,W} =$ 64W and $P_{con,C} =$ 50W we find a daily electricity consumption of 0.912 kWh for the office. Additional dimming strategies can further reduce this maximum electricity consumption.

10.2.4 Aesthetic aspects of building integration and expectable cost

Façade-integrated daylighting systems not only have to create a comfortable lighting environment inside a building: an appealing external building design must also be achieved. As explained in Chapter 2, anidolic façades are not only able to meet common aesthetic requirements of building design. A recent example for successful building integration of ADS is the new Zero Energy Building, recently constructed on the campus of the National University of Singapore. It can be assumed that a commercial AIC-façade would be around 20% more expensive than an average façade in most cases, depending on material and installation costs. Costs for system maintenance are very low, the AIC being a passive system and bi-annual cleaning of the system being far and away sufficient. The components suggested for the artificial lighting design are commercially available luminaires and fluorescent tubes, pricewise comparable to lighting equipment installed in buildings with conventional façades. The proposed electric lighting system can even be expected to cost less than a conventional installation (less material needed due to lower LPD).

10.2.5 Conclusion

The results obtained during this study make it clear that the concepts discussed during the previous Chapters of this Thesis can be applied to a variety of settings with LPDs still below 5 W/m^2. The system discussed here will lead to a daily electricity consumption lower than 1 kWh per working day; an aesthetic and cost-effective integration of the system in building design is possible. The suggested electric lighting system can be used as a starting point in a 1:1 scale test setup in Singapore. Occupant satisfaction assessments, further simulations and in-situ monitoring can contribute to optimize this energy-efficient lighting solution for open space of office room in Singapore. In order to improve the wellbeing, mood and productivity of office workers in such a room, the use of PC-screen-mounted BlueLum devices (as introduced in Chapter 8) could be considered.

10.3 Splitting up the Anidolic Integrated Ceiling into small pieces: Cost optimization of AIC reflective components

10.3.1 Introduction

Amongst other factors, the reflective coating material has a major impact on the efficiency of the AIC. The best-performing reflective coating materials currently available on the market reach total reflections (23) of 98% (e.g. MiroSilver™by ALANOD (4)). Using such highly reflective coating materials on the entire AIC of course yields the largest optical efficiency, but it is also the most expensive solution. The questions are therefore: Which parts of an AIC should be coated with which reflective material? How do we get good trade-offs between efficiency and cost? A new computer model of the AIC has been developed during this doctoral thesis. The great advantage of this new model is the fact that it consists of more than 30 different components. Different coating materials can be assigned to each of them. This makes it possible to identify those AIC components, where the use of expensive, highly reflective coatings makes the most sense and other components, where cheaper materials can be used without significantly decreasing the AIC's overall optical efficiency. So far, all simulations carried out for this particular system (17; 120) were based on a basic computer model where the entire AIC was considered as one piece. A global specular total reflection of 90% has been assigned to the entire AIC in this case. Within the framework of the design of the Zero Energy Building in Singapore, this basic computer model has been optimized and various simulations for Singapore sky conditions using the software tool Photopia 3.0 (70) have been carried out. In this new model, the AIC is not represented as one single piece, but has rather been split up into different components. Theoretically, it is possible to assign a different coating material to each single component. This opens a whole lot of new simulation options and is an important step towards the development of optimized ADS.

10.3.2 Methodology

Figure 10.6 shows the main elements into which the "Collector" part of the AIC can be split up. The elements "Collector Side" could additionally be split up into eight distinct sub-elements, the elements "Anidolic Collector 1" and "Anidolic Collector 2" into six distinct sub-elements.

The elements into which the "Duct" and the "Distributor" parts can be split up are shown in Figure 10.7. It is possible to additionally split the element "Anidolic Distributor" into six sub-elements and the "Distributor Sides" into three sub-elements each.

Each of the AIC elements shown in Figures 10.6 and 10.7 was saved on a separate layer in an AutoCAD file. This file was then imported as a luminaire into the software Photopia. During the computer simulations, a Virtual Sky Dome (VSD) (118; 119) was used as a light source. A VSD is basically a hemisphere composed of 145 subdivisions. It imitates the spatial luminance distribution of the sky vault by 145 distinct light sources whose distribution over the hemisphere follows the conventions of sky patch luminance IDMP monitoring protocol and whose individual luminous flux are calculated using a special set of equations for the 15 CIE sky types (20; 21). The appropriate luminances for each VSD patch have been calculated following the definition of the Singapore Representative Sky, previously used by Wittkopf et al. (121). Details on how to simulate AICs with Photopia are given in Appendix B.3 of this Thesis. Figure 10.8

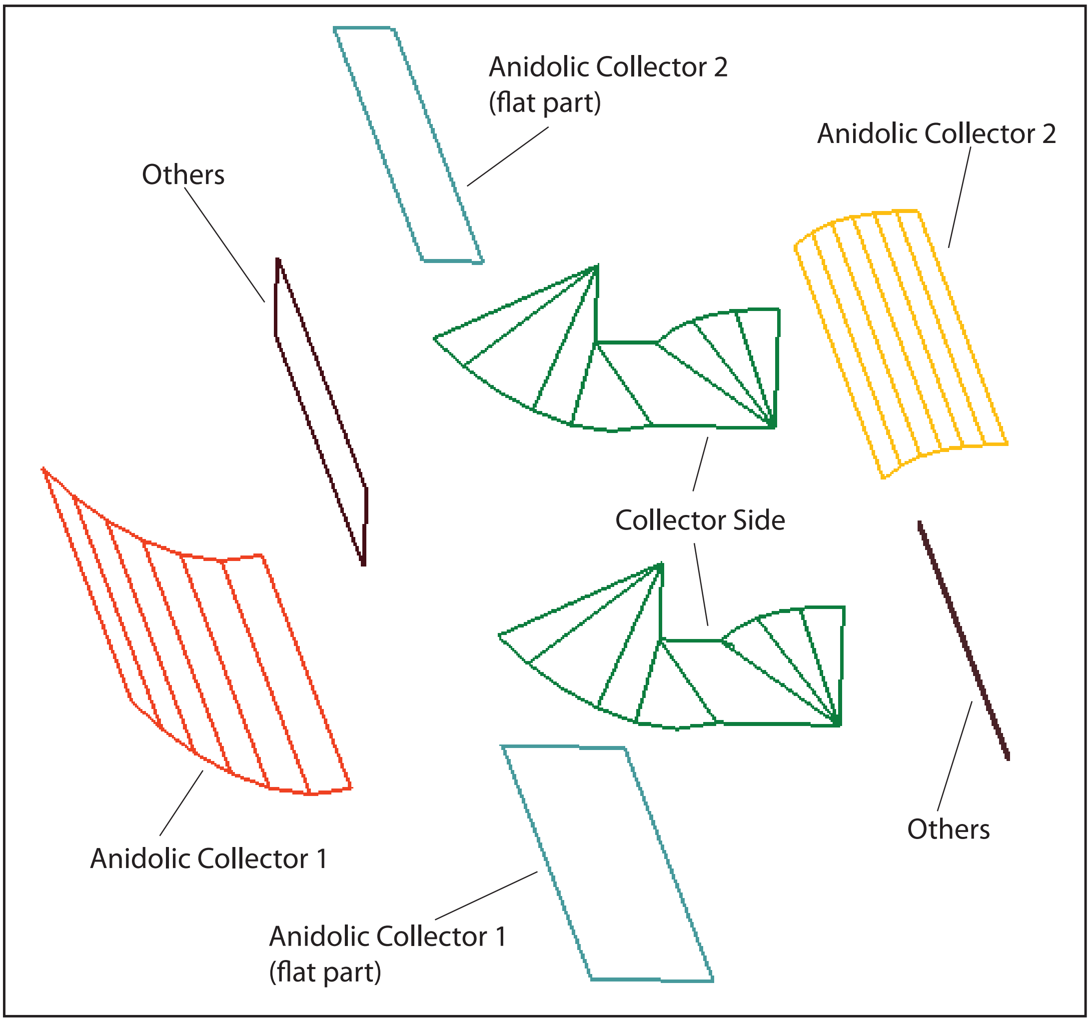


Figure 10.6: Main elements of the AIC's "Collector" part. - The figure shows the main elements into which the "Collector" part of the AIC can be split up.

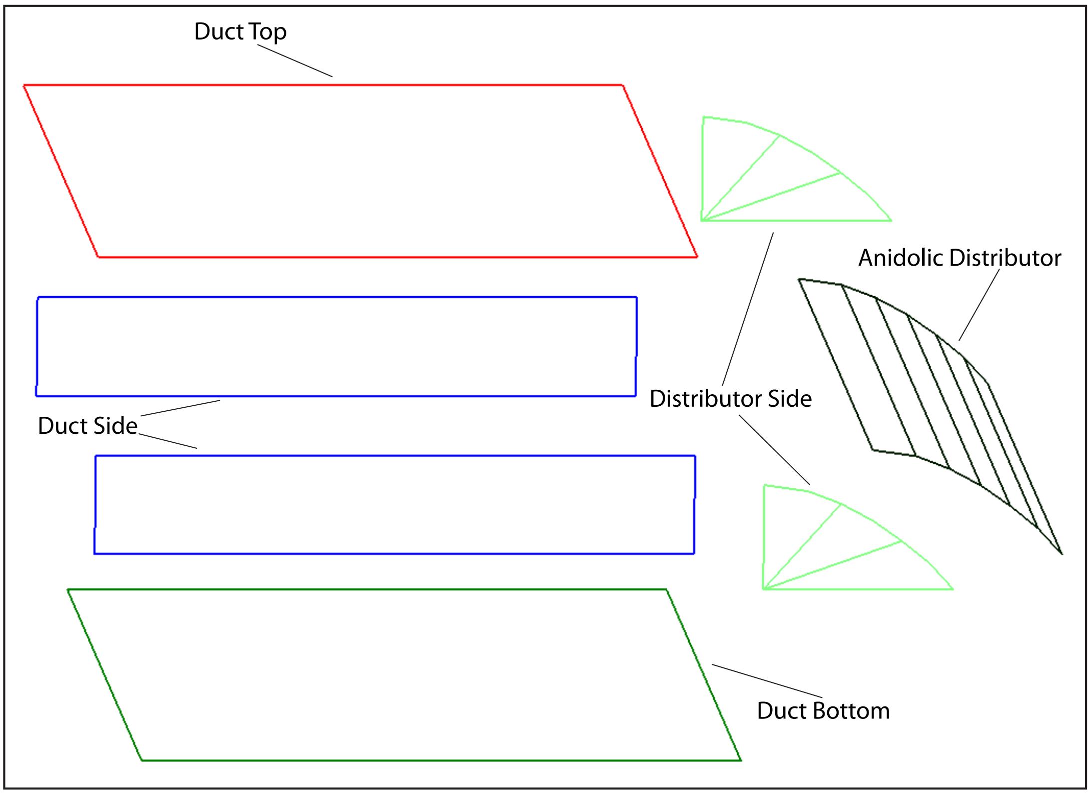


Figure 10.7: Main elements of the AIC's "Duct"- and "Distributor"-parts. - The figure shows the main elements into which the "Duct" and the "Distributor" parts can be split up.

shows a graphical representation of the VSD and the sky patch luminances used during the simulations. This VSD was imported into Photopia as a light source. The AIC was fixed under the VSD in such a way that the center of the AIC's entry coincided with the VSD-hemisphere's center. Via Photopia's menu "Design Properties", the different elements' reflective coatings were then gradually switched from "specular 90%" (the reference coating) to MiroSilver™.

Patch	0	1	2	3	4	5	6	7	8	9
0		4352	4207	4123	4086	4081	4092	4109	4119	4119
10	4109	4092	4081	4086	4123	4207	4352	4567	4857	5215
20	5620	6025	6364	6559	6559	6364	6025	5620	5215	4857
30	4567	5022	5451	5982	6594	7230	7781	8110	8110	7781
40	7230	6594	5982	5451	5022	4693	4454	4290	4185	4124
50	4093	4079	4074	4074	4079	4093	4124	4185	4290	4454
60	4693	5517	5089	4806	4628	4525	4474	4458	4474	4525
70	4628	4806	5089	5517	6135	6992	8109	9410	10586	11086
80	10586	9410	8109	6992	6135	7428	8650	10342	12523	14805
90	15914	14805	12523	10342	8650	7428	6569	5973	5568	5300
100	5135	5045	5017	5045	5135	5300	5568	5973	6569	7840
110	6869	6281	5948	5797	5797	5948	6281	6869	7840	9421
120	12006	16223	22327	22327	16223	12006	9421	12170	17578	23954
130	17578	12170	9288	7797	7083	6872	7083	7797	9288	10619
140	8739	8739	10619	14624	14624	11201				

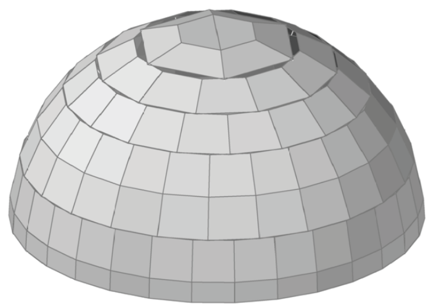


Figure 10.8: VSD and the sky patch luminances. - The figure shows a graphical representation of the VSD and the sky patch luminances used during the simulations. This VSD was imported into Photopia as a light source.

10.3.3 Results

At the beginning of this study, five initial computer simulations were carried out: one reference simulation where the entire AIC was coated with a specular anodized aluminum coating (90% total reflection), one where the entire AIC was coated with the highly reflective MiroSilver™coating (98% total reflection), and three where this coating was applied to the entire "Collector", the entire "Duct" and the entire "Distributor", respectively (the other components where kept at 90% total reflection in those latter cases). The overall optical efficiency of the reference AIC is equal to 32.5%. Figure 10.9 (left) gives an overview of the remaining four of the initial simulation runs. Coating the entire AIC with MiroSilver™leads to an overall efficiency of 49%. This corresponds to a relative efficiency improvement of 50.8% compared to the reference case (efficiency of 32.5%). Coating either the "Collector", the "Duct" or the "Distributor" with MiroSilver™resulted in relative efficiency improvements of 15.4%, 22.2% and 6.5%, respectively.

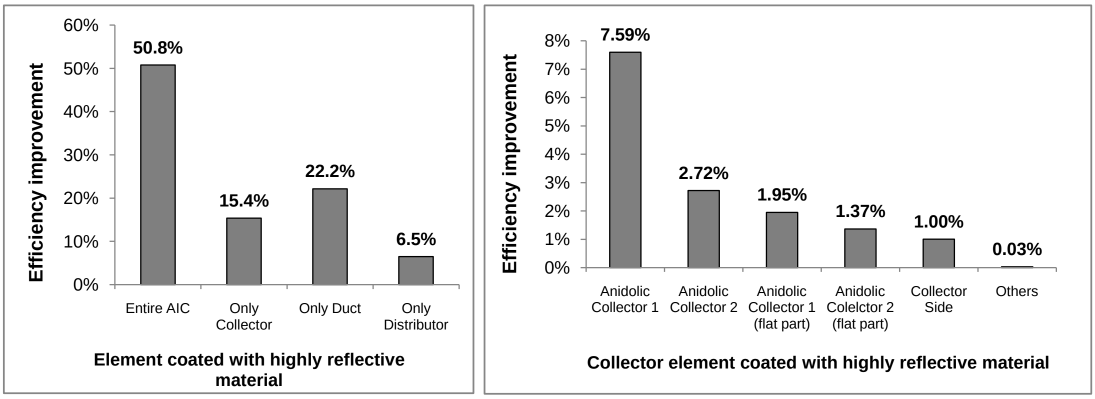


Figure 10.9: Efficiency improvement global & Collector only. - Left: Results of the four simulation runs where the highly reflective MiroSilver™coating (98% total reflection) was applied to the entire AIC, the entire "Collector", the entire "Duct" and the entire "Distributor", respectively. Right: Obtained relative efficiency improvements for the different "Collector" elements

During the following simulations, only one AIC element per simulation run (or one group of elements for the side elements and the "Others", see Figures 10.6 and 10.7 was coated with MiroSilver™; all other elements remained coated with the reference coating. Figure 10.9 (right) shows the obtained relative efficiency improvements for the different "Collector" elements. They range from almost no improvement (in the case where only the "Other" elements are coated with MiroSilver™) up to an efficiency improvement of 7.59% in the case where the "Anidolic Collector 1" is coated with this highly reflective material.

