Proceedings

EXPERIENCING LIGHT 2009

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International Conference on the Effects of Light on Wellbeing

Y. A. W. de Kort, W. A. IJsselsteijn, I. M. L. C. Vogels,
M. P. J. Aarts, A. D. Tenner, & K. C. H. J. Smolders (Eds.)

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Preface

Perhaps Led Zeppelin said it best when they sang "Everybody needs the light". It is hard to overestimate the importance that light has for the human condition. From the comforting atmosphere of a quietly lit living room, to the invigorating effects of morning light, preparing you for your day, light has dramatic effects on mood, health and productivity, and can deeply influence the way we experience an environment. Biologists acknowledge the powerful influence that Earth's 24-hour light–dark cycle has on the behaviour and physiology of animals and humans that evolved on this planet. Psychiatrists and clinical psychologists, treating patients for sleep disorders or seasonal affective disorders, can attest to the importance of light for psychological wellbeing. Human factors professionals too recognise light as a significant factor in people's health, performance, and safety in a variety of contexts, including factories, offices, schools, and homes. Artists - from Golden Age painters to modern day cineasts - all have been keenly aware of the aesthetic and emotional impact light has on our experience of art; its power to create mood, suspense and mystery, to capture our gaze, and to challenge our curiosity. Similarly, in architecture and urban planning, the importance of getting the lighting right, whether from natural or artificial sources, is generally acknowledged. The right light enhances and improves a space; bad lighting degrades it. Light has the power to transform the social context, creating zones of safety and comfort, making spaces more visible, more agreeable, more habitable, and stimulating social interactions. In short, light is fundamental to the quality of life.

Experiencing Light 2009 was the first international conference that has as its sole focus the effects of light and light design on human wellbeing. It approaches wellbeing in its broadest sense, including mood, emotions, subjective and objective health, comfort, atmosphere perception, productivity and performance. Rapid developments in lighting technology are allowing for intelligent and interactive lighting designs, dynamically illuminating public and private spaces, and embedding light in consumer electronic devices, information displays, artistic objects, and clothing. Experiencing Light 2009 provided a timely and necessary international forum to discuss the impact of such recent technological developments on user experience. Experiencing Light 2009 builds on the rich multidisciplinary tradition in lighting research and design, with inputs from perception research, environmental psychology, human factors, architecture, lighting design and industrial design.

Experiencing Light 2009 was organized as a two-day scientific event in Eindhoven on 26-27 October 2009. In addition to our exciting keynotes, Jim Tetlow and Martine Knoop, the program of Experiencing Light 2009 consisted of a number of selected presentations, both oral and in interactive poster format, on new research and findings, new conceptualizations and designs, and new reflections on light and its psychological impact. The full papers you find in these Proceedings were selected from the large collection of submitted papers through a carefully conducted review process, using blind peer-review. We are greatly indebted to the members of the Scientific Committee for their excellent work in reviewing the submitted papers and selecting the best papers for presentation at the conference. Short papers that accompany the interactive posters can be found in the Adjunct Proceedings.

Experiencing Light 2009 was hosted by the Eindhoven University of Technology (TU/e), in Eindhoven, The Netherlands, as a joint effort between the Human-Technology Interaction (HTI) Group of the Department of Industrial Engineering and Innovation Sciences (IE&IS), the Department of Architecture, Building, and Planning, and Philips Research. It is no coincidence that Experiencing Light was initiated in Eindhoven. Eindhoven has a particularly rich history as a City of Light. Starting at the beginning of the previous century with the mass production of light bulbs at Philips, it is now a major science, technology, and design hub, home to Philips Lighting, Philips Design, and Philips Research, Eindhoven University of Technology, TNO (Dutch Organisation for Applied Scientific Research), SOLG (Light and Health Research Foundation), and the Design Academy. The city hosts a range of light-oriented events, such as the annual "Lichtjesroute" (Route of Lights) and the international light festival GLOW – Forum of Light in Art and Architecture. A recent collaborative initiative to establish a Technological Top Institute Light (TTIL) in Eindhoven provides a further significant impulse to the joint efforts of the university, industry, and government in the area of lighting science, technology, and design.

We gratefully acknowledge the sponsors of Experiencing Light 2009: TU/e, HTI, TTIL, the city of Eindhoven, KNAW (Royal Dutch Academy of Sciences), Philips Research, and Davita. Moreover, we would like to thank all of those who supported the organization of Experiencing Light 2009 and who worked hard to make it a successful event, including Atike Pekel, who designed the beautiful website (http://www.experiencinglight.nl/) and conference materials, our secretarial and logistics support, and our student volunteers. Thank you all.

October 2009

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Contents

KEYNOTE LECTURE

Creating and Altering Perceptions with Lighting
or
How to Sell with Light

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ABSTRACT

A look at how a practicing lighting designer establishes and modifies people's perceptions of environments, products and people through the craft of lighting.

INTRODUCTION

Perception can be defined as “the process of attaining awareness or understanding from sensory information”. Through the sense of sight, we can use lighting to influence people’s perception of spaces and objects, and as a working lighting designer, that is what I’m called upon to do in many circumstances.

The presentation shall consist of several case studies, which will include a combination architectural/exhibit project, several highlights from theatrical introductions of new automobiles, and the American Presidential Debates. The common theme of these different projects is that lighting, in conjunction with other disciplines, is used as a sales tool, whether it is for products or presidential candidates.

To illustrate how lighting can be used to alter the perception of an environment, I would like to discuss the Hewlett Packard Exhibit at The International Telecommunication Union, or ITU conference, which is the major exhibit and conference for the telecommunications industry. As is typical of these large international exhibits, the convention floor environment was noisy, crowded, and certainly not a conducive environment for having a serious conversation with a potential client. Contrary to the typical exhibit booth at the ITU, Hewlett Packard wanted to create a different environment. One where their potential clients perceive that they have been transported away from the crowded and noisy convention floor to a much calmer space where they could hold private meetings and provide hospitality. To accomplish this, a two storey structure was fabricated with an exhibit space on the ground floor and a hospitality lounge and private meeting rooms on the first floor. The lighting for this project was architectural in style, but needed to be installed and dismantled rapidly. Lighting was used for establishing the exterior of the exhibit structure as a landmark that could be seen from far away in the large convention hall. It was also used to create a sense of privacy for the hospitality lounge and intimacy for the meetings rooms and adjoining hallways.

To illustrate how lighting can be used to enhance our perception of products, I would like to discuss the lighting of several product launches in the automobile industry. Every year, the major automobile manufacturers introduce dozens of new car models. In order to get the public excited about their new products, the first step is to make the employees and salesman excited about what they will be selling. This is especially true in dealerships where a more than one brand of automobile is sold. Each brand needs to make their product more attractive than the next and in an era where many of the products are very similar in performance and appearance; it is the perception of the product that becomes important as a sales tool. Contrary to the architectural style of lighting used for the Hewlett Packard exhibit, these product launches are real shows, many times incorporating dancers and special effects. Specific examples will be shown from productions for Mercedes Benz and Toyota.

Every four years America has a presidential election and for the past 20 years the Presidential Debates have been a critical part of the election process. Produced by the non-partisan Commission on Presidential Debates, these forums are the only opportunity that voters have to see and hear the two candidates speaking with each other. There are normally three presidential debates and one vice-presidential debates produced in several different formats. The goal of the Commission is to provide a neutral environment where each candidate can be comfortable and present themselves and their platform to the American people. For the candidates, this is a critical opportunity to shape the public’s perception of themselves and their beliefs, and to that end each candidate’s team is constantly striving for the upper hand. The lighting is different from any of the previous examples in that it is essentially portrait lighting for television. The solution is simplistic but flexible enough to provide the ability to make each candidate appear their best. As one might expect, the most interesting part of this project is not the lighting, but the politics.

BIO

Jim Tetlow is a theatre consultant, television and theatrical lighting designer, and principal of Nautilus Entertainment Design, based in San Diego, California. He was Lighting Designer for the US Presidential Debates, and lighting consultant for many of the Obama Inaugural Events.

Jim Tetlow is a graduate of Carnegie Mellon University and has been working as a lighting designer and consultant for television, theatre, and architecture since 1975. He has been the recipient of an Emmy Award, won in 1990 for Sesame Street, two other nominations, and a 1985 Monitor Award for a music video with Jim Henson's Muppets.

He has been referred to as the guru of entertainment systems design for his work on 29 ships for various brands of the Carnival Corporation cruise ship fleet. He has also worked extensively as a lighting designer on corporate videos and live theatrical productions for such clients as General Motors, Hewlett-Packard, Daimler-Chrysler, Mercedes Benz, Nissan, Porsche, Michelin, Polaroid, IBM, and an interactive live/video presentation with Mummenschanz for AT&T.

KEYNOTE LECTURE

Experiencing LED: Let music lead the way?

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ABSTRACT

LEDs seem to be the promising light sources of today and tomorrow. They are small, offer high brightness and saturated colours. Due to the fact that it is a revolutionary different light source, new possibilities in experiencing light are assumed, but difficult to pin point. The presentation will look into the evolution of another technology, showing similarities in origin and experience, but being in a later stage of development. Can we learn from this? Can we expect experiences that go beyond those that we are used to, using LED technology?

INTRODUCTION

LEDs seem to be the promising light sources of today and tomorrow. They are small, offer high brightness and saturated colours. Due to the fact that it is a revolutionary different light source, new possibilities in experiencing light are assumed, but difficult to pin point down.

The presentation will look into the evolution of the technologies related to experiencing sound and experiencing light. These technologies show similarities in development as well as the way to experience it. It is postulated that a flashlight is the equivalent of a ghettoblaster and visiting a concert is comparable to heliotherapy. In the same line of thought, one could consider that the work of Olafur Eliasson can be compared with classical music, whereas Dan Flavin and James Turell could be seen as rock star equivalents.