Figure 10.10 (left) shows the efficiency improvements obtained during the three simulation runs where one "Duct" element at a time was coated with MiroSilver™. The corresponding efficiency improvements for the two "Distributor" elements are displayed in Figure 10.10 (right). Based on the results of these initial simulations, an additional 11-step simulation series was then carried out during which all AIC elements have gradually been coated with MiroSilver™. Table 10.5 shows the chosen steps for this simulation series. Taking the reference AIC as a starting point (Step 0), the "Duct Top" was first coated with MiroSilver™because this leads to the highest immediate efficiency improvement (see Figure 10.10 (left)). Subsequently, the same logic was

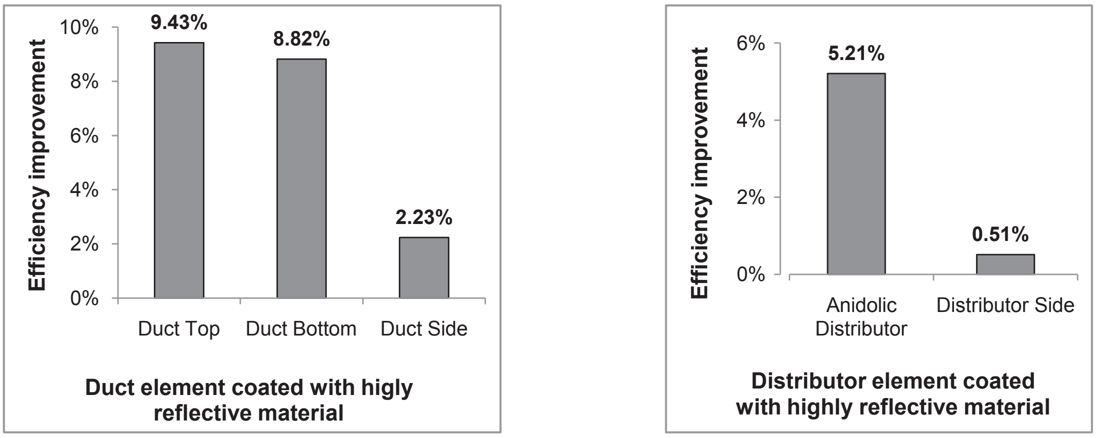


Figure 10.10: Efficiency improvement Duct & Distributor. - Left: efficiency improvements obtained during the three simulation runs where one "Duct" element at a time was coated with MiroSilver™. Right: The corresponding efficiency improvements for the two "Distributor" elements.

used (i.e. always coating the element that can be expected to lead to the highest immediate efficiency improvement). As a matter of fact, in Step 2 the "Duct Bottom" was coated, in Step 3 the "Anidolic Collector 1" and so on. In this way, a maximum efficiency improvement was obtained while changing the coating on a minimum number of elements (Quickest Efficiency Improvement).

Figure 10.11 shows the obtained relative efficiency improvement for each of the steps listed in Table 10.5. For comparative reasons, the theoretical curve obtained through simple addition of the efficiency improvement values for the distinct components (see Figure 10.9 (right) and Figure 10.10) is also plotted in Figure 10.11.

The efficiency improvement sequence outlined in Table 10.5 was set up based on the absolute efficiency improvements for the distinct AIC elements shown in Figure 10.9 (right) and Figure 10.10. However, it also makes sense to look at the efficiency improvements per surface area (surface-specific efficiency improvement) of each distinct AIC component that is coated with MiroSilver™. Table 10.6 gives an overview of all AIC elements' surface areas.

Figure 10.12 shows the surface-specific efficiency improvements based on the results of the "one at a time"-simulations (see Figure 10.9 (right) and Figure 10.10) and the surface areas of the different AIC elements given in Table 10.6.

Coating Step	AIC elements coated with MiroSilver™
Step 0 (Reference)	none
Step 1	Duct Top
Step 2	All the above & Duct Bottom
Step 3	All the above & Anidolic Collector 1
Step 4	All the above & Anidolic Distributor
Step 5	All the above & Anidolic Collector 2
Step 6	All the above & Duct side
Step 7	All the above & Anidolic Collector 1 (flat part)
Step 8	All the above & Anidolic Collector 2 (flat part)
Step 9	All the above & Collector Side
Step 10	All the above & Distributor Side
Step 11	All AIC elements

Table 10.5: Quickest Efficiency Improvement - Simulation steps for the efficiency improvement strategy "Quickest Efficiency Improvement".

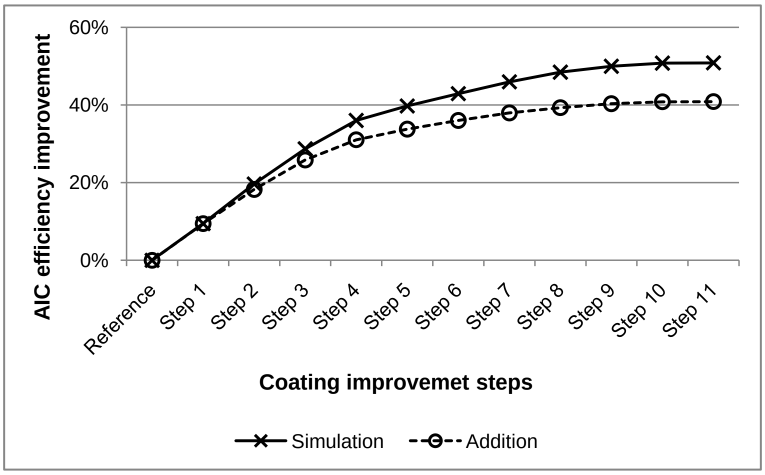


Figure 10.11: Quickest Efficiency Improvement. - Obtained efficiency improvement for each of the steps listed in Table 10.5.

AIC element	Surface area [m^2]
Anidolic Collector 1	4.74
Anidolic Collector 2	2.49
Anidolic Collector 1 (flat part)	2.335
Anidolic Collector 2 (flat part)	1.15
Collector Side	0.492
Others	1.595
Duct Top	14.4785
Duct Bottom	14.4785
Duct Side	1.39008
Anidolic Distributor	5.41
Distributor Side	0.306

Table 10.6: AIC surface areas - Overview of all AIC elements' surface areas.

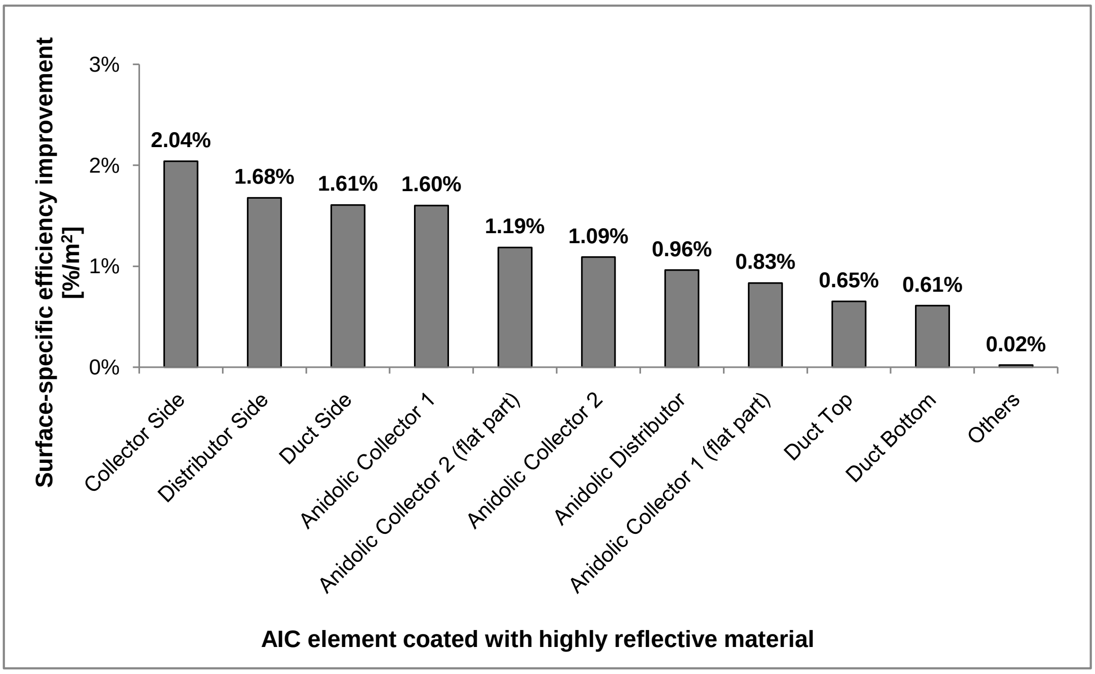


Figure 10.12: Surface-specific efficiency improvements. - Surface-specific efficiency improvements (expressed in per cent per square meter) for the different main AIC elements.

Based on these surface-specific efficiency improvements, a second efficiency improvement sequence was defined. In perfect analogy with the sequence described in Table 10.5, an 11-step simulation series was carried out, during which all AIC elements were gradually coated with MiroSilver™. However, instead of always coating the element that leads to the highest immediate efficiency improvement, the steps of this second sequence were determined by the surface-specific efficiency improvements displayed in Figure 10.12. In this way, the best possible trade-off between efficiency improvement and amount of MiroSilver™coating material was guaranteed in each improvement step (Minimal Coating Material). This second efficiency improvement sequence is outlined in Table 10.7. It starts off by coating the "Collector Side" (surface-specific efficiency improvement of 2.04% per m^2), then the "Distributor Side" (surface-specific efficiency improvement of 1.68% per m^2) and so on.

Coating Step	AIC elements coated with MiroSilver™
Step 0 (Reference)	none
Step 1	Collector Side
Step 2	All the above & Distributor Side
Step 3	All the above & Duct Side
Step 4	All the above & Anidolic Collector 1
Step 5	All the above & Anidolic Collector 2 (flat part)
Step 6	All the above & Anidolic Collector 2
Step 7	All the above & Anidolic Distributor
Step 8	All the above & Anidolic Collector 1 (flat part)
Step 9	All the above & Duct Top
Step 10	All the above & Duct Bottom
Step 11	All AIC elements

Table 10.7: Minimal Coating Material - Simulation steps for the efficiency improvement strategy "Minimal Coating Material".

The results of this simulation sequence are plotted in Figure 10.13. For comparative reasons, the theoretical curve obtained through simple addition of the efficiency improvement values for the distinct components (see Figure 10.9 (right) and Figure 10.10) is also plotted.

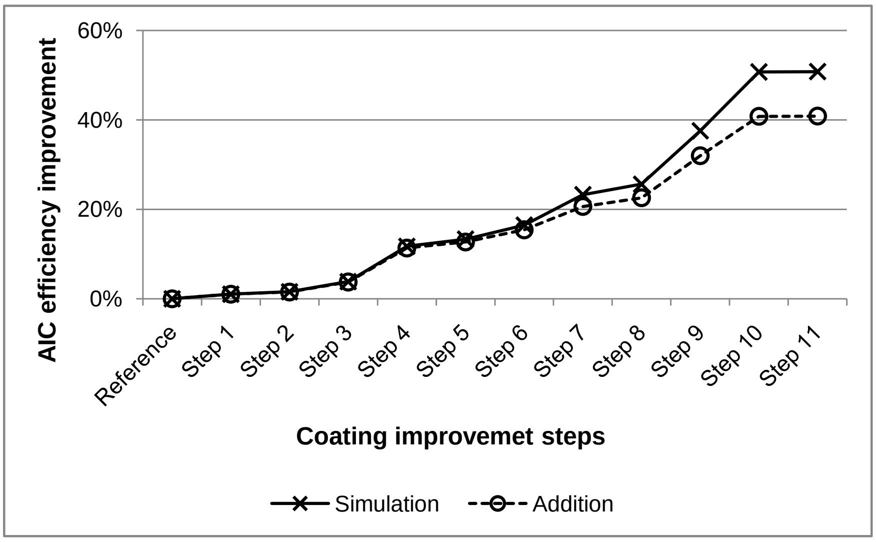


Figure 10.13: Minimal Coating Material. - Obtained efficiency improvement for each of the steps listed in Table 10.7

10.3.4 Discussion

The results displayed in Figure 10.9 (left) illustrate the enormous potential of highly reflective coating materials (such as MiroSilver™) in daylighting applications: increasing the coating material's total reflection by 8.9% (i.e. from 90% to 98%) leads to a relative efficiency improvement of more than 50% in the AIC. The "Duct" has the highest potential for efficiency improvement, followed by the "Collector" and the "Distributor". The reason for this distribution between "Duct", "Collector" and "Distributor" lays principally in the large sizes of the "Duct Top" and the "Duct Bottom", compared to the rest of the AIC (see Table 10.6). Figure 10.9 (right) and Figure 10.10 show that the AIC elements "Duct Top", "Duct Bottom", "Anidolic Collector 1", "Anidolic Distributor" and "Anidolic Collector 2" have the highest potential for efficiency improvement. As a matter of fact, coating only these five AIC elements with MiroSilver™yields already 80% of the overall possible efficiency increase (i.e. efficiency increase of 40%, see Figure 10.11). This means that, if one's objective is to achieve a sound efficiency improvement by coating a minimum number of AIC elements with a highly reflective coating (Quickest Efficiency Improvement), those five AIC elements would be a very good choice. This choice does, nevertheless, not correspond to the optimal coating decision from a financial point of view. If one's objective is to achieve efficiency improvement while keeping the amount of coating material (and the associated cost) as low as possible, it makes more sense to follow the improvement sequence outlined in Table 10.7, the latter being based on the surface-specific efficiency improvements of the different AIC elements shown in Figure 10.13.

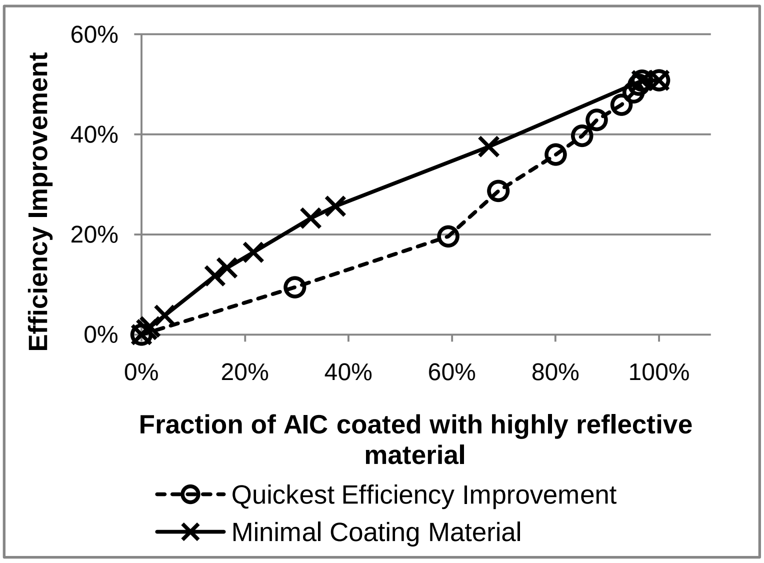


Figure 10.14: Comparison of the two strategies. - Difference between the two improvement sequences "Quickest Efficiency Improvement" and "Minimal Coating Material".

Figure 10.14 visualizes the difference between the two improvement sequences: when following the strategy for "Quickest Efficiency Improvement", two improvement steps (i.e. coating the Duct Top and the Duct Bottom with MiroSilver™) are sufficient for reaching a relative efficiency improvement of 20%. However, this corresponds to 60% of the overall AIC surface coated with the highly reflective material. The improvement strategy "Minimal Coating Material" makes it possible to reach a relative efficiency improvement of more than 25%, while keeping the AIC fraction coated with MiroSilver™lower than 40%. However, eight improvement steps are needed in this case. If we assume market prices of 25 /kg for anodized aluminum (showing about 90% of total reflection) and 35 /kg for MiroSilver™(98% total reflection), material costs would equal approximately 1750 for an AIC fully coated with anodized aluminum versus 2450 for an AIC fully coated with MiroSilver™(based on 70 kg of aluminum). Coating 40% of the AIC with MiroSilver™would correspond to a material cost increase of 280 versus an increase of 420 when coating 60% of the AIC surface area with MiroSilver™. This means that following the strategy for "Minimal Coating Material" rather than that for "Quickest Efficiency Improvement" offers a savings potential of 140 per AIC.

In Figure 10.12 and Figure 10.13, the fact that the simulated values are getting higher and higher towards the end of the simulation series compared to the values obtained through addition are probably due to synergy effects that are not taken into account when simply adding up the single improvement values displayed in Figure 10.9 (right) and Figure 10.10. This means that summing up these distinct efficiency improvement values leads to conservative estimations of the real efficiency improvement for a given combination of coated AIC elements.

10.3.5 Conclusion

In any case, coating the "Anidolic Collector 1" with MiroSilver™instead of anodized aluminum is suggested, as it offers a considerable efficiency improvement (see Figure 10.9 (right)) together with a good surface-specific efficiency improvement (see Figure 10.12). In AICs with smaller widths (e.g. 1m instead of 5m), the potential of the AICs side elements becomes even more important, because the surfaces will remain equal while the horizontally oriented surfaces (such as "Duct Top" and "Duct Bottom") will decrease.

11

Final Discussion

The overall objective of this doctoral thesis was to combine knowledge from several scientific fields (e.g. daylighting technology, artificial lighting technology, lighting simulation and chronobiology) to discuss how Sustainable Lighting Solutions (i.e. lighting solutions that are optimized in terms of energy-efficiency, visual comfort and performance as well as non-visual aspects of lighting) can be achieved in office rooms.

11.1 Overview of Accomplished Research Work

A research strategy that used a test office room equipped with an Anidolic Daylighting System (ADS) as a starting point has been followed throughout the thesis. The daylighting performance of this ADS-equipped test office room at the LESO-PB has first been assessed. In a second step, a detailed occupant satisfaction assessment has been carried out amongst 23 human subjects working in very similar office rooms. Based on these results, optimization potential for this type of ADS, in order to achieve better visual comfort, visual performance and user satisfaction with this ADS, has been revealed.

Since even in office rooms with abundant access to daylight complementary electric lighting is sometimes necessary, appropriate state-of-the-art technology for general lighting in office rooms has been identified subsequently. Computer simulations with the software tool RELUX Vision (85) have then been carried out in order to compare different options for complementary, energy-efficient electric lighting solutions for the test office room. Following these simulation results, a highly energy-efficient electric lighting system, based on recent fluorescent and LED technology, has then been installed in the test office room. The next step of this doctoral thesis consisted of the preparation and realization of a POE-study, during which visual comfort and performance tests were carried out in the test office room with twenty human subjects. The results of this study show that the new lighting scenario in the test office room is not only more energy-efficient than the previous installation but also leads to better visual performance and acceptance amongst the study participants.

Subsequently, the non-visual (or chronobiological) properties of the ADS-equipped test office room were assessed. It was shown that most of the time, the luminous flux and its spectral composition supplied to the test office room via the ADS can be expected to lead to better non-visual lighting conditions than commonly experienced in conventional office rooms. However, it was found that supplementary blue-enriched artificial lighting might be indicated at some times. An energy-efficient LED-luminaire (BlueLum) for enhancing the chronobiological properties of office lighting scenarios has therefore been developed and compared to existing fluorescent lamp technology for chronobiological lighting.

In order to enable further applied chronobiological studies at the LESO-PB, a Controlled Lighting Conditions (CLC) Exposure Room has been set up in the LESO building towards the end of this doctoral thesis and a first chronobiological study (currently on the way of being extended) has been initiated. The objective of this study is to evaluate whether exposure to different lighting conditions during daytime has an influence on visual performance, mood, alertness and hormone secretion during the evening.

In parallel to the energetic, visual and non-visual optimization of the test office room in the LESO building, several computer simulations for other types of office rooms, different geographical locations and other ADS than the one installed at the LESO building were carried out within the framework of this doctoral thesis. In particular, it has been shown that low-LPD lighting designs are possible in open plan office rooms under tropical skies and that good trade-offs between cost and optical efficiency can be found by using an optimized, split computer model of the Anidolic Integrated Ceiling (AIC).

11.2 Discussion of Results

This doctoral thesis has revealed that ADS are an ideal basis for Sustainable Lighting Solutions. Not only are they able to provide adequate illumination (i.e. sufficiently high illuminances) in office rooms during large fractions of normal office hours, under various sky conditions and over the entire year, but they are also highly appreciated by office occupants at the condition that effective glare control mechanisms are available. As a matter of fact, occupants of the LESO solar experimental building in Lausanne judge glare-situations to be more persistent in ADS-equipped office rooms than not-enough-light-situations (see Chapter 2). The ideas for improving glare protection in ADS-equipped office rooms that are given in Chapter 2 can be of great interest when it comes to designing ADS for other types of buildings in the future. Furthermore, the results presented in Chapter 7 show that the ADS installed within the south-facing office rooms of the LESO building offer high c(λ)-corrected irradiances throughout large parts of most working days and can therefore be considered to be appropriate from a chronobiological point of view. In particular, the elevated c(λ)-corrected irradiances can be expected to lead to similar positive effects on health and well-being (e.g. better alertness, performance and sleep quality) as the blue-enriched fluorescent tubes used by Viola et al. (111).

Even if ADS are a very good basis for energy-efficient, high-quality office lighting, complementary electric lighting installations will always be necessary. Office occupants have to be able to work also during periods of external darkness, for example in the evenings or when the sky is extremely obscure (e.g. due to a thunderstorm). The challenge when designing these complementary electric lighting installations is to find solutions that consume a minimum of electricity while creating a maximum of visual comfort. In our particular situation, where the electric lighting installations are mainly a back-up option for times when there is not enough daylight available, the most interesting trade-offs between energy-efficiency and visual comfort are obtained by using a combination of ceiling-mounted directly emitting luminaires with very high luminaire efficiencies (such as the ZEN3 luminaire by Tulux (104)) for ambient lighting and portable desk lamps for temporary task lighting. The most appropriate lamps for the ceiling-mounted luminaires are still highly efficient fluorescent tubes. However, white

LED tubes for replacing fluorescent tubes in ceiling-mounted luminaires have recently become available and can be considered a realistic option for the future. The most suitable light sources for desk lamps for temporary task lighting are currently compact fluorescent lamps (CFLs, also called energy-saving lamp). However, these lamps have some significant disadvantages, for example the comparably long start-up time (see Chapter 5). A possible option for the future are white LED light bulbs, which offer an instantaneous start-up and a highly elevated lifetime, but which are still very expensive and which do not yet reach the luminous efficacies of CFLs. Nevertheless, white LEDs can be expected to become more and more performing over the next few years and will most likely play a major role in future lighting scenarios.

In addition to white LEDs for general lighting purposes, blue LEDs can be used for improving the chronobiological appropriateness of future office lighting scenarios. The "BlueLum" and the "BlueRedLum" devices developed during this doctoral thesis can be used for such purposes. For example, they can be mounted on computer screens in ADS-equipped office rooms and can be switched on in the early mornings and under overcast sky conditions in order to adjust the ocular $c(\lambda)$-corrected irradiances to levels which can be expected to have beneficial effects on health and well-being. The spectroradiometric measurements presented in Chapter 8 of this thesis show that three BlueLum devices would be necessary to create (together with the regular ambient lighting installation) $c(\lambda)$-corrected irradiances comparable to those occuring under the lighting scenario described by Viola et al. (111).

The applied chronobiological study presented in Chapter 9 of this thesis shows that the CLC Exposure Room, for which a highly flexible electric lighting system has been designed during this doctoral thesis, is a good basis for carrying out chronobiological studies at LESO-PB. The analysis of the preliminary results presented in Section 9.4 has not revealed a significant difference in performance and alertness of study participants after Daylight (DL) or Artificial Light (AL) exposure. However, if day 2 was analyzed separately, it was found that the subjects performed better after DL exposure. This might be due to group differences (e.g. one group performed in general better than the other one), but it might also indicate a positive influence of daylight on the performance of office workers. Taking into account only day 2 might be justified because there was no intra-day practice effect on day 2. A larger number of participants might yet lead to more detailed results.

As intended in the beginning of the doctoral project in 2006, a Sustainable Lighting Solution for the ADS-equipped test office room in the LESO building has been developed over the last three and a half years. Detailed computer simulations carried out with RELUX Vision have made it possible to identify two promising electric lighting solutions based on fluorescent lighting technology with LPDs of 3.9 W/m^2 and 3 W/m^2, respectively. Possible (future) LED lighting scenarios have also been simulated. In order to run in-situ tests of these solutions, a flexible ceiling-mounted rail system with movable carriages was installed in the test office room. The 3.9 W/m^2-solution was set up on this rail system and was intensively tested in a study with twenty human subjects (see Chapter 6). This study revealed that the 3.9 W/m^2-solution improved the subjects' performance during a paper-based task compared to the usual lighting installation in this office. The visual comfort was good and comparable to that of the usual lighting installation. In average, the test persons preferred the 3.9 W/m^2-solution over the usual lighting installation in this office.

If combined with a portable desk lamp equipped with a 7 W light bulb (CFL or LED) and three BlueLum devices (combined power consumption of 12 W), a suitable complementary electric lighting system for the ADS already installed in the test office can be obtained. This leads to an installed LPD of 5.1 W/m^2. Since this complementary electric lighting system is not operating during the entire length of a normal working day (i.e. from 08:00 to 18:00), it makes sense to define an effective LPD (LPD_{eff})

$$LPD_{eff} = \frac{LPD_{amb} * \tau_{amb} + LPD_{task} * \tau_{task} + LPD_{blue} * \tau_{blue}}{10h} \qquad (11.1)$$

where LPD_{amb} stands for the installed LPD that results from the ambient lighting (3.9 W/m^2 in our case), LPD_{task} stands for the installed LPD that results from the task lighting (0.4375 W/m^2 in our case), LPD_{blue} stands for the installed LPD that results from the 3 BlueLums (0.75 W/m^2 in our case) and τ_{amb}, τ_{task} and τ_{blue} stand for the respective average operating hours during the normal working day (10 hours length). With worst case estimations of five hours per day for the ambient lighting and two hours per day for the task lighting and the BlueLums, we find an effective LPD of slightly more than 2 W/m^2. These values for the installed LPD and the effective LPD are significantly lower than typical LPDs in Swiss office rooms (7.5 to 15 W/m^2 for illuminances between 300 and 500 Lux, (82)). Yet, the described office room achieves good visual comfort and occupant performance as well as appropriate chronobiological properties (in terms of c(λ)-corrected irradiances) in addition to its low LPDs.

It is, however, not sufficient to limit this work to the particular situation of the LESO solar experimental building in Switzerland and its small office rooms. It must also be possible to apply the concepts for sustainable office lighting discussed in this thesis to other types of office buildings at different locations. In addition to that, ADS must be further improved in such a way that they are capable of illuminating other office types, for example large open plan offices. The results in Chapter 10 show that an "exportation" of these concepts to different climatic regions (e.g. Singapore) is possible and that, also in such cases, installed LPDs around 5 W/m^2 can be achieved. In addition to that, the performance of AICs can be further improved by using highly reflective coating materials like MiroSilver™(4), and cost-effective solutions for customized ADS can be found. This is a crucial point because the base for any sustainable lighting scenario will always be daylight:

- Daylight is ideal from an energetic point of view (if unnecessarily high heat gains can be avoided) because no electricity for artificial lighting is needed.
- Daylight is highly appreciated by office occupants (if appropriate glare control mechanisms are in place).
- Daylight yields the highest c(λ)-corrected irradiances and can thus be considered to be ideal from a chronobiological point of view (at least as much as melatonin suppression is concerned.)

11.3 Scope for Further Work

Possibilities for further work include:

- **Improvement of the ADS installed at the LESO building**
  The discussions in Chapter 2 have shown that there is scope for improving the

ADS installed at the LESO-building. Interesting possibilities for future research in this regard might be the testing of telecommunication technologies (e.g. PC or iPhone) for improving the control possibilities of window blinds and lighting installations.

- **Installation and test of other low-LPD lighting scenarios in the the test office room**
  The test office room, which was equipped with a highly flexible, ceiling-mounted rail system during this doctoral thesis, could be used to test other low-LPD lighting scenarios during POE-studies with human subjects in the future. Interesting possibilities include the 3 W/m^2 fluorescent lighting solution or the 3.25 W/m^2 LED solution described in Chapter 4, or yet a solution based on the white LED tubes presented in Chapter 3.

- **Development of strategies for retrofitting existing buildings with ADS**
  Since renovations of exisiting buildings represent a considerable fraction of today's requirements in the construction sector, it is crucial to develop strategies for achieving Sustainable Lighting Solutions for existing buildings. In particular, ways to retrofit existing buildings with ADS should be a main focus of future research because well-performing advanced daylighting systems are the base for Sustainable Lighting Solutions in buildings.

- **Use of the BlueLum and BlueRedLum devices in applied chronobiological studies**
  The BlueLum and the BlueRedLum devices could be improved and used for further applied chronobiological studies, for example to define appropriate thresholds for creating the described positive effects on office workers (e.g. better alertness, better sleep quality) with blue-enriched light.

- **Further chronobiological studies in the CLC Exposure Room**
  Further studies using the CLC Exposure Room established during this doctoral work could be carried out. In particular, studies with longer exposures (i.e. over several days) and at other times of the year (i.e. in summer) might be of great interest.

- **Development of different types of ADS**
  Because daylight can be considered an ideal base for sustainable office lighting solutions, different types of ADS could be developed based on the ADS installed at the LESO building and the AIC. In particular, the design of multi-opening ADS for illumination of deeper office rooms is highly important. Preliminary simulations in this field have already been initiated in parallel to this doctoral thesis (22).

- **Sustainable Lighting Solutions for other types of buildings**
  Sustainable Lighting Solutions are not only required for office buildings, but also for many other buidling types such as residential buildings, hospitals, schools, factories or shopping centers. Based on the strategies for appropriate combination of day- and electric lighting systems presented in this thesis, strategies for sustainable lighting in such other building types should be developed.

- **Sustainable Lighting Solutions for transportation systems**
  Also for various types of transportation systems, for example in trains, airplanes or yet in space flight applications, strategies for achieving Sustainable Lighting Solutions are needed. The results of this thesis can be used for future research in this field as well.

Scope for further work is of course manifold and not at all limited to the above ideas.

11.4 Final Conclusion

This doctoral thesis shows that if daylight is provided to an office room through an advanced daylighting system that is able to supply sufficient daylight flux during large parts of most working days while minimizing the risk of discomfort glare, then the electric lighting installation in such an office room can become mainly complementary. If highly efficient lamps (e.g. fluorescent tubes, CFLs or LEDs), luminaires (e.g. based on non-imaging optics theory) and electronic control gear are used, it is possible to reduce the LPD in such an office room to values of less than 5 W/m^2. In addition to this large potential for energy-efficient, comfortable office lighting, the appropriate combination of advanced daylighting systems and carefully chosen artificial lighting technology (in particular fluorescent and LED lighting) has another huge benefit: it is able to create ocular c(λ)-corrected irradiances that can be expected to be sufficiently elevated to lead to positive effects on health and well-being (e.g. better alertness, performance and sleep quality).

Effective LPDs (taking into account that the electric lighting installation in such office rooms is mainly complementary and therefore not switched on during the entire duration of most working days) of around 2 W/m^2 are achievable in office rooms equipped with an appropriate combination of day- and electric lighting systems. This corresponds to only 13% to 27% of the typical LPDs in conventional Swiss office rooms. Compared to such conventional office rooms without advanced daylighting systems in which electric lighting is not mainly complementary (and is therefore switched on during large parts of most working days), electricity savings between 70% and 80% are achievable using the strategies presented in this doctoral thesis.

In conclusion, this doctoral thesis has successfully demonstrated that it is possible to achieve Sustainable Lighting Solutions that are optimized in terms of energy-efficiency, visual comfort and performance as well as non-visual aspects by combining day- and electric lighting technologies in an appropriate way.

References

[1] AG-DALI. **Website of AG-DALI**. http://www.dali-ag.org/, 2009. 53

[2] Y. Akashi and P.R. Boyce. **A field study of illuminance reduction**. *Energy & Buildings*, **38**(6):588–599, 2006. 4, 21, 63, 116

[3] T. Åkerstedt and M. Gillberg. **Subjective and objective sleepiness in the active individual**. *International Journal of Neuroscience*, **52**(1-2):29–37, 1990. 102, 160

[4] ALANOD. **Website of ALANOD**. http://www.alanod.ch/, 2009. 188, 206

[5] R. Altherr and J.B. Gay. **A low environmental impact anidolic facade**. *Building and Environment*, **37**(12):1409–1419, 2002. 3, 11, 13, 20, 131

[6] Apple. **Website of Apple Inc.** http://www.apple.com/, 2009. 34, 49

[7] ares Truly Italian. **Website of ares**. http://www.aresill.net/, 2009. 73, 74

[8] M.B.C. Ariës, S.H.A. Begemann, and A.D. Tenner. *Human lighting demands: healthy lighting in an office environment*. PhD thesis, Technische Universiteit Eindhoven, 2005. 8

[9] M.B.C. Aries and G.R. Newsham. **Effect of daylight saving time on lighting energy use: A literature review**. *Energy Policy*, **36**(6):1858–1866, 2008. 3

[10] M. Bach. **The Freiburg Visual Acuity test-automatic measurement of visual acuity**. *Optometry & Vision Science*, **73**(1):49, 1996. 102, 161

[11] D.M. Berson. **Strange vision: ganglion cells as circadian photoreceptors**. *TRENDS in Neurosciences*, **26**(6):314–320, 2003. 1, 5

[12] Z. Boulos, M.M. Macchi, M.P. Sturchler, K.T. Stewart, G.C. Brainard, A. Suhner, G. Wallace, and R. Steffen. **Light visor treatment for jet lag after westward travel across six time zones**. *Aviation Space and Environmental Medicine*, **73**(10):953–963, 2002. 7

[13] G.C. Brainard, J.P. Hanifin, J.M. Greeson, B. Byrne, G. Glickman, E. Gerner, and M.D. Rollag. **Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor**. *Journal of Neuroscience*, **21**(16):6405, 2001. 5, 6, 121, 123, 149

[14] C. Cajochen. **Alerting effects of light**. *Sleep Medicine Reviews*, **11**(6):453–464, 2007. 5, 149

[15] E. Cardani. **Quando l'architettura é verde.** *L'Arca Plus: Philippe Samyn (17)*, pages 104–107, 1998. 20

[16] CIE. **CIE Collection on glare: Commission international de l'éclairage**. Technical Report CIE: 147:2002, CIE, 2002. 57