Experiencing sound has changed over time due to the development of technology. Due to recording and reproduction possibilities it already shifted from a public only, occasional experience to a – in general – more private, for everyone available, experience. The most recent and revolutionary developments though have been in digital recording, with the development of digital audio file formats, processors capable and fast enough to convert the digital data to sound in real time, and inexpensive mass storage. This again has lead to development of small music devices containing an enormous amount of pieces of music. The LED offers similar possibilities. It is a very small source and, due to it's dim and color characteristics, it gives the opportunity to realize an enormous amount of light settings. The comparison of both technologies shows that 'sound' seems to be ahead of 'lighting'. As we have seen a change in sound experience due to technology development, the question is raised whether we can expect a similar change in experiencing light.

The presentation will discuss the key learnings of the latest technology development and it's effect on the experience of sound. It will present the opportunities as well as the drawbacks and risks of adopting the 'sound' achievements into lighting practice. Resulting, it will discuss whether we can expect lighting experiences that go beyond those that we are used. Or is the the knowledge gathered from this related technology and experience actually not applicable?

The concluding part of the presentation will evaluate the conclusions drawn from the above mentioned analysis in view of social changes as well as changes in specific applications, such as offices and elderly homes. Interestingly enough, even in a broader perspective, there seems to be a similarity in experiencing sound and experiencing light. In this view, it will be discussed if LED, possibly combined with OLED, will be the single lighting source(s) used in the (near) future, or will we reach out to the old fashioned 'CD equivalent' more often then we think?

BIO

Martine Knoop is a senior application specialist at the LiDAC International (Lighting Design and Application Center) of Philips Lighting in Eindhoven, the Netherlands. After studying architecture and building physics at Delft University of Technology, her PhD dealt with day lighting systems, glare from daylight and acceptance studies in day-lit rooms.

Martine Knoop worked in Berlin for the Marketing department of a manufacturer of luminaires and lighting controls for four years. After this she started at Philips, and was also part-time visiting professor at Eindhoven University of Technology, July 2005 till December 2008. In this position she focused on the balance of light requirements for human beings and possibilities offered by technology and architecture.

Martine Knoop now focuses on lighting solutions for physical and mental wellbeing.

Influence of Ambient Lighting in Vehicle Interior on the Driver's Perception

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INTRODUCTION

Ambient interior lighting for vehicles is an issue of dramatically growing relevance in the automotive industry. In the last decade the number of light sources in the car interior providing this illumination has drastically increased. A steadily growing amount of cars in the high and middle class segments are equipped with such lighting.

Ambient lighting provides an indirect illumination of the passenger compartment in low light settings, such as during the night. Its importance lays in the fact that it provides a better orientation in the car, an improved sense of spaciousness, as well as an impression of safety, value and comfort. Furthermore it conveys an emotional and brand-oriented atmosphere to the otherwise dark car interior at night. Moreover, ambient lighting can harmonise the luminance level between the vehicle interior and the external environment, thus decreasing the driver's fatigue when driving at night [20]. Ambient lighting does not perform a pure functional role and therefore it can be designed in any colour, since it does not require a high colour rendering. Indeed, car makers use different colours also in order to give a branded image of the car interior.

It is important to notice that since ambient lighting is an indirect illumination, the materials upon which it reflects acquire new value and quality. Night design thus plays a central role, since the materials and the lines of the car interior are visible not only during daytime but at night too. On the other hand, disability and discomfort glare caused by ambient lighting should be avoided, in order not to impair vision and decrease safety during drives at night.

MOTIVATION

Previous studies by Grimm [7] proved that disability and discomfort glare originating from ambient lighting can be eliminated by keeping maximum luminance under 0.1cd/m². In this way, negative effects on the safety can be neglected.

Studies by Schellinger et al. [15] and Klinger and Lemmer [11] stated that the driver's contrast vision won't be negatively affected by ambient lighting, if the driver can control its brightness.

Other studies on vehicle interior lighting addressed the issue of possible glare caused by reading lamps or dome lights through veiling luminance and unwanted mirror effects [3] [14].

However, there are no guidelines which indicate how to correctly and consequently arrange ambient lighting in the car interior in order to maximise its positive effects. In fact, this procedure is based nowadays upon experts' personal judgement.

Many studies investigate the effects of lighting on mood [12] [13], emotions [6] and perceptions [8] [18], within the scope of lighting design in buildings and in office-environments. Of interest in this study is if such effects can be caused even in the relatively small environment of the vehicle and with such small luminance levels as in the case of ambient lighting.

Thus, in order to fully understand the advantages of ambient lighting in relationship to its characteristics and parameters, an experimental research study has been conducted and will be presented in this paper.