[17] G. Courret, J.L. Scartezzini, D. Francioli, and J.J. Meyer. **Design and assessment of an anidolic light-duct**. *Energy & Buildings*, **28**(1):79–99, 1998. 177, 189

[18] Gilles Courret. *Systémes anidoliques d'éclairage naturel.* PhD thesis, Swiss Federal Institute of Technology in Lausanne, 1999. 105, 106, 177

[19] Daqtix. **Daqtix GmbH**. `http://www.daqtix.com/`, 2009. 157

[20] S. Darula and R. Kittler. **CIE general sky standard defining luminance distributions**. *Proceedings eSim*, pages 11–13, 2002. 189

[21] S. Darula, R. Kittler, and S.K. Wittkopf. **Outdoor Illuminance Levels in the Tropics and their Representation in Virtual Sky Domes**. *Architectural Science Review*, **49**(3):301–313, 2006. 189

[22] F. Davila Alotto, F. Linhart, and J.L. Scartezzini. **CIE Standard Skies in Switzerland: Relative Occurence and Impact on Daylighting System Performance**. In *Int'l. Conf. on Solar Energy in Buildings (CISBAT)*, pages 237–242, 2009. 208

[23] DIN5036-3. **DIN 5036-3: Strahlungsphysikalische und lichttechnische Eigenschaften von Materialien; Meverfahren fr lichttechnische und spektrale strahlungsphysikalische Kennzahlen**, 2009. 188

[24] Dürrenberger, G. and Klaus, G. **EMF von Energiesparlampen**. 2004. 43

[25] N.H. Eklund and P.R. Boyce. **The development of a reliable, valid, and simple office lighting survey**. *Journal of the Illuminating Engineering Society*, 1996. 21, 22

[26] A.J. Elliot, M.A. Maier, A.C. Moller, R. Friedman, and J. Meinhardt. **Color and psychological functioning: The effect of red on performance attainment**. *Journal of Experimental Psychology General*, **136**(1):154, 2007. 146

[27] I. FERGUSON, A. MELTON, N. LI, D. NICOL, E.H. PARK, and G. TOSINI. **Imitating Broadband Diurnal Light Variations Using Solid State Light Sources**. *Journal of Light & Visual Environment*, **32**(2):63–68, 2008. 136, 147

[28] M.G. Figueiro, A. Bierman, B. Plitnick, and M.S. Rea. **Preliminary evidence that both blue and red light can induce alertness at night**. *BMC neuroscience*, **10**(1):105, 2009. 146

[29] W.J. Fisk. **Health and productivity gains from better indoor environments and their ralationship with building energy efficiency**. *Annual Review of Energy and the Environment*, **25**(1):537–566, 2000. 68

[30] C. Franzetti, G. Fraisse, and G. Achard. **Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings**. *Energy & Buildings*, **36**(2):117–126, 2004. 2

[31] M.S. Freedman, R.J. Lucas, B. Soni, M. von Schantz, M. Muñoz, Z. David-Gray, and R. Foster. **Regulation of mammalian circadian behavior by non-rod, non-cone, ocular photoreceptors**. *Science*, **284**(5413):502, 1999. 5

[32] A.A. Freewan, L. Shao, and S. Riffat. **Optimizing performance of the lightshelf by modifying ceiling geometry in highly luminous climates**. *Solar Energy*, **82**(4):343–353, 2008. 3

[33] R.L. Fucci, J. Gardner, J.P. Hanifin, S. Jasser, B. Byrne, E. Gerner, M. Rollag, and G.C. Brainard. **Toward optimizing lighting as a countermeasure to sleep and circadian disruption in space flight**. *Acta Astronautica*, **56**(9-12):1017–1024, 2005. 7

[34] A. Gabrani, F. Linhart, and J.L. Scartezzini. **White LEDs for office lighting: Technical background, available products and possible integration.** Technical report, EPFL, 2007. 46, 73

[35] A.D. Galasiu and J.A. Veitch. **Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: A literature review**. *Energy & Buildings*, **38**(7):728–742, 2006. 56

[36] Gavin, G. and Deschamps, L. **Domotique Configuration et installation d'un microserveur KNX MyHomeBox.** Technical report, EPFL, 2008. 33

[37] A. Guillemin. *Using genetic algorithms to take into account user wishes in an advanced building control system*. PhD thesis, Swiss Federal Institute of Technology in Lausanne, 2002. 14

[38] A. Guillemin. *Using genetic algorithms to take into account user wishes in an advanced building control system*. PhD thesis, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, 2003. 15

[39] R. Heinz. *Grundlagen der Lichterzeugung, 2. Auflage*. Highlight Verlag, 2006. 49

[40] R.A. Hill and R.A. Barton. **Psychology Red enhances human performance in contests**. *Nature*, **435**(7040):293, 2005. 146

[41] M. Hinnells. **Technologies to achieve demand reduction and microgeneration in buildings**. *Energy Policy*, **36**:588–599, 2008. 2

[42] G. Hoffmann, V. Gufler, A. Griesmacher, C. Bartenbach, M. Canazei, S. Staggl, and W. Schobersberger. **Effects of variable lighting intensities and colour temperatures on sulphatoxymelatonin and subjective mood in an experimental office workplace**. *Applied Ergonomics*, **39**(6):719–728, 2008. 149

[43] J.A. Horne and O. Ostberg. **A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms.** *International Journal of Chronobiology*, **4**(2):97, 1976. 156

[44] S. Hubalek, D. Matthaei, and C. Schierz. **Beleuchtung von Bildschirmarbeitsplätzen-Energieeinsparung versus Ergonomie? Laborversuch zur teilflächenbezogenen Beleuchtung**. Technical report, Zürich, ETH and für Organisations, Z. and Arbeitswissenschaften, F.U., 2006. 67

[45] S. Hubalek, D. Zoschg, and C. Schierz. **Ambulant recording of light for vision and non-visual biological effects**. *Lighting Research & Technology*, **38**(4):314, 2006. 5, 6, 122

[46] IKEA. **Website of IKEA**. `http://www.ikea.ch/`, 2009. 93, 95

[47] PST Inc. **Psychological Software Tools Inc.** `http://www.pstnet.com/`, 2009. 162

[48] T. Inoue, M. Ichinose, and N. Ichikawa. **Thermotropic glass with active dimming control for solar shading and daylighting**. *Energy & Buildings*, **40**(3):385–393, 2008. 3

[49] S.M. Jaeggi, R. Seewer, A.C. Nirkko, D. Eckstein, G. Schroth, R. Groner, and K. Gutbrod. **Does excessive memory load attenuate activation in the prefrontal cortex? Load-dependent processing in single and dual tasks: functional magnetic resonance imaging study**. *Neuroimage*, **19**(2):210–225, 2003. 161, 162, 166

[50] D. Jenkins and M. Newborough. **An approach for estimating the carbon emissions associated with office lighting with a daylight contribution**. *Applied Energy*, **84**(6):608–622, 2007. 3

[51] JETI. **Website JETI Technische Instrumente GmbH**. `http://www.jeti.com/`, 2009. 222

[52] Ö. Johansson, P.O. Wanvik, and R. Elvik. **A new method for assessing the risk of accident associated with darkness**. *Accident Analysis and Prevention*, 2009. 39

[53] J.S. Kim, P.E. Jeon, J.C. Choi, H.L. Parka, S.I. Mho, and G.C. Kim. **Warm-white-light emitting diode utilizing a single-phase full-color Ba3MgSi2O8: Eu2+, Mn2+ phosphor**. *Applied Physics Letters*, **84**:15, 2004. 46

[54] J.S. Kim, P.E. Jeon, Y.H. Park, J.C. Choi, H.L. Park, G.C. Kim, and T.W. Kim. **White-light generation through ultraviolet-emitting diode and white-emitting phosphor**. *Applied Physics Letters*, **85**:3696, 2004. 46

[55] C.W. Ko and Y.T. Tao. **Bright white organic light-emitting diode**. *Applied Physics Letters*, **79**:4234, 2001. 49

[56] M. Krarti, P.M. Erickson, and T.C. Hillman. **A simplified method to estimate energy savings of artificial lighting use from daylighting**. *Building and Environment*, **40**(6):747–754, 2005. 3

[57] H. Kuchling. *Taschenbuch der Physik, 16. Auflage*. Fachbuchverlag Leipzig, 1999. 141, 226

[58] R. Kuller and L. Wetterberg. **Melatonin, cortisol, EEG, ECG and subjective comfort in healthy humans: impact of two fluorescent lamp types at two light intensities**. *Lighting Research & Technology*, **25**(2):71, 1993. 149

[59] K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen, and E. Ikonen. **Realization of the luminous-flux unit using an LED scanner for the absolute integrating-sphere method**. *Metrologia*, **37**:595–598, 2000. 46, 225

[60] D.H.W. Li and J.C. Lam. **An analysis of lighting energy savings and switching frequency for a daylit corridor under various indoor design illuminance levels**. *Applied Energy*, **76**(4):363–378, 2003. 2

[61] D.H.W. Li, T.N.T. Lam, and S.L. Wong. **Lighting and energy performance for an office using high frequency dimming controls**. *Energy Conversion and Management*, **47**(9-10):1133–1145, 2006. 2, 58

[62] D.H.W. Li, T.N.T. Lam, SL Wong, and E.K.W. Tsang. **Lighting and cooling energy consumption in an open-plan office using solar film coating**. *Energy*, **33**(8):1288–1297, 2008. 3

[63] D.H.W. Li, E.K.W. Tsang, K.L. Cheung, and C.O. Tam. **An analysis of light-pipe system via full-scale measurements**. *Applied Energy*, 2009. 3

[64] M. Li, W.H. Chen, M.T. Lin, M.A. Omary, and N.D. Shepherd. **Near-white and tunable electrophosphorescence from bis [3, 5-bis (2-pyridyl)-1, 2, 4-triazolato] platinum (II)-based organic light emitting diodes**. *Organic Electronics*, 2009. 49

[65] D. Lindelöf and N. Morel. **A field investigation of the intermediate light switching by users**. *Energy & Buildings*, **38**(7):790–801, 2006. 14, 15

[66] F. Linhart and J.L. Scartezzini. **Efficient lighting strategies for office rooms in tropical climates**. In *Sun, wind and architecture: the proceedings of the 24th International Conference on Passive and Low Energy Architecture: PLEA2007, 22-24 November 2007, National University of Singapore, Singapore*, pages 360–367, 2007. 21

[67] F. Linhart and J.L. Scartezzini. **Minimizing connected lighting power in office rooms equipped with Anidolic Daylighting Systems**. In *Int'l. Conf. on Solar Energy in Buildings (CISBAT)*, pages 4–5, 2007. 131

[68] F. Linhart and J.L. Scartezzini. **Occupant satisfaction in office rooms equipped with anidolic daylighting systems**. In *Int'l Conf. Sol. Heating Cooling Build.(EUROSUN)*, pages 355–362, 2008. 26, 97, 131

[69] F. Linhart and J.L. Scartezzini. **Minimizing lighting power density in office rooms equipped with Anidolic Daylighting Systems**. *Solar Energy*, 2009. 58

[70] LTI. **Website of Lighting Technologies Inc.** http://www.ltioptics.com/, 2009. 189, 229

[71] M.A. Marwaee and D.J. Carter. **A field study of tubular daylight guidance installations**. *Lighting Research & Technology*, **38**(3):241, 2006. 3

[72] I. Meir, Y. Garb, D. Jiao, and A. Cicelsky. **Post-Occupancy Evaluation: An Inevitable Step Toward Sustainability**. *Advances in Building Energy Research*, **3**(1):189–220, 2009. 21

[73] METEOSUISSE. **Website of Meteosuisse**. `http://www.meteosuisse.ch`, 2009. 36, 123

[74] J. MOHELNIKOVA. **Tubular light guide evaluation**. *Building and Environment*, **44**(10):2193–2200, 2009. 3

[75] C.E. OCHOA AND I.G. CAPELUTO. **Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates**. *Building and environment*, **41**(8):1128–1135, 2006. 3

[76] Y. OHNO. **Detector-based luminous-flux calibration using the Absolute Integrating-Sphere Method**. *Metrologia*, **35**:473–478, 1998. 46, 225, 226

[77] OSRAM. **Website of OSRAM**. `http://www.osram.ch`, 2009. xx, 80, 81, 138

[78] PHILIPS. **Website of PHILIPS**. `http://www.philips.ch`, 2009. 49, 59, 89, 147

[79] J. PHIPPS-NELSON, J.R. REDMAN, D.J. DIJK, AND S.M. RAJARATNAM. **Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance.** *Sleep*, **26**(6):695, 2003. 149, 174

[80] T. RAMASOOT AND S. FOTIOS. **Lighting for the Classrooms of the Future**. *Electronic Classrooms: a New Challenge for School Lighting Guidance. BalkanLight*, 2008. 21

[81] R.D. RAUH. **Electrochromic windows: an overview**. *Electrochimica Acta*, **44**(18):3165–3176, 1999. 3

[82] RAVEL-SCHRIFTENREIHE. **Industriebeleuchtungen**. Technical report, Bundesamt für Konjunkturfragen, 1996. 58, 206

[83] M.S. REA. *The IESNA lighting handbook: reference & application.* Illuminating Engineering Society of North America, 2000. 7, 40, 43, 50, 53

[84] REGENT. **Website of Regent Beleuchtungskörper AG**. `http://www.regent.ch`, 2009. 59, 60, 98, 150

[85] RELUX. **Website of RELUX Informatik AG**. `http://www.relux.ch`, 2009. 65, 82, 151, 201

[86] A. ROSEMANN AND H. KAASE. **Lightpipe applications for daylighting systems**. *Solar Energy*, **78**(6):772–780, 2005. 3

[87] A. ROSEMANN, M. MOSSMAN, AND L. WHITEHEAD. **Development of a cost-effective solar illumination system to bring natural light into the building core**. *Solar Energy*, **82**(4):302–310, 2008. 3

[88] M. RUGER, M. GORDIJN, D.G.M. BEERSMA, B. DE VRIES, AND S. DAAN. **Time-of-day-dependent effects of bright light exposure on human psychophysiology: comparison of daytime and nighttime exposure**. *American Journal of Physiology- Regulatory, Integrative and Comparative Physiology*, **290**(5):R1413, 2006. 174

[89] F. SAMEDOV AND M. DURAK. **Realization of luminous flux unit lumen at National Metrology Institute of Turkey (UME)**. *Optica Applicata*, **34**(2):265–274, 2004. 46, 225

[90] Samsung. **Website of SAMSUNG**. `http://www.samsung.com/`, 2009. 49

[91] J.L. Scartezzini and G. Courret. **Anidolic daylighting systems**. *Solar Energy*, **73**(2):123–135, 2002. 3, 4, 131

[92] B. Schlomann, E. Gruber, B. Geiger, H. Kleeberger, U. Wehmhörner, T. Herzog, and D.M. Konopka. **Energieverbrauch des Sektors Gewerbe, Handel, Dienstleistungen (GHD) für die Jahre 2004 bis 2006**. Technical report, Fraunhofer-Institut für System-und Innovationsforschung (ISI), Lehrstuhl für Energiewirtschaft und Anwendungstechnik (IfE), GfK Marketing Services GmbH & Co. KG Karlsruhe, München, Nürnberg, 2008. 2

[93] E.F. Schubert and J.K. Kim. **Solid-state light sources getting smart**. *Science*, **308**(5726):1274, 2005. 48, 136

[94] Schweizerische Normen Vereinigung. **Light and Lighting Lighting of work places. Part 1: Indoor work places**. Technical Report SN EN 12464-1 :2003 e, SNV, 2003. 15, 57

[95] Sony. **Website of SONY**. `http://www.sony.ch/`, 2009. 49

[96] StatSoft. **Website of StatSoft, the creators of STATISTICA**. `http://www.statsoft.com`, 2009. 167

[97] R.G. Stevens and M.S. Rea. **Light in the built environment: potential role of circadian disruption in endocrine disruption and breast cancer**. *Cancer causes and control*, **12**(3):279–287, 2001. 7

[98] P.D. Swift. **Splayed mirror light pipes**. *Solar Energy*, 2009. 3

[99] Sylvania. **Website of Sylvania**. `http://www.sylvania.com/`, 2009. 60

[100] A. Thanachareonkit and J.L. Scartezzini. **Modelling Complex Fenestration Systems using physical and virtual models**. *Solar Energy*, 2009. 3

[101] K. Thapan, J. Arendt, and D.J. Skene. **An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans**. *The Journal of physiology*, **535**(1):261, 2001. 5, 121, 123, 149

[102] J.M. Torrington and P.R. Tregenza. **Lighting for people with dementia**. *Lighting Research & Technology*, **39**(1):81, 2007. 7

[103] Toshiba. **Website of TOSHIBA**. `http://www.toshiba.ch/`, 2009. 49

[104] Tulux. **Website of Tulux AG**. `http://www.tulux.ch`, 2009. 69, 70, 98, 123, 203

[105] W.J.M. Van Bommel. **Non-visual biological effect of lighting and the practical meaning for lighting for work**. *Applied ergonomics*, **37**(4):461–466, 2006. 5, 7, 121

[106] W.J.M. Van Bommel. **Good lighting with less energy - Editorial**. *Lighting Research & Technology*, **41**(3):207–208, 2009. 8

[107] G. Vandewalle, S. Gais, M. Schabus, E. Balteau, J. Carrier, A. Darsaud, V. Sterpenich, G. Albouy, D.J. Dijk, and P. Maquet. **Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure**. *Cerebral Cortex*, 2007. 149, 174

[108] J.A. Veitch. **Lighting for high-quality workplaces. Creating the productive workplace**, 2006. 3, 7

[109] J.A. Veitch and G.R. Newsham. **Quantifying lighting quality based on experimental investigations of end user performance and preference**. In *Proceedings of Right Light Three, The Third European Conference on Energy-Efficient Lighting, Newcastle-upon-Tyne, England*, **1**, pages 119–127, 1995. 4

[110] J.A. Veitch, G. van den Beld, G. Brainard, and J.E. Roberts. **Ocular lighting effects on human physiology and behavior**. In *CIE*, **158**, pages 1–50, 2004. 5, 7

[111] A.U. Viola, L.M. James, L.J. Schlangen, and D.J. Dijk. **Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality.** *Scandinavian journal of work, environment & health*, **34**(4):297, 2008. 122, 123, 124, 133, 135, 147, 203, 204

[112] A.R. Webb. **Considerations for lighting in the built environment: non-visual effects of light**. *Energy & Buildings*, **38**(7):721–727, 2006. 7, 118, 121

[113] W.T. Welford and R. Wilson. *Non-imaging optics.* Academic Press, New York, 1989. 4, 69, 147

[114] Y.J. Wen, J. Granderson, A.M. Agogino, and U.C. Berkeley. **Towards embedded wireless-networked intelligent daylighting systems for commercial buildings**. In *IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, 2006*, **1**, 2006. 2

[115] M.E. Wewers and N.K. Lowe. **A critical review of visual analogue scales in the measurement of clinical phenomena**. *Res Nurs Health*, **13**(4):227–236, 1990. 161

[116] J. Wienold and J. Christoffersen. **Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras**. *Energy & Buildings*, **38**(7):743–757, 2006. 98, 101

[117] A. Wirz-Justice, C. Quinto, C. Cajochen, E. Werth, and C. Hock. **A rapid-cycling bipolar patient treated with long nights, bedrest, and light**. *Biological Psychiatry*, **45**(8):1075–1077, 1999. 7

[118] S.K. Wittkopf. **A method to construct Virtual Sky Domes for use in standard CAD-based light simulation software**. *Architectural Science Review*, **47**(3):275–286, 2004. 189

[119] S.K. Wittkopf. **Evaluation of Virtual Sky Domes for the prediction of daylight performance with Radiosity-based light simulation software**. *Architectural Science Review*, **48**(2):173–178, 2005. 189

[120] S.K. Wittkopf. **Daylight performance of anidolic ceiling under different sky conditions**. *Solar Energy*, **81**(2):151–161, 2007. 3, 178, 189

[121] S.K. Wittkopf, E. Yuniarti, and L.K. Soon. **Prediction of energy savings with anidolic integrated ceiling across different daylight climates**. *Energy & Buildings*, **38**(9):1120–1129, 2006. 3, 11, 178, 179, 181, 189

[122] T. Wolff, H.H. Ho, J.M. Foley, and S.K. Mitra. **H. 264 coding artifacts and their relation to perceived annoyance**. In *European Signal Processing Conference*, 2006. 26

[123] J. Zhu, W. Li, B. Chu, F. Yan, D. Yang, H. Liu, and J. Wang. **Non-doped-type white organic light-emitting diodes for lighting purpose**. *Journal of Luminescence*, **In Press, Accepted Manuscript**, 2009. 49

Appendix A

Spectroradiometer

The sprectroradiometer used during the described doctoral thesis was a Specbos 1201 by JETI Technische Instrumente GmbH, Illmenau (D). The technical descriptions shown in the following were downloaded from the company's website (51).

JETI

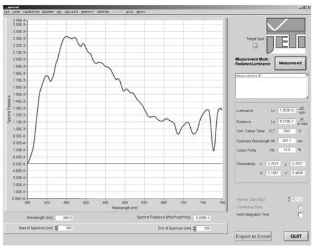
Spectroradiometer

specbos 1201

specbos 1201 is a precise and compact VIS spectroradiometer. It can be used in laboratory as well as production env ironment to measure the following quantities:

- Luminance, Radiance
- Illuminance, Irradiance
- xy and u´v´ coordinates
- Dominate wavelength, Color purity
- Correlated Color Temperature
- Color Rendering Index
- Circadian metrics, Photosynthetically Active Radiation

Luminous Intensity and Luminous Flux measuring heads are optional.



Screenshot of the radiom etric software (daylight)

The instrument can be operated with the intuitive measuring software LiMes (for a demo version see www.jeti.com). Furthermore it is possible to implement the instrument into individual applications using the virtual COM port directly by the following ways:

- Radiometric DLL
- Radiometric Virtual Instruments for LabView
- Serial commands

Advantages:

- USB powered
- Internal target spot laser (luminance measurement)
- Easy to install
- Start of measurement with external trigger signal (short cut or TTL)

Measuring objects:

- TV, Monitors, LCD-, LED-Displays
- Digital projectors
- Traffic lights, car lights
- Room illumination
- Lamps, LEDs

Specification

Optical parameters	
Spectral range	380 nm ... 780 nm
Optical bandwidth	5 nm (specbos 1201), 9 nm (specbos 1201 M)
Wavelengths resolution	1 nm
Digital electronic resolution	15 bit ADC
Viewing angle	1,8°
Measuring distance/ diameter	20 cm - ∅ 6 mm; 100 cm - ∅ 31 mm (luminance)
Measuring values	Spectral radiance Total luminance / total radiance Total illuminance / total irradiance Chromaticity coordinates x,y; u',v' Correlated Color Temperature, Color purity Color Rendering Index Circadian metrics, Photosynthetically Active Radiation
Measuring ranges and accuracies	
Measuring range luminance	2 ... 7 $x \cdot 10^4$ cd/m^2 (higher values with optional filter)
Measuring range illuminance	20 ...5 x 10^5 lx
Luminance accuracy	± 2 % (@ 1000cd/ m^2 and 2856 K)
Luminance repeatability	± 1 %
Chromaticity accuracy	± 0.002 x, y (@ 2856 K)
Color repeatability	± 0.0005 x, y
CCT repeatability	± 20 K (@ 2856 K)
Wavelength accuracy	± 0.5 nm
Other technical data	
Dispersive element	Imaging grating (flat field)
Light receiving element	Photodiode array 1024 pixel (binned)
Power supply	Hub powered
Interface	USB 2.0 fullspeed
Dimensions	140 mm x 58 mm x 34 mm
Weight	350 g
Operating conditions	Temperature 10 ... 40 °C Humidity < 85 % relative humidity at 35 °C
Accessories (included)	PC software JETI LiMeS for Windows 2000/XP DLL, LabVIEW VI's USB cable and trigger connector Cosine diffusor (for irradiance measurement) Calibration certificate, operation instructions Tripod, transport box
Accessories (optional)	Integrating spheres of different diameters, Luminous intensity measurement set up (CIE 127, cond. A and B)
NIST traceable calibration	Recommended interval: one year

JETI Technische Instrumente GmbH
Tatzendpromenade 2
D-07745 Jena

Tel. +49(3641)225 680
Fax. +49(3641)225 681
e-mail: sales @ jeti.com
Internet: www.jeti.com

Appendix B

Methods

B.1 Absolute Integrating Sphere Method

In order to be able to accurately measure the luminous efficacy of various light sources, a test facility based on an Integrating Sphere (also called Ulbricht sphere) was set up at the LESO-PB during this doctoral thesis. The illuminance that a given light source creates at a point located in the sphere's inner wall (this point is ideally shilded from the light source by a baffle) is compared to the illuminance at the same point created by a known reference flux; in this way, the light flux of any lamp can be accurately measured. The setup uses the so-called Absolute Integrating Sphere Method (59; 76; 89): instead of simply using a reference lamp inside the sphere that creates a known reference flux, a reference light flux is created using an external projector, a precision aperture and a luxmeter (which measures the illuminance that the projector's light flux creates at the precision aperture). In this way, the reference is not a lamp but the luxmeter itself. This is a great advantage because luxmeter calibrations are generally much more reliable than lamp calibrations. According to (76), the flux Φ_e from the external source (projector in our case) is given by

$$\Phi_e = E \cdot A \tag{B.1}$$

where E [Lux] is the illuminance created by the external source at the entry aperture of the sphere with a known area A. From Φ_e, the total luminous flux of the internal source Φ_i (the luminous flux which is subject to measurement) is obtained as follows:

$$\Phi_i = f\Phi_e \frac{y_i}{y_e} \tag{B.2}$$

where y_i is the illuminance measured by the internal luxmeter for the internal light source and y_e that of the external light source. The quantity f is a correction factor for various non-ideal behaviours of the integrating sphere and can be precisely calculated following a complicated assessment procedure (see (76) for details. Because in our case (i.e. when measuring the light flux of a long LED tube) the internal light source is not for all placement angles fully shielded by the baffle, a value for f smaller than unity has to be adopted. It has been decided to choose a conservative value of $f = 0.7$ for the measurements.

Figure B.1 shows the projector used in the measurement setup. The precision aperture, through which the external luminous flux Φ_e enters the sphere is shown in Figure B.2.

The luxmeter described in Appendix XXX was used for measuring the illuminance at the precision aperture E whereas the illuminances inside the sphere were measured with a second luxmeter (Luxmeter 106, PRC Krochmann, Berlin (D)).

If we assume that the maximal measuring error of the second luxmeter (for which documentation is unavailable) is the same than for the luxmeter described in Appendix XXX (7%), then the maximal relative measuring error $\frac{\Delta F}{F}$ of the Absolute Integrating Sphere Method described here becomes (57):

$$\frac{\Delta F}{F} = \pm (0.07 + 0.07 + 0.07) = 0.21 \tag{B.3}$$

It can thus be assumed that the luminous flux of the LED tube described in Chapter 3 of this Thesis is determined with a maximal relative measuring error of ±21%.

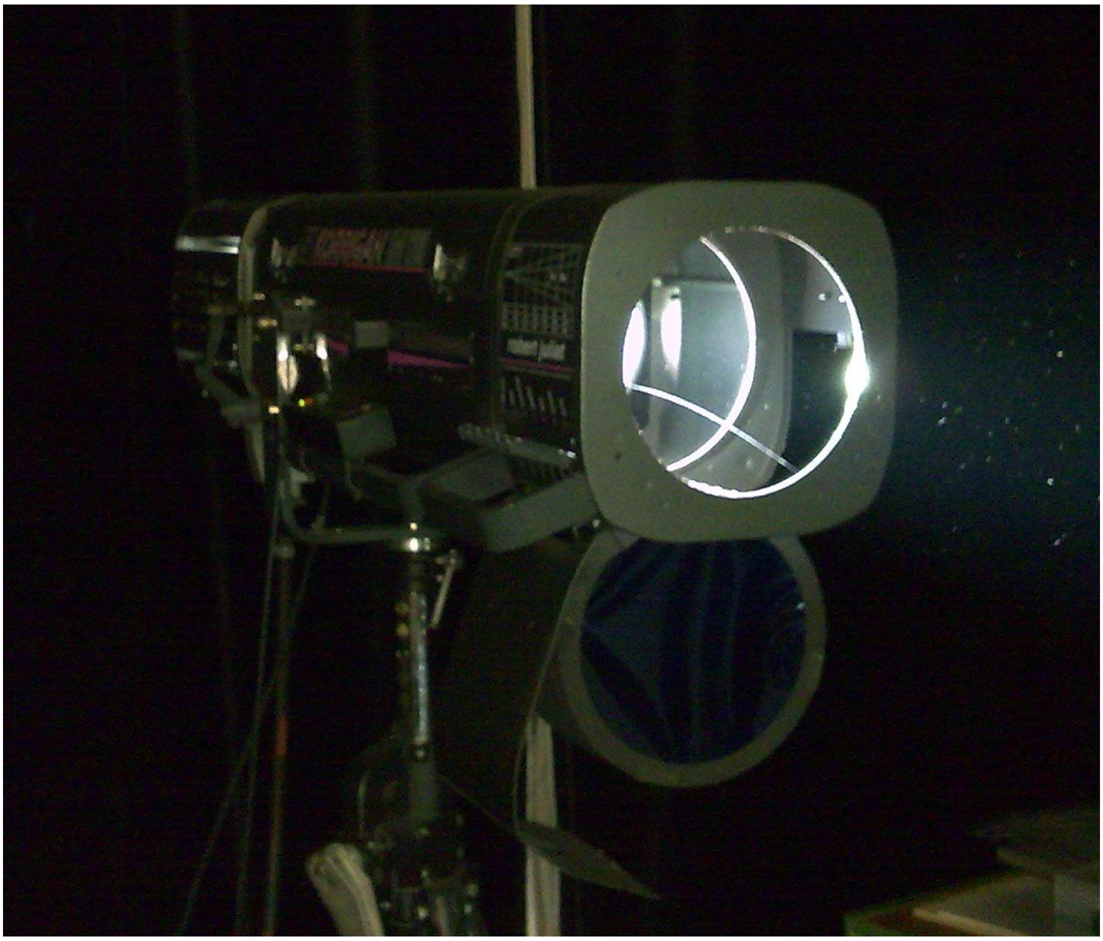


Figure B.1: The projector. - This photograph shows the projector used during the luminous flux measurements with the Absolute Integrating Sphere Method.

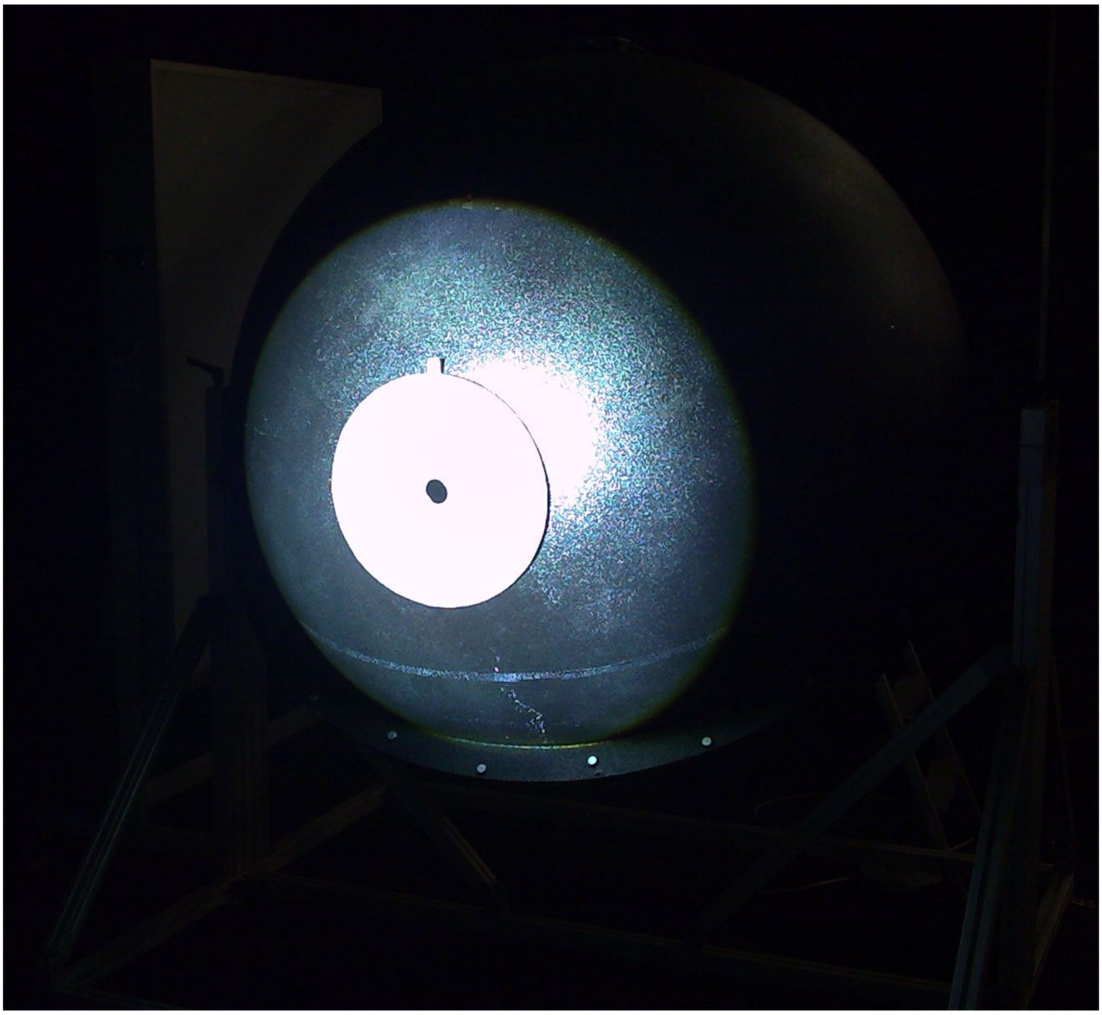


Figure B.2: The pecision aperture. - This photograph shows the precision aperture in the integrating spheres wall used during the luminous flux measurements with the Absolute Integrating Sphere Method.