METHOD

In an immersive virtual test environment, 31 test persons had the task of "driving" a real stationary vehicle on a virtual highway. In the vehicle, a different ambient lighting scenario was displayed in each run. In total twelve different scenarios were tested, in which the following parameters were varied: light colour, luminance and position.

Experimental Setup

The test took place in a static driving simulator at the BMW Group research centre [9]. The choice of using a simulator environment rather than leading the test on real streets gave a complete control on the environmental variables, guaranteed the repeatability of the experiment, and thus increased the significance of the results.

A BMW 3 Series equipped with special interior light features was used for the experiment. It was connected to the simulator in a way that allowed the driver to steer the car but not to accelerate and brake (a collision with the preceding vehicle was impossible because of the control mechanisms in the driving simulation software). The driving simulation was projected on three screens placed in front and around the car, which covered a viewing angle of about 135°. In the simulator room, an ambient luminance between 0.01 cd/m² and 0.1 cd/m² was present, which caused a mesopic visual adaptation. The luminance level on the simulated street lane was between 0.1 cd/m² and 1.5 cd/m², a range of values which matches the measured street luminances in reality [1] [2] [16] [19].

Test subjects

The investigation took place with 31 participants, 8 women and 23 men, between 21 and 58 years-old (mean age 35 years). 18 of them had already experienced ambient lighting while driving. 14 of them wore glasses or contact lenses. For each participant the experiment lasted 1.5 to 2 hours.

Execution of the test

After the execution of the Ishihara Colour Vision Test [10] (all the participants had a good colour vision) the room was darkened. The test persons had 10 minutes for dark adaptation. During this time the investigator described the objectives and the methods of the research. Afterwards the participants drove the vehicle a few minutes on the simulator in order to become familiar with its steering feeling. After this period of adaptation the test started.

The investigator sat in a separated room and communicated with the test persons through a radio. After he started the simulation, the vehicle accelerated to 100 km/h and then remained at this speed. During the acceleration the appropriate lighting scene was activated and then maintained for 3 minutes. Meanwhile, the participants drove according to their main task, which was to follow a car on the right highway lane. Since the attention of the test persons was focused on the driving task, the ambient lighting was only perceived peripherally, as in reality.

Each minute the participants were asked to accomplish a secondary task. The aim of these tasks was to give the test persons the possibility to evaluate the functionality of the current lighting situation in enabling normal actions that take place while driving. For example, typical secondary tasks were the adjustment of the climate ventilation nozzles or the finding and operation of a specific control button. When the driver was unable to accomplish the secondary task, he was allowed to refuse it.

After 3 minutes, the ambient lighting was turned off and the vehicle was stopped by the investigator and brought on the side-strip. The participants then completed the questionnaire relating to the perceived lighting scenario. This process was repeated with all twelve lighting scenarios, which were presented in random order to each test person.

Ambient Lighting Scenarios

In the test vehicle twelve different ambient lighting scenarios were realised (Table 1). Three parameters were varied: colour, position of the lighting sources and luminance, as described in Table 2.

Table 1 Description of the tested lighting scenarios

Nr.	Lighting Scenario
1.	Everything on – bright level with accents
2.	Series (Centre console + Door trims)
3.	Doors – bright level
4.	Doors – low level
5.	Without lighting
6.	Everything on – bright level
7.	Everything on – low level
8.	Everything on – middle level
9.	Foot space – bright level
10.	Foot space – low level
11.	Centre console
12.	Everything on blue – low level

Table 2 Experimental parameters

Parameter	States
Colour	Orange (605 nm)
	Blue (471 nm)
Position	Centre console
	Doors
	Foot space
	Series (Centre console + Door trims)
	Complete
Mean luminance	Bright (more than 0.04 cd/m²)
	Middle (0.02 – 0.01 cd/m²)
	Low level (0.007 cd/m²)

The lighting colours presented in the test were orange and blue, with dominant wavelengths of 605 nm and 471 nm respectively. Lighting positions were selected among the ones commonly adopted in practice in the automotive industry. The centre console light is placed inside the roof node and illuminates the centre console area, where usually the gear selector lever and the controls for entertainment and conditioning are placed. Foot space lighting was realised with two LEDs placed in the cockpit, on both the driver and passenger sides. The illumination of each door consists of four LEDs and two light guides, which combined provide a homogeneous coverage of the door handles and of the upper part (door trims) and lower part (map case) of the door.

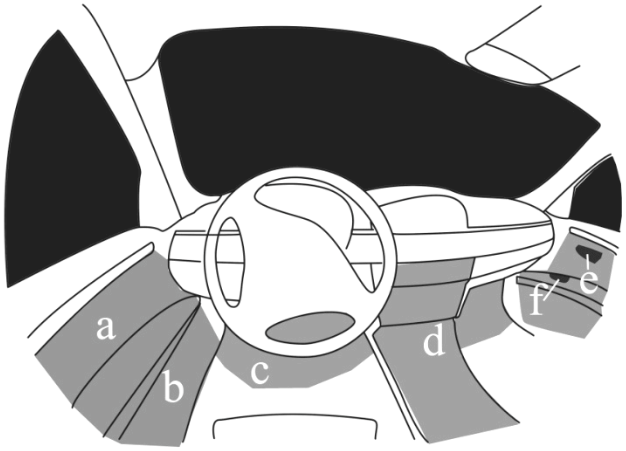


Figure 1 Positions of the ambient lighting. a. door trim, b. map case, c. foot space, d. centre console. With e. and f. the accents on the right door are highlighted (door handle and door pull respectively)

The combination of door trims and centre console lighting are a common setting in series vehicles and therefore was named series lighting. The setting "everything on" included all the above-mentioned lighting fixtures properly adjusted so that they could provide a homogeneous appearance. The setting "everything bright – with accents" provided a few additional points (door handles and pulls) with higher luminance (up to 2 cd/m²).

Cockpit instruments, display lighting and backlit symbols were always turned on, as in a real night drive situation. Anyway their luminosity level was constant during the whole research.

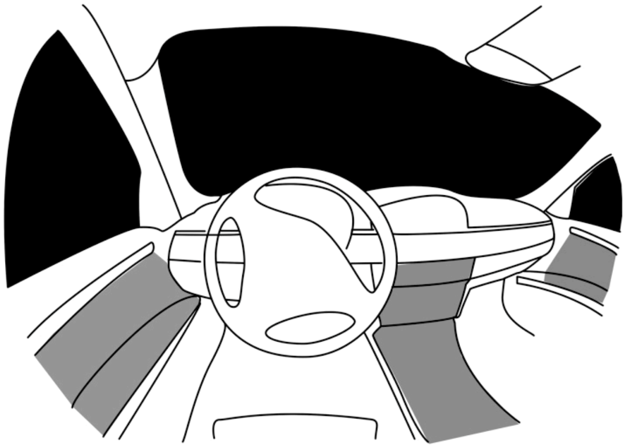


Figure 2 Example of lighting scenario: series setting - centre console and upper door trims are on.

Luminance Measurements

The luminance of the lighting fixtures in the vehicle was measured using a luminance camera provided with fish-eye optic (LMK Mobile Advanced, TechnoTeam, Ilmenau / Germany). In this way, the brightness in the whole field of view could be measured from the driver's perspective. The visual field has been divided into 4 zones (Figure 3). In these 4 zones, only the measure points with a photopic luminance between 0.003 cd/m² and 0.5 cd/m² have been considered. These areas can be considered illuminated by ambient lighting. Luminances below the 0.003 cd/m² have been considered dark, while those above the 0.5 cd/m² have been considered symbol lighting, and so not to be measured together with ambient lighting. In Table 3, the mean luminances L_M for these areas are displayed.

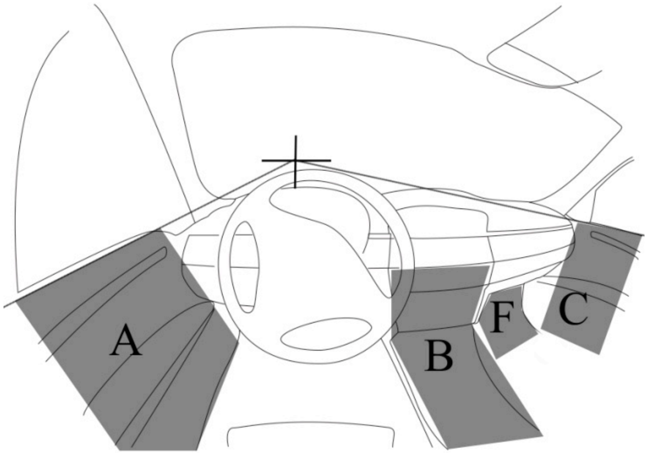


Figure 3 Luminance measure zones. A: left door; B: centre console; C: right door; F: foot space.

Table 3 Mean Luminance L_M for the different measure zones and the different lighting scenarios [cd/m²].

Scenario	1	2	3	4	5	6
A	0.023	0.009	0.023	0.022	-	0.023
B	0.012	0.011	0.009	-	-	0.010
C	0.023	0.006	0.029	0.017	-	0.026
F	0.008	-	-	-	-	0.008
Scenario	**7**	**8**	**9**	**10**	**11**	**12**
A	0.021	0.015	-	-		0.028
B	0.008	0.010	-	-	0.010	0.013
C	0.017	0.017	-	-	-	0.016
F	-	-	0.008	0.004	-	-

Since the lit area changes with the intensity of the illumination, the solid angle under which the area is seen by the driver (Ω) has also been calculated. The product of the solid angle and the mean luminance $L_M\Omega$ for each considered zone, displayed in Table 4, gives the eye illuminance, measured in the direction of the area.

Cockpit lighting as well as backlit symbols have not been considered in the measures, since they did not vary in intensity for the whole experiment.