B.2 AIC simulations with Photopia

Photopia (70) is a software tool for probabilistic forward raytracing and can be of great value during the design process and performance evaluation of complex luminaire geometries and non-punctual light sources. An excessive material database with directional reflectance data for various luminaire materials is also available for Photopia. The software allows importing from and exporting to CAD software (using .dxf or .dwg files), it offers different possibilities to create lamps and luminaries, gives the user various possibilities to assess their performance and finally allows exporting some of the performance data directly into standard lamp description files (i.e. IES or EULUMDAT formats). Figure B.3 summarizes the functioning of Photopia in terms of importing lamps and luminaries and gives a first overview of the different file types and their interactions.

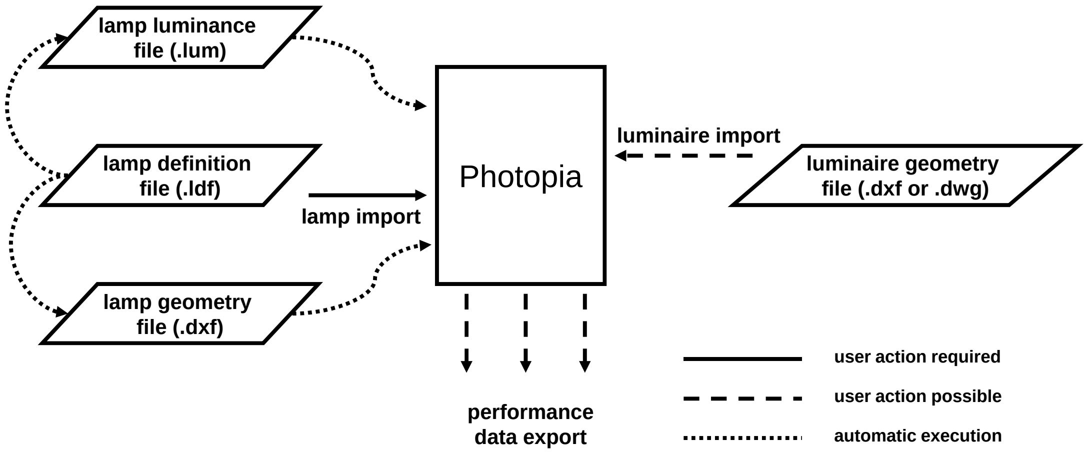


Figure B.3: Overview of AIC simulations with Photopia. - This Figure shows the functioning of Photopia in terms of importing lamps and luminaries and gives a first overview of the different file types and their interactions.

In order to run a simulation, Photopia requires at least one lamp. Lamps are created in Photopia through import of so-called lamp definition files, basically text files with the extension .ldf. For the lamp to be properly imported, a lamp geometry file in the drawing exchange format (.dxf) that carries the same name as the lamp definition file has to be located in Photopia's "Lib"-folder. The software automatically searches the lamp geometry file and gets the necessary information out of it. Even though all lamp parameters can be defined in the .ldf - file, the use of supplementary lamp luminance files (.lum) is common. They are extremely helpful in cases where the lamp geometry file contains different layers: the luminance of each layer is then separately defined in one .lum - file. When .lum-files are used, they have to be located in Photopia's "Lib"-folder and to be addressed within the .ldf - file. Yet again, Photopia automatically locates the files and gets the necessary information out of them. Luminaires can be created directly in Photopia by using some implemented basic CAD tools. However, it is much more convenient to import them as CAD drawing files (.dwg) or as .dxf - files. In both cases, different layers should be used for the different luminaire components, because in Photopia material properties are not directly assigned to luminaire components but rather to the layers on which the components are located. Once the lamps and luminaries have been created, the user can run simulations and export selected performance data to various file formats. Post-processing of these files with other software tools (e.g. MS Excel) is then possible.

For the simulations carried out during this doctoral thesis, AutoCAD was used to create a VSD corresponding to the SPRS previously presented and was imported to Photopia as a lamp. A model of the previously presented AIC was also created with with AutoCAD and imported to Photopia as a luminaire.

Appendix C

Questionnaires

C.1 Optimized OLS

Questionnaire

Voici un questionnaire avec 21 questions. Veuillez prendre tout votre temps pour y répondre !

Merci d'avance !

Partie A - Questions concernant l'éclairage

Voici quelques questions concernant l'environnement lumineux de votre bureau. Veuillez cocher la réponse qui vous convient le plus (1 = oui, 2 = plutôt oui, 3 = plutôt non, 4 = non) :

(1)	J'aime la lumière dans ce bureau.	OUI 1 2 3 4 NON
(2)	En tout, l'éclairage de ce bureau est confortable.	OUI 1 2 3 4 NON
(3)	Ce bureau me semble trop lumineux.	OUI 1 2 3 4 NON
(4)	Ce bureau me semble trop sombre.	OUI 1 2 3 4 NON
(5)	Il n'y a pas assez de lumière pour bien effectuer les différentes taches.	OUI 1 2 3 4 NON
(6)	Il y a trop de lumière pour bien effectuer les différentes taches.	OUI 1 2 3 4 NON
(7)	La lumière est mal repartie dans ce bureau.	OUI 1 2 3 4 NON
(8)	L'éclairage de ce bureau cause trop d'ombre.	OUI 1 2 3 4 NON
(9)	Il y a des réflexions de lumière dans ce bureau qui m'empêche de bien travailler.	OUI 1 2 3 4 NON
(10)	Les luminaires au plafond sont trop lumineux.	OUI 1 2 3 4 NON

(11)	Ma peau apparait peu naturelle dans cette lumière.	OUI 1 2 3 4 NON
(12)	J'ai l'impression que la lumière scintille dans ce bureau.	OUI 1 2 3 4 NON
(13)	La lumière dans ce bureau est trop « chaude » pour un lieu de travail.	OUI 1 2 3 4 NON
(14)	La lumière dans mon bureau est trop « froide » pour un lieu de travail.	OUI 1 2 3 4 NON

(15) Si je compare la situation lumineuse dans ce bureau avec d'autres bureaux dans lesquels j'ai travaillé auparavant, je dirais que la situation lumineuse ici est …

<… plutôt meilleure > **<… plutôt pareille >** **<… plutôt pire >**

(16) Lors d'une journée de travail, je pourrais bien m'imaginer travailler dans cette lumière pendant …

< … moins de 2 heures > **< … 2 à 4 heures >** **< …plus que 4 heures >**

Partie B - Questions générales

Pour finir, encore quelques questions générales…

(17) Mon âge : ________

(18) **Aujourd'hui,** j'ai passé la plupart de la journée …

<… à l'extérieur > **<… dans un bâtiment >** **<… ni l'un ni l'autre >**

Si vous avez répondu « …dans un bâtiment » :
Est-ce que vous avez bénéficié de beaucoup de
lumière naturelle dans ce bâtiment?

OUI | 1 | 2 | 3 | 4 | NON

Si vous avez répondu « …ni l'un ni l'autre » : Précisez, svp !

____

____

(19) **Normalement**, je travaille …

<… à l'extérieur > **<… dans un bâtiment >** **<… ni l'un ni l'autre >**

Si vous avez répondu « …dans un bâtiment » :
Est-ce que vous avez bénéficié de beaucoup de
lumière naturelle dans ce bâtiment?

OUI | 1 | 2 | 3 | 4 | NON

Si vous avez répondu « …ni l'un ni l'autre » : Précisez, svp !

____

____

(20)	Je pense que nous devons tous faire un effort pour économiser de l'énergie.	OUI 1 2 3 4 NON
(21)	Je pense qu'on peut économiser beaucoup d'énergie en utilisant un minimum de lumière artificielle.	OUI 1 2 3 4 NON

Merci de votre participation!

C.2 General Questionnaire for Chronobiological Study

Questionnaire d'Entrée

Nom : ____________________

Prénom : ____________________

Adrèsse : ____________________

Lieu : ____________________

Numéro de téléphone : ____________ Numéro de Natel : ____________

Email Adrèsse : ____________________

Date de naissance : ____________________

Occupation : ____________________

Sexe : ____________________

Gaucher : ________ Droitier : ________

Lieu, date : ____________________

Signature : ____________________

Code :

Prière de périmètrer la vraie réponse :

Avez-vous besoin de prendre des médicaments ?	Oui	Non
Si vous êtes actuellement en traitement médical?	Oui	Non
Prenez-vous des drogues?	Oui	Non
Consommez-vous de l'alcool, et si oui, combien par semaine?	Oui	Non
Fumez-vous? Si oui, combien par jour?	Oui	Non
Etes-vous enceinte?	Oui	Non
Avez-vous travaillé la nuit pendant les trois derniers mois ?	Oui	Non
Avez-vous dans les deux derniers mois pris des voyages en avion et si oui où et quand?	Oui	Non

Pendant le mois dernier, quand êtes vous habituellement allé vous couché?

___h___min

Pendant le mois dernier, combien vous a t il habituellement fallu de temps (en minutes) pour vous endormir?

____min

3-Pendant le mois dernier, quand vous êtes vous habituellement levé le matin?

___h___min

C.3 Horne & Östberg Questionnaire for Chronobiological Study

HORNE & ÖSTBERG Nom: Prénom:

QUESTIONNAIRE DE TYPOLOGIE CIRCADIENNE DE HORNE ET OSTBERG

ATTENTION METTRE UNIQUEMENT UNE REPONSE PAR QUESTION

1. Lisez attentivement chaque question avant d'y répondre
2. Répondez à toutes les questions
3. Répondez aux questions dans l'ordre
4. Vous pouvez répondre aux questions les unes indépendamment des autres
5. Ne revenez pas en arrière pour vérifier vos réponses
6. Ne cochez qu'une seule réponse
7. Répondez à chaque question aussi sincèrement que possible.

Date :

1. Si vous viviez à votre rythme (celui qui vous plaît le plus), à quelle heure vous lèveriez-vous, étant entièrement libre d'organiser votre journée ?

5h et 6h30 du matin ☐

6h30 et 7h45 du matin ☐

7h45 et 9h45 du matin ☐

9h45 et 11h du matin ☐

11h et midi ☐

2. Si vous viviez à votre rythme (celui qui vous plaît le plus), à quelle heure vous mettriez-vous au lit, étant entièrement libre d'organiser votre journée ?

20h et 21h ☐

21h et 22h15 ☐

22h15 et 0h30 ☐

0h30 et 1h45 du matin ☐

1h45 et 3 h du matin ☐

3. Si vous devez vous lever tôt, le réveil vous est-il indispensable ?

Pas du tout ☐

Peu ☐

Assez ☐

Beaucoup ☐

1

HORNE & ÖSTBERG Nom: Prénom:

4. Dans des conditions adéquates (environnement favorable, sans contraintes particulières..), à quel point vous est-il facile de vous lever le matin ?

Très pénible ☐
Pénible ☐
Assez facile ☐
Très facile ☐

5. Comment vous sentez-vous durant la demi-heure qui suit votre réveil du matin ?

Endormi ☐
Peu éveillé ☐
Assez éveillé ☐
Tout a fait éveillé ☐

6. Quel est votre appétit durant la demi-heure qui suit votre réveil du matin ?

Pas bon du tout ☐
Pas bon ☐
Assez bon ☐
Très bon ☐

7. Comment vous sentez-vous durant la demi-heure qui suit votre réveil du matin ?

Très fatigue ☐
Relativement fatigue ☐
Relativement en forme ☐
Très en forme ☐

8. Quand vous n'avez pas d'obligations le lendemain, à quelle heure vous couchez-vous par rapport à votre heure habituelle de coucher ?

Rarement ou jamais plus tard ☐
Moins d'1 heures plus tard ☐
De 1 à 2 heures plus tard ☐
Plus de 2 heures plus tard ☐

2

HORNE & ÖSTBERG Nom: Prénom:

9. Vous avez décidé de faire du sport. Un ami vous propose une séance d'entraînement 2 fois par semaine, de 7 h à 8 h du matin. Ne considérant que le rythme qui vous convient le mieux, dans quelle forme pensez-vous être en l'accompagnant ?

Bonne forme ☐

Forme raisonnable ☐

Vous trouvez cela difficile ☐

Vous trouvez cela très difficile ☐

10. A quel moment de la soirée vous sentez-vous fatigué(e) au point de vous endormir ?

De 20h à 21h ☐

De 21h à 22h15 ☐

De 22h15 à 00h45 ☐

De 00h45 à 2h du matin ☐

De 2h à 03h00 du matin ☐

11. Vous souhaitez être au mieux de votre forme pour un examen qui vous demande un effort intellectuel intense durant deux heures.

Vous êtes entièrement libre de le passer quand vous le souhaitez. Quelle est l'heure que vous choisiriez ?

De 08h00 à 10h00 ☐

De 11h00 à 13h00 ☐

De 15h00 à 17h00 ☐

De 19h00 à 21h00 ☐

12. Si vous alliez au lit à 23 heures, à quel niveau de fatigue seriez-vous ?

Pas du tout fatigué ☐

Un peu fatigué ☐

Relativement fatigué ☐

Très fatigué ☐

3

HORNE & ÖSTBERG Nom: Prénom:

13. Pour une raison quelconque, vous vous couchez quelques heures plus tard que d'habitude, mais vous n'êtes pas obligé(e) de vous lever à une heure précise le lendemain. Laquelle des propositions suivantes choisiriez-vous ?

Vous vous réveillez comme d'habitude et vous ne vous re-endormez plus ☐

Vous vous levez comme d'habitude mais vous vous recouchez ensuite ☐

Vous vous réveillez comme d'habitude mais vous vous rendormez ☐

Vous vous réveillez plus tard que d'habitude ☐

14. Pour effectuer une garde de nuit, vous êtes obligé(e) d'être réveillé(e) entre 4 h et 6 h du matin. Vous n'avez pas d'obligation le lendemain. Laquelle des propositions suivantes vous convient le mieux ?

Vous n'irez au lit qu'une fois la garde terminée ☐

Vous faites une sieste avant et dormez après la garde ☐

Vous dormez le plus possible avant et faites une sieste après ☐

Vous dormez avant et vous ne vous recouchez pas après ☐

15. Vous devez faire deux heures de travail physique intense, mais vous êtes entièrement libre d'organiser votre journée. Laquelle des périodes suivantes choisiriez-vous ?

De 08h00 à 10h00 ☐

De 11h00 à 13h00 ☐

De 15h00 à 17h00 ☐

De 19h00 à 21h00 ☐

16. Vous avez décidé de faire du sport. Un ami vous propose une séance d'entraînement 2 fois par semaine, de 22 h à 23 h.

Ne considérant que le rythme qui vous convient le mieux, dans quelle forme pensez-vous être en l'accompagnant ?

Bonne forme ☐

Forme raisonnable ☐

Vous trouvez cela difficile ☐

Vous trouvez cela très difficile ☐

4

HORNE & ÖSTBERG Nom: Prénom:

17. Si vous deviez choisir un horaire pour travailler 5 heures consécutives, intéressant et bien payé quel que soit l'horaire, vous choisiriez ?

Entre 04h00 et 08h00 du matin ☐

Entre 8h et 9h ☐

Entre 09h et 14h ☐

Entre 14h00 et 17h00 ☐

Entre 17h00 et 04h00 du matin ☐

18. Quand vous sentez vous le plus en forme ?

Entre 05h00 et 08h00 du matin ☐

Entre 08h00 et 10h00 du matin ☐

Entre 10h00 et 17h00 ☐

Entre 17h00 et 22h00 ☐

Entre 22h00 et 05h00 du matin ☐

19. On dit parfois que quelqu'un est un "sujet du matin" ou un "sujet du soir". Vous considérez vous comme étant du matin ou du soir ?

Tout à fait un sujet du matin ☐

Plutôt un sujet du matin ☐

Plutôt un sujet du soir ☐

Tout à fait un sujet du soir ☐

Merci pour votre participation

5

C.4 Karolinska Sleepiness Scale for Chronobiological Study

Subject Code :Liper_19_01 December 08, 2009

L'échelle de somnolence du Karolinska

Veuillez indiquer votre niveau de somnolence <u>lors des 10 dernières minutes</u>

Très alerte	1
Intermédiaire	2
Alerte – normal	3
Intermédiaire	4
Ni alerte ni somnolent	5
Intermédiaire	6
Somnolent, mais aucun effort pour rester éveillé	7
Intermédiaire	8
Très somnolent, beaucoup d'effort pour rester éveillé	9

Test Number: 1

C.5 VAS-MWT for Chronobiological Study

Subject Code : Liper_19_01 December 08, 2009

Indiquez sur l'échelle suivante avec un trait, comment vous vous sentez en ce moment.