Table 4 Eye illuminance (measured in the area's direction)($L_M\Omega$) values for the different measures zones and the different lighting scenarios [10^{-3} cd·sr/m²].

Scenario	1	2	3	4	5	6
A	3.17	0.65	2.60	0.62	-	2.64
B	0.71	0.50	0.04	0.03	0.02	0.54
C	1.11	0.05	0.91	0.31	-	0.92
F	0.27	-	-	-	-	0.27
Scenario	**7**	**8**	**9**	**10**	**11**	**12**
A	0.63	1.41	0.01	-	-	0.86
B	0.13	0.49	0.03	0.03	0.48	0.69
C	0.31	0.48	0.01	-	-	0.37
F	0.05	0.05	0.26	0.04	-	0.01

Questionnaire

Subjective perception of the lighting

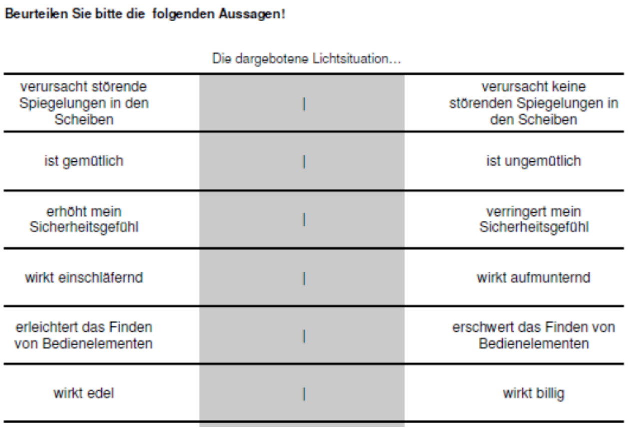
After each experimental run, each test person was asked to fill out a questionnaire in the form of 18 semantic differential pairs, which were arranged according to the following criteria: space perception, perceived interior quality, interior attractiveness, perceived safety, alertness and functionality.

The questions were the following: the displayed light situation...

- *(Space perception)* ...allows the perception of the whole car interior / does not allow the perception of the whole car interior; ...causes a small impression of interior space / causes a big impression of interior space.
- *(Perceived interior quality)* ...looks cheap / looks luxurious; ...gives a lesser quality impression / gives a good quality impression.
- *(Interior attractiveness)* ...has a really unpleasant light colour / ...has a really pleasant light colour; ...is too dark / is too bright; ...appears pleasant / appears unpleasant; ...is comfortable / is uncomfortable; ...I really liked / I really disliked.
- *(Perceived safety)* ...increases the perceived safety / decreases the perceived safety.
- *(Functionality)* ...enables a better orientation in the car interior / complicates the orientation in the car interior; ...facilitates the finding of controls / complicates the finding of controls; ...makes me more powerful / makes me less powerful; ...causes distracting reflections in the windshields / does not cause reflections in the windshields;
- *(Alertness)* ...distracts me from driving / keeps my attention on the driving; ...complicates the concentration / enables concentration; ...makes me tired / activates me; ...makes me sleepy / animates me.

The questions were presented in random order and so arranged that the positive sentences were equally distributed on both sides of the questionnaire.

The answers were given by the test persons on a continuous scale with a vertical line signalising the middle, as represented in Figure 4.



Beurteilen Sie bitte die folgenden Aussagen!

	Die dargebotene Lichtsituation...	
verursacht störende Spiegelungen in den Scheiben	|	verursacht keine störenden Spiegelungen in den Scheiben
ist gemütlich	|	ist ungemütlich
erhöht mein Sicherheitsgefühl	|	verringert mein Sicherheitsgefühl
wirkt einschläfernd	|	wirkt aufmunternd
erleichtert das Finden von Bedienelementen	|	erschwert das Finden von Bedienelementen
wirkt edel	|	wirkt billig

Figure 4 Example of the differential pairs questionnaire

Emotional state

Influences of the three lighting parameters on the emotional state of the test persons were also researched, using a Self-Assessment Manikin (SAM) procedure [4]. This questionnaire method, displayed in Figure 5, is based on the PAD Model (Pleasure-Arousal-Dominance), which has been already adopted to describe the emotional state caused by colours [17] and lighting situations [5] [6].

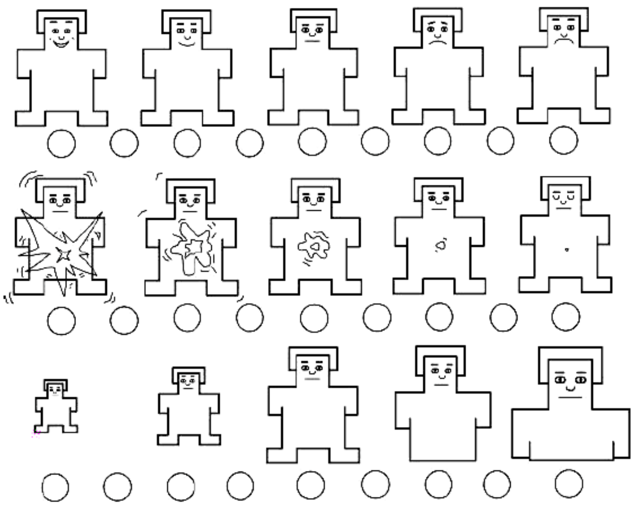


Figure 5 Self-Assessment Manikin (SAM) questionnaire **[4]**.

The three independent dimensions pleasure, arousal and dominance are assessed separately, by checking the box under the manikin which the test person feels more to his or her state. The pleasure dimension spans from happy, content (corresponding to 1 on its scale) to unhappy, displeased (9). Arousal mirrors the activity of the person, ranging from agitated, wide awake and aroused (1) to sleepy, calm and inactive (9). Dominance states if a person feels controlled (1) or rather in command of the situation (9).

The test persons were asked to fill out this form at the beginning of the test (in order to know the emotional state at the starting point) and after each experimental run.

RESULTS

Although the influence of ambient lighting on the emotional state of the test-persons could not be verified, this study confirmed that the different light scenarios significantly influenced space perception, perceived interior quality, interior attractiveness, as well as perceived safety and functionality. In particular the parameter colour had a great influence on the space perception and the attractiveness of the interiors.

Subjective perception of the car interior

In the following the results of the questionnaire on the subjective perception will be displayed. Different scenarios were compared in order to understand the influence of each parameter: brightness, position and colour of the lighting.

The significance of the results was assessed using a Wilcoxon test for two related samples of nonparametric data. No significant differences originated from differences in the test persons' gender or age.

Effects of brightness

The effects of luminance variations were verified by comparing the following settings: without lighting – everything on low level – everything on bright level with accents (scenarios 5 – 7 – 1).

The comparison between the scenarios "without lighting" and that "everything on – low level" showed highly significant ($p<0.01$) improvements for the second one in five criteria: space perception, interior attractiveness, functionality, perceived interior quality and perceived safety. Regarding the criterion alertness, no clear trend could be found: no degradation could be seen either.

Increasing the luminance and getting to the "everything on - bright level" scenario brought a significant ($p<0.05$) decrease in comfort, pleasantness and safety perception, increasing the distraction and complicating the concentration for the drive.

Luminance variations on single lighting elements produced no significant differences in the answer distribution, apart from the brightness assessment, in which the test persons recognized which scenario was actually brighter. Two comparisons were employed for this evaluation: doors bright – doors low level (scenarios 3 – 4) and foot space bright – foot space low level (scenarios 9 – 10).

The comparison between the scenario without ambient lighting and that with the centre console illumination (scenarios 5 – 11) is also interesting, because the latter represents the minimal ambient lighting that can be found in today's series cars. This kind of illumination provided better interior attractiveness and functionality ($p<0.01$), and improved perceived interior quality and space perception ($p<0.05$). This means that a minimum quantity of light in the car interior constitutes already a considerable advantage, regarding the subjective perception, in comparison to dark.

Effects of Colour

Two particular scenarios were assessed, which provided the same luminance level and same light positions, but different colours: orange and blue (scenarios 7 – 12).

It could be verified that the blue lighting appeared brighter than the orange and facilitated the finding of control elements, although being uncomfortable ($p<0.01$). Orange light colour looked more luxurious and gave a better quality perception ($p<0.05$). Few other effects could be told from the comparison of the mean answers, although they resulted not significant: blue light allowed a more complete perception of the car interior and enhanced the orientation, while orange light had a more pleasant light colour and was found more appealing.

Effects of Position

Three different lighting positions were evaluated: doors, centre console and foot space (scenarios 4 – 9 – 11). The differences between these three scenarios were quite small. As a trend it can be said that the more peripheral doors lighting offered a better perception of the whole interior and a higher perceived value, appeared more comfortable and pleasant and offered a better orientation. On the other hand the central illumination of the centre console facilitated the finding of control elements. The foot space lighting obtained slightly lower assessments than the other two illumination places, although the differences were not significant.

Effects on Driver's Emotional State

The results obtained from the Self-Assessment-Manikin test showed two aspects. On one side, there was quite a wide variance of the answers on the Pleasure and Arousal axis, this probably due to the different sensations and feelings which animated the different participants, independently from the test and the tested scenarios. On the other side the answers on the Dominance axis concentrated more on the middle point, this effect explained by the apparently difficult understanding of this dimension by the test persons.

In order to understand the change in the emotional state of the participants, each scenario rating was compared to the answer given at the beginning of the experiment. The difference between these two ratings gave a dimension of the emotional change caused by the scenario ($\Delta = - 0$; $\Delta = - 0$; $\Delta = - 0$, where 0, 0, 0 are the values gathered at the beginning of the test).