Extrêmement relaxé	______	Extrêmement tendu
Physiquement à l'aise	______	Physiquement pas du tout à l'aise
Extrêmement éveillé	______	Extrêmement fatigué
Rassasié	______	Affamé
De mauvaise humeur	______	De très bonne humeur
Extrêmement froid	______	Extrêmement chaud

Remarques :

Test Number: 1

C.6 Analog OLS for Chronobiological Study

Questionnaire 1

Voici un questionnaire avec 16 questions. Veuillez prendre tout votre temps pour y répondre !

Merci d'avance !

Subject code: Liper_23_02 **Date: 09.12.09**

Partie A - Questions concernant l'éclairage

Voici quelques questions concernant l'environnement lumineux de cette salle. Veuillez marquer votre consentement avec chaque déclaration sur la ligne correspondante.

(1) J'aime la lumière dans cette salle.

OUI ______________________________ **NON**

(2) Globalement, l'éclairage de cette salle est agréable.

OUI ______________________________ **NON**

(3) Cette salle me semble trop lumineuse.

OUI ______________________________ **NON**

(4) Cette salle me semble trop sombre.

OUI ______________________________ **NON**

(5) Il n’y a pas assez de lumière pour travailler / lire correctement.

OUI ———————————————— **NON**

(6) Il y a trop de lumière pour travailler / lire correctement.

OUI ———————————————— **NON**

(7) La lumière est mal repartie dans cette salle.

OUI ———————————————— **NON**

(8) L’éclairage de cette salle cause trop d’ombre.

OUI ———————————————— **NON**

(9) Il y a des réflexions de lumière dans cette salle qui m'empêchent de bien travailler / lire.

OUI ―――――――――――――――――――― **NON**

(10) Les luminaires au plafond sont trop lumineux.

OUI ―――――――――――――――――――― **NON**

(11) La couleur de ma peau apparait peu naturelle sous cet éclairage.

OUI ―――――――――――――――――――― **NON**

(12) J'ai l'impression que la lumière scintille dans cette salle.

OUI ―――――――――――――――――――― **NON**

(13) La lumière dans cette salle est trop « chaude » pour un lieu de travail.

OUI ———————————————— **NON**

(14) La lumière dans cette salle est trop « froide » pour un lieu de travail.

OUI ———————————————— **NON**

(15) Si je compare la situation lumineuse de cette salle avec d'autres dans lesquels j'ai travaillé auparavant, je dirais que la situation lumineuse ici est …

<… meilleure >

<… plutôt meilleure >

<… plutôt pareille >

<… plutôt pire >

<… pire >

(16) Dans le cadre d’une journée de travail, je pourrais bien m’imaginer travailler dans cet environnement lumineux pendant …

<… moins de 2 heures >

<… 2 à 4 heures >

<… 4 à 6 heures >

<… plus que 6 heures >

(17) Comment ressentez-vous l’éblouissement dans cette salle.

Juste Perceptible | **Juste acceptable** | **Juste inconfortable** | **Juste intolérable**

Imperceptible | **Perceptible** | **Acceptable** | **Inconfortable** | **Intolérable**

C.7 Visual Comfort Scale for Chronobiological Study

Subject Code :Liper_19_01 December 08, 2009

Echelle de confort visuel

Voici quelques questions concernant l'environnement lumineux de cette salle. Veuillez marquer votre consentement avec chaque déclaration sur la ligne correspondante.

(1) J'aime la lumière dans cette salle.

OUI ———————————— **NON**

(2) Globalement, l'éclairage de cette salle est agréable.

OUI ———————————— **NON**

(3) Cette salle me semble trop lumineuse.

OUI ———————————— **NON**

(4) Cette salle me semble trop sombre.

OUI ———————————— **NON**

(5) Il n'y a pas assez de lumière pour travailler / lire correctement.

OUI ———————————— **NON**

(6) Il y a trop de lumière pour travailler / lire correctement.

OUI ———————————— **NON**

(7) Comment ressentez-vous l'éblouissement dans cette salle.

Juste Perceptible | **Juste acceptable** | **Juste inconfortable** | **Juste intolérable**

Imperceptible | **Perceptible** | **Acceptable** | **Inconfortable** | **Intolérable**

Test Number: 1

Appendix D

Vertical Illuminances During DL Exposure

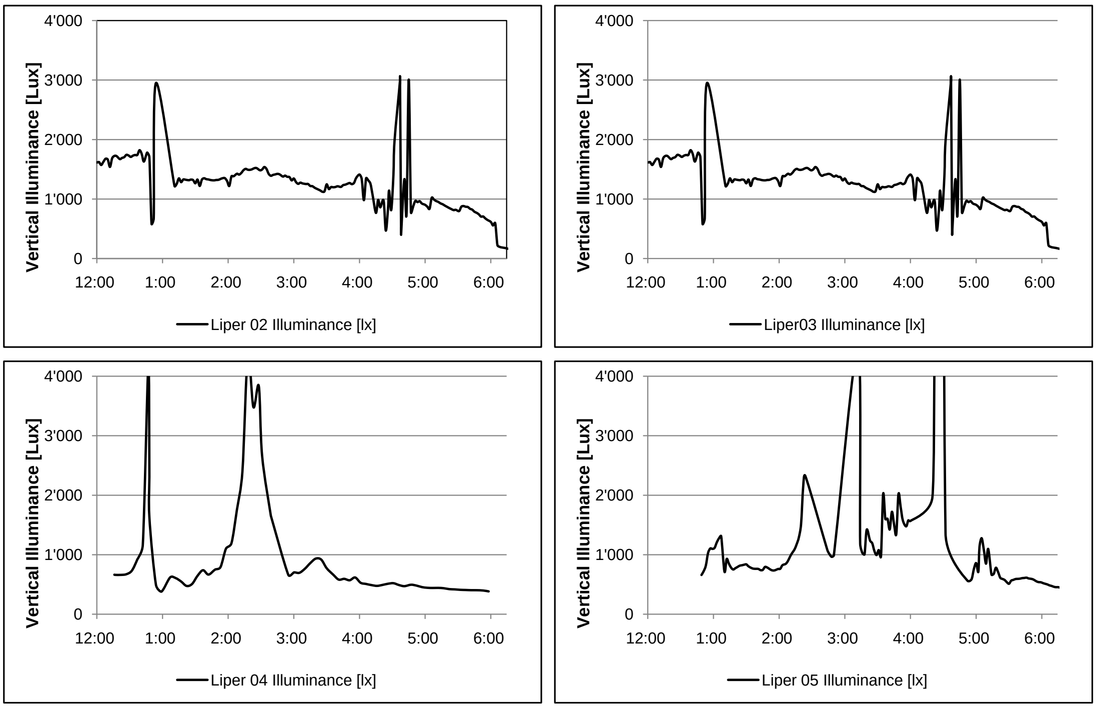


Figure D.1: Vertical illuminances 1/5. - Vertical illuminance measurements 1 to 4 measured during the chronobiological study.

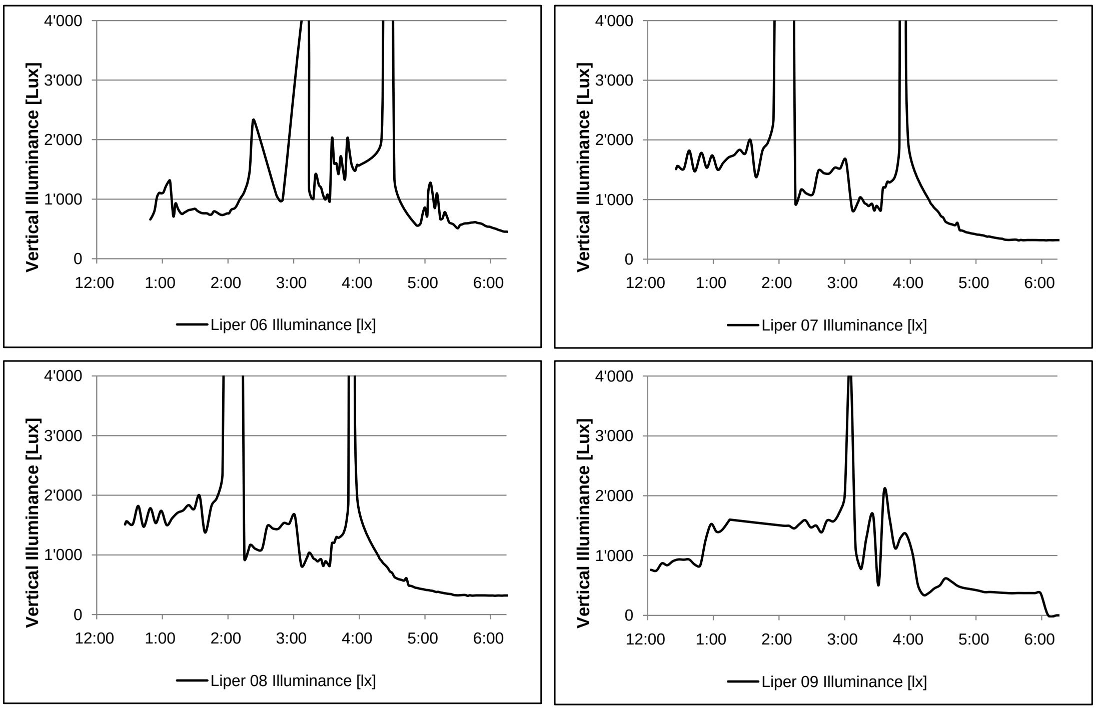


Figure D.2: Vertical illuminances 2/5. - Vertical illuminance measurements 5 to 8 measured during the chronobiological study.

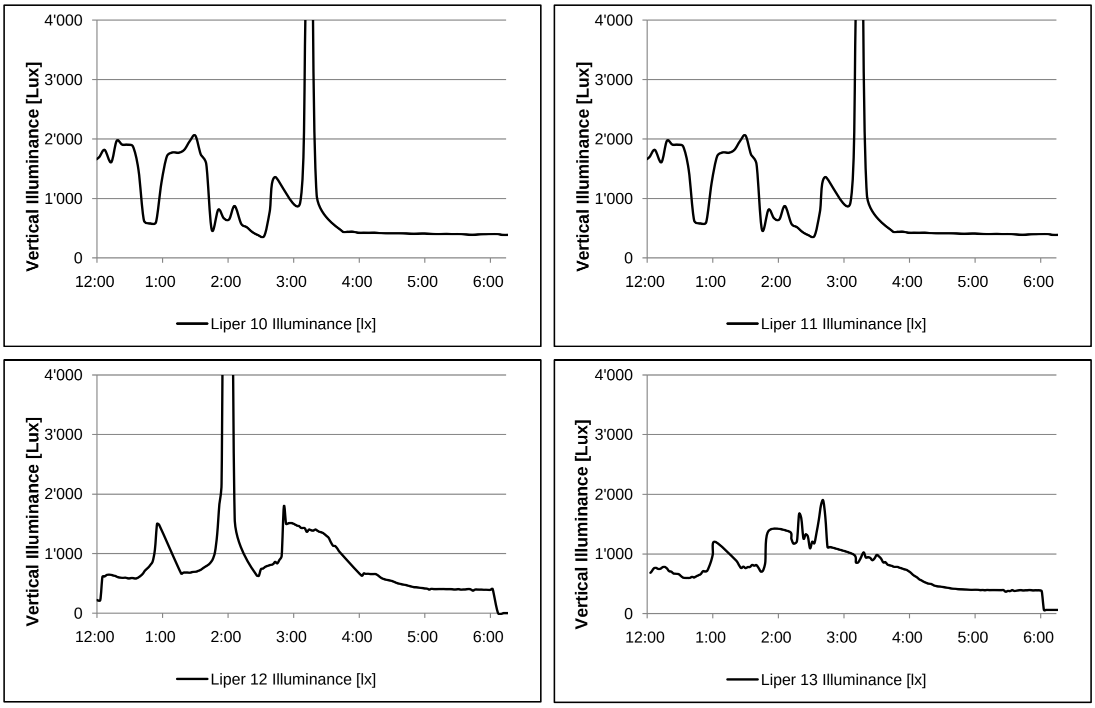


Figure D.3: Vertical illuminances 3/5. - Vertical illuminance measurements 9 to 12 measured during the chronobiological study.

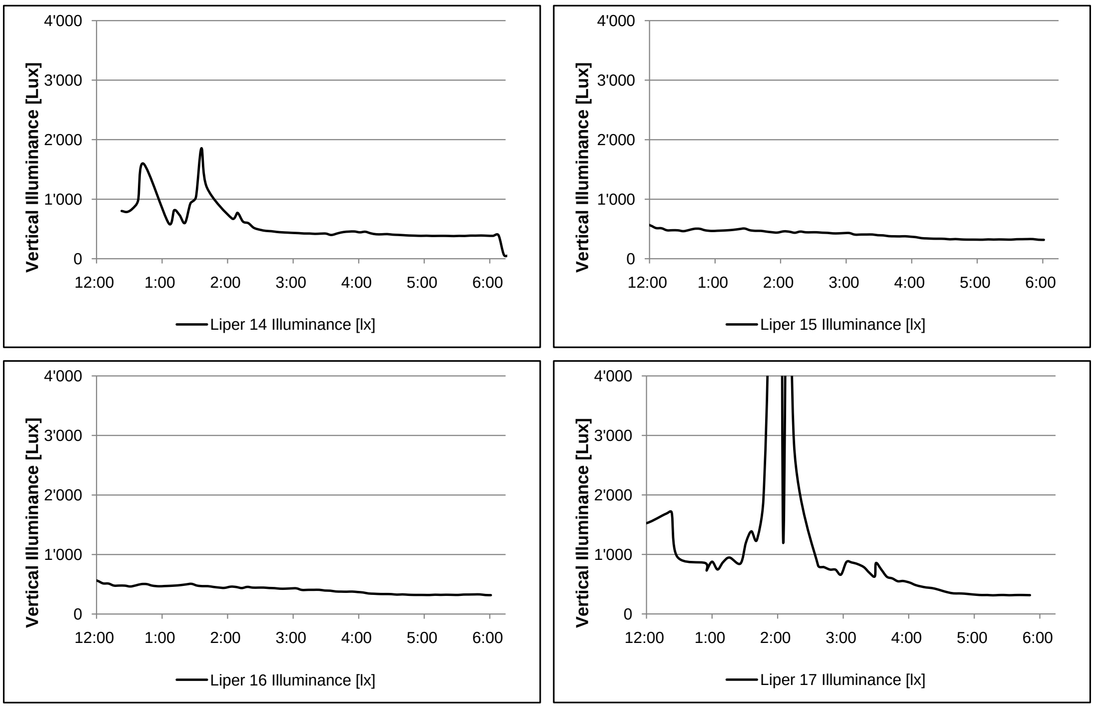


Figure D.4: Vertical illuminances 4/5. - Vertical illuminance measurements 13 to 16 measured during the chronobiological study.

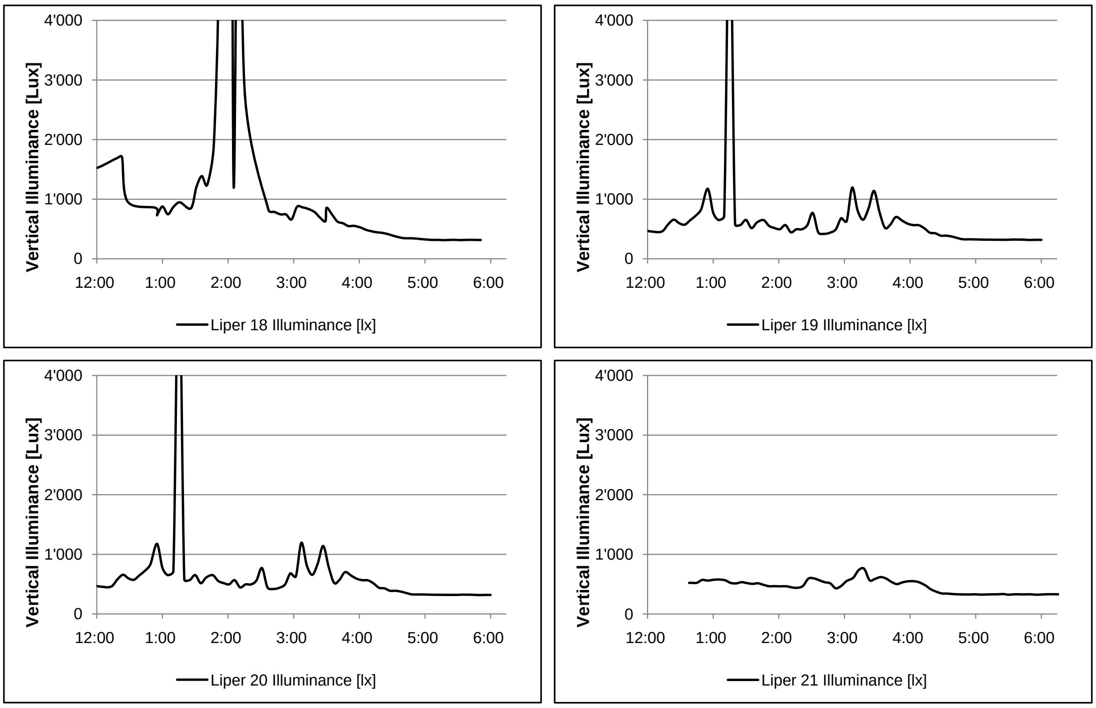


Figure D.5: Vertical illuminances 5/5. - Vertical illuminance measurements 17 to 20 measured during the chronobiological study.

Curriculum Vitae

Friedrich Linhart

Dipl.-Ing. TU Darmstadt (Electrical Engineering)

Ingénieur EC Lyon (General Engineering)

Dr ès Sciences EPF Lausanne (Environmental Engineering)

- born on 26.08.1978 in Heidelberg (D)
- married, one daughter

Fliederweg 36
D-78187 Geisingen
Germany
+49 7708 911502
friedrich.linhart@gmail.com

WORK EXPERIENCE & INTERNSHIPS

Since 03/2010	**Dres. Weiss, Arat & Stern**, Patent Attorneys, Engen (D): Technical Expert in the field of intellectual property management and Patent Attorney Candidate.
06/2006 - 02/2010	**Swiss Federal Institute of Technology in Lausanne (EPFL)** Research Assistant at the Solar Energy and Building Physics Laboratory (LESO-PB), various tasks: - **Project Work:** Design of integrated lighting solutions (daylight and artificial light) for office buildings ("Green Lighting" project, funded by the Swiss Federal Office of Energy), Assessment of the influence of different lighting scenarios on comfort, performance, mood and hormone secretion in office occupants. - **Research:** Writing of more than 15 scientific publications since 2006, presentations at various international conferences, preparation of a doctoral thesis (see „Education"). - **Teaching:** Lectures, tutorials, master thesis and internship supervision. - **Committee work:** International Energy Agency (Task „Energy efficient electric lighting for buildings"), EPFL Section Directors' Conference (CDS) (representative of non-professorial faculty)
2005	10 weeks of internship with **AT Kearney GmbH** Frankfurt: Member of an international project team working with one of Britain's leading utility companies, analysis of sales channels, requirement analysis for a future data warehouse model, project planning.
2003	8 weeks of internship with **Robert Bosch France** in Vénissieux: production process optimization, machine setup coordination, software relocations German / French, negotiations with suppliers.
2000 - 2001	Teaching assistant in the course "Engineering Drawing" at **Technische Universität Darmstadt**.
1998 - 2001	**Setup of an own company**, rental service for light and sound equipment, organization of music events.
1998 - 1999	10 months of compulsory **military service** with the German mountain infantry Berchtesgaden, facultative reserve sergeant training in spring 2000.
1998	6 weeks of internship with **ABB Kraftwerke AG**, Mannheim.

EDUCATION

06/2006 - 02/2010	Swiss Federal Institute of Technology in Lausanne (EPFL) Preparation of a doctoral thesis (Doctoral Program „Environment") entitled „Energetic, visual and non-visual aspects of office lighting".
2007	National University of Singapore 8 weeks of visiting scholarship, simulation of mirror light ducts.
1999 - 2006	Technische Universität Darmstadt Graduate studies in „Electrical Engineering and Information Technology" (Specialization „Electrical Energy Systems"), Graduation in February 2006, Final grade „very good" (1 on a scale from 1 to 4, top 5% of year).
2005 - 2006	Murdoch University Perth Master thesis in Perth/Australia: Development of a lightning protection strategy for the Rockingham PV System and design of a software tool for PV-system-specific lightning protection.
2001 - 2003	Ecole Centrale de Lyon Participation in double degree program between TU Darmstadt and Ecole Centrale de Lyon, 2 years of studies in „General Engineering Science".
1989 – 1998	High School in Heidelberg
1994	3 months at Leaside High School, Toronto (Canada)
1996	4 months at Lycée Jean Monnet, Montpellier (France)
1998	High School graduation with final grade 1.1 (top 5% of year)

LANGUAGE SKILLS

German:	mother tongue
English, French:	fluent
Spanish, Italian, Mandarin:	beginner

SOFTWARE SKILLS

All common office applications, Assembler, Turbo Pascal, Java, C, C++, Visual Basic, UML, MATLAB/ SIMULINK, AutoCAD, Relux, LabView, LESOSAI, LESOKAI, ECOTECT, Photopia, Illustrator, LATEX.

SCHOLARSHIPS

Konrad-Adenauer-Foundation (2001-2005), German-French University (2001-2003), German Academic Exchange Service (DAAD) (2005), National University of Singapore (2007).

NOMINATIONS AND SHORTLISTINGS

01/2010: Nominated for Assistant Professorship at Bern University of Applied Sciences (Switzerland) in "Photovoltaics and Electrical Engineering" (*nomination offer refused*).

01/2010: Shortlisted (last 6 out of 280 candidates) for Assistant Professorship at Stanford University (USA) in "Sustainability and the Built Environment", Seminar at Stanford University on 01.02.2010.

MEMBERSHIPS

International Solar Energy Society (ISES), International Society for Optics and Photonics (SPIE), Swiss Alpine-Club, Toastmasters International.

HOBBIES

Outdoor sports, backpacking, skiing, triathlon, scuba diving, playing music (guitar and harmonica).

SCIENTIFIC PUBLICATIONS

Published:

Linhart, F., Wittkopf, S. K. and Scartezzini, J.-L.: Performance of Anidolic Daylighting Systems in tropical climates - Parametric studies for identification of main influencing factors. Solar Energy (2010). doi:10.1016/j.solener.2010.01.014

Linhart, F. and Scartezzini, J.-L.: Minimizing lighting power density in office rooms equipped with Anidolic Daylighting Systems. Solar Energy 84 (4), pp. 587-595, 2010. doi:10.1016/j.solener.2009.05.001

Wittkopf, S. K., Grobe, L. O., Geisler-Moroder, D. Compagnon, R., Kämpf, J., Linhart, F. and Scartezzini, J.-L.: Ray tracing study for non-imaging daylight collectors. Solar Energy (2010). doi:10.1016/j.solener.2010.03.008

Linhart, F. and Scartezzini, J.-L.: Green Lighting: Energy-Efficient Integrated Lighting Systems. Technical Report for the Swiss Federal Office of Energy, Research Program "Energy in Buildings", 2009. http://www.bfe.admin.ch/php/modules/enet/streamfile.php?file=000000010382.pdf&name=000000290192

Linhart, F., Scartezzini, J.-L. and Münch, M.: Ocular daylight exposure in office rooms equipped with Anidolic Daylighting Systems. Conference proceedings of "CISBAT 2009", Lausanne, 2009.

Linhart, F. and Scartezzini, J.-L.: Recent achievements in research and technological development on high performance integrated lighting systems. Conference proceedings of "CISBAT 2009", Lausanne, 2009.

Davila Alotto, F., Linhart, F. and Scartezzini, J.-L.: CIE standard skies in Switzerland: relative occurrence and impact on daylighting system performance. Conference proceedings of "CISBAT 2009", Lausanne, 2009.

Linhart, F., Wittkopf, S.K., Münch, M. and Scartezzini, J.-L.: Recent Research on Anidolic Daylighting Systems: Highly Reflective Coating Materials and Chronobiological Properties, Conference Proceedings of „SPIE Optics and Photonics 2009", San Diego, 2009. Invited Paper. doi:10.1117/12.826136

Linhart, F., Wittkopf, S.K. and Scartezzini, J.-L.: Splitting up anidolic daylighting systems. Invited article in SPIE Newsroom, 2009. doi:10.1117/2.1200908.1743

Münch, M., Linhart, F. and Scartezzini, J.-L.: The built environment and the human response to (day-) light. Conference Proceedings of "21st Annual Meeting of the Society for Light Treatment and Biological Rhythms 2009", Berlin, 2009.

Linhart, F. and Scartezzini, J.-L.: Occupant satisfaction in office rooms equipped with Anidolic Daylighting Systems. Conference Proceedings of „EUROSUN 2008", Lisbon, 2008.

Linhart, F. and Scartezzini, J.-L.: Energieeffiziente Bürobeleuchtung - Das Projekt "Green Lighting". Conference Proceedings of „Status-Seminar 2008", pp. 155-162, Zurich, 2008. www.brenet.ch/pdfstat_2008/03_ht_e_linh.pdf

Linhart, F. and Scartezzini, J.-L.: Efficient lighting strategies for office rooms in tropical climates. Conference Proceedings of „PLEA 2007", pp. 360-367, Singapore, 2007.

Linhart, F. and Scartezzini, J.-L.: **Green Lighting project focuses on energy-efficient offices.** Invited article in SPIE Newsroom, 2007. doi:10.1117/2.1200708.0843

Linhart, F. and Scartezzini, J.-L.: **Minimizing connected lighting power in office rooms equipped with Anidolic Daylighting Systems.** Conference Proceedings of „CISBAT 2007“, pp 421-426, Lausanne, 2007 (Article selected for special issue „CISBAT 2007“ of the journal „Solar Energy“).

Scartezzini, J.-L., Linhart, F. and Kaegi-Kolisnychenko, E.: **Optimal integration of daylighting and electric lighting systems using non-imaging optics.** Conference Proceedings of „SPIE Optics and Photonics 2007“, San Diego, 2007.

Linhart, F., Calais, M., Cole, G. and Hinrichsen, V.: **Design of a software tool for PV-system-specific lightning protection.** Conference Proceedings of „ANZSES 2006“, Canberra, 2006.

Submitted for publication:

Linhart, F. and Scartezzini, J.-L.: **Evening Office Lighting: Visual Comfort vs. Energy Efficiency vs. Performance?** Manuscript submitted to Building and Environment Journal, 2010.

Borisuit, A., Linhart, F., Scartezzini, J.-L. and Münch, M.: **Effects of two different office lighting conditions on subjective alertness and visual comfort in young volunteers.** Abstract submitted to Design and Health 7th World Congress & Exhibition 2011, Boston.

TALKS AND POSTER PRESENTATIONS

Von Integrativer Lichtplanung und Nachhaltiger Bürobeleuchtung. Seminar at „Future Light“ meeting, Lucerne University of Applied Sciences, 11.03.2010.

From „Green Lighting“ to „Zero Energy“ – Recent Trends in Sustainable Building Design. Demonstration lesson at Stanford University, 01.02.2010.

Trends im Bereich der Photovoltaik – Relevanz für angewandte Forschung und Praxis. Demonstration lesson at Bern University of Applied Sciences, 14.01.2010.

Recent achievements in research and technological development on high performance integrated lighting systems. Talk at conference „CISBAT 2009“, Lausanne, 02.09.2009.

Ocular daylight exposure in office rooms equipped with Anidolic Daylighting Systems. Poster presentation at conference „CISBAT 2009“, Lausanne, 02.09.2009.

Recent Research on Anidolic Daylighting Systems: Highly Reflective Coating Materials and Chronobiological Properties. Invited Talk at conference “Optics & Photonics 2009”, San Diego, 03.08.2009.

Ocular daylight exposure in office rooms equipped with Anidolic Daylighting Systems. Poster presentation at „EUCLOCK 2009 annual conference“, Frauenchiemsee, 26.01.2009.

Occupant satisfaction in office rooms equipped with Anidolic Daylighting Systems. Talk at conference „EUROSUN 2008“, Lisbon, 09.10.2008.

Energieeffiziente Bürobeleuchtung - Das Projekt "Green Lighting". Talk at conference „Status-Seminar 2008“, Zurich, 11.09.2008.

Energetic, visual and non-visual aspects of office lighting. Poster presentation at „EPFL Research Day 2008“, Lausanne, 15.04.2008.

Efficient lighting strategies for office rooms in tropical climates. Talk at LESO Lunchtime Lectures, Lausanne, 04.04.2008.

Efficient lighting strategies for office rooms in tropical climates. Talk at conference „PLEA 2007“, Singapore, 23.11.2007.

Optimal integration of day- and electric lighting systems using non-imaging optics. Talk at the 6th Expert meeting of IEA ECBCS Annex 45 „Energy-efficient electric lighting“, Lyons, 03.10.2007.

Présentation du projet OFEN/URE "Green Lighting". Talk at SFOE-Session, Lausanne, 10.09.2007.

Minimizing connected lighting power in office rooms equipped with Anidolic Daylighting Systems. Talk at conference „CISBAT 2007“, Lausanne, 05.09.2007.

Lighting Research at the Solar Energy and Building Physics Laboratory (LESO-PB) - Overview and selected example. Talk at the 5th Expert meeting of IEA ECBCS Annex 45 „Energy-efficient electric lighting“, Brussels, 19.04.2007.

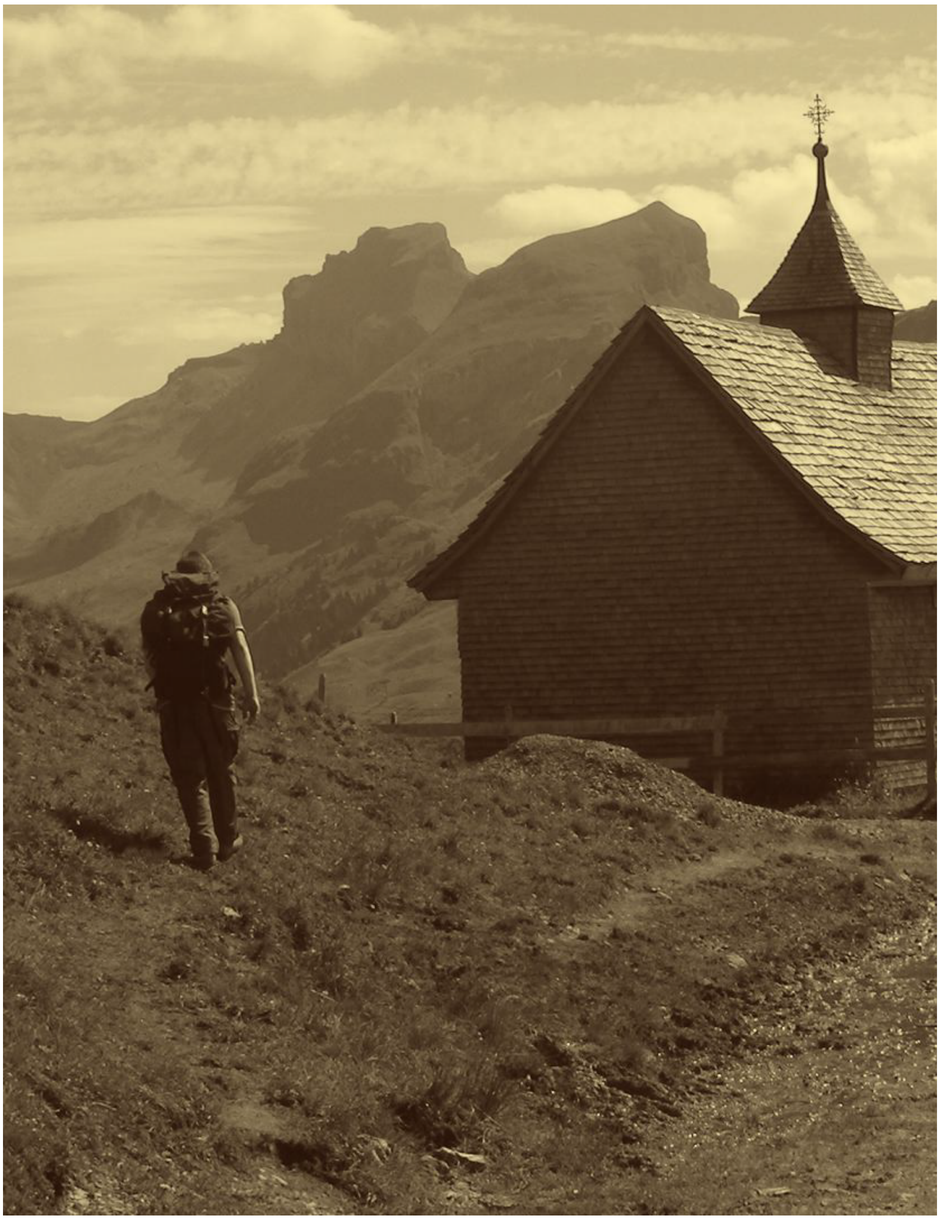
Design of a software tool for PV-system-specific lightning protection. Talk at conference „ANZSES 2006“, Canberra, 14.09.2006.

SUPERVISED STUDENT PROJECTS

Davila Alotto, F. (Politecnico di Torino): CIE standard skies in Switzerland: relative occurrence and impact on daylighting system performance. Master Thesis at LESO-PB, supervised from 09/2008 through 02/2009.

Gabrani, A. (Delhi College of Engineering): White LEDs for Office Lighting: technical background, available products and possible integration. Internship at LESO-PB, supervised in 07/2007.

Nun aber bleiben Glaube, Hoffnung, Liebe, diese drei;
aber die Liebe ist die grösste unter ihnen.
1.Korintherbrief 13.13



Im Andenken an meinen lieben Bruder

Georg Wolfgang Linhart

*13.11.1982 †25.11.2008