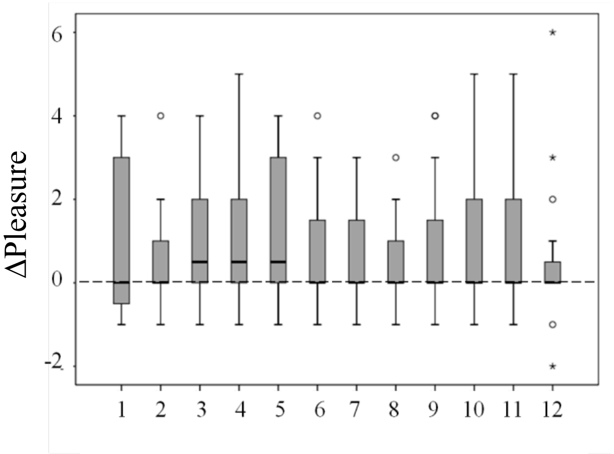


Figure 6 Boxplot graph of the distribution of the difference in the Pleasure rating between each scenario and the answer at the beginning of the experiment.

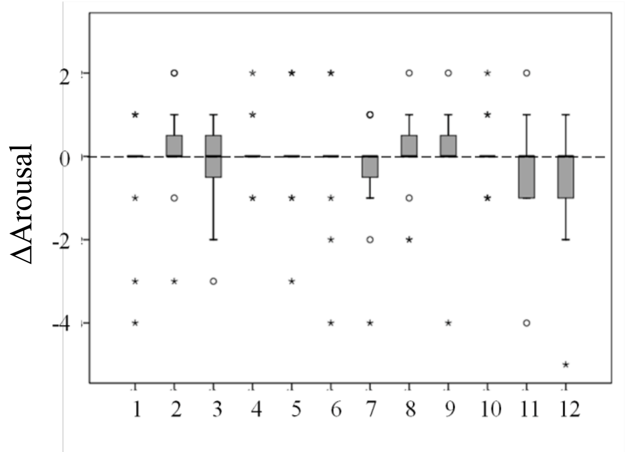


Figure 7 Boxplot graph of the distribution of the difference in the Arousal rating between each scenario and the answer at the beginning of the experiment.

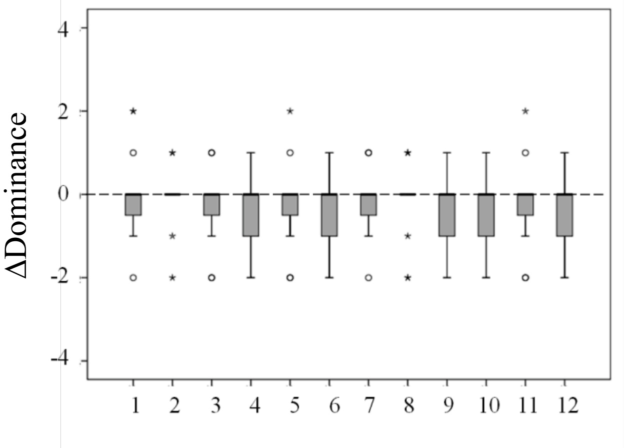


Figure 8 Boxplot graph of the distribution of the difference in the Dominance rating between each scenario and the answer at the beginning of the experiment.

The differences distributions are displayed in Figure 6, Figure 7 and Figure 8. Small changes can be seen in the dimensions of arousal and dominance, while in the pleasure dimension the distribution is wider. Though, the median value, represented in the graphs by the solid middle line, remains in most cases 0. Moreover, this distribution should not mislead in finding a negative trend in the influences of ambient lighting: many test persons judged their state at the beginning already "happy" (values 1 and 2 on the pleasure dimension) and therefore there was no room for improvement in the scenario ratings.

The data were analysed through a Friedman-test with p=5%. No significant effect could be found on any of the three dimensions. This has probably been caused by the short time (3 minutes) in which the participants tested the light scenario added to the lighting small luminance (maximum 1 cd/m²) and mostly peripheral position.

Effects on Driver’s Performance

During the whole experiment the following data was collected by the simulator system: elapsed time, car position (x,y,z), absolute velocity, steering wheel angle, road curvature, distance from the road’s edge and covered distance. Every parameter was collected with a frequency of 25 Hz.

The primary driver’s task was to drive in the middle of the right lane of a three-lane highway, following another vehicle. The aim of the task was to focus the driver’s attention on the street, thus enabling him to perceive ambient lighting only peripherally or through the secondary tasks.

These secondary tasks were designed to make the driver aware of the functionality of ambient lighting, in recognizing controls and objects inside the car. Without a proper lighting the test persons could not be able to push the right button, or find the control for the air nozzle.

Since the test persons could not accelerate and brake, the only parameter indicative of the driving performance is the distance from road’s edge (D_e), measured in meters (Figure 9). Its standard deviation $\sigma(D_e)$ evaluated over the whole 3 minutes experimental run is indicative of the driver’s performance in following the street lane in a specific lighting scenario.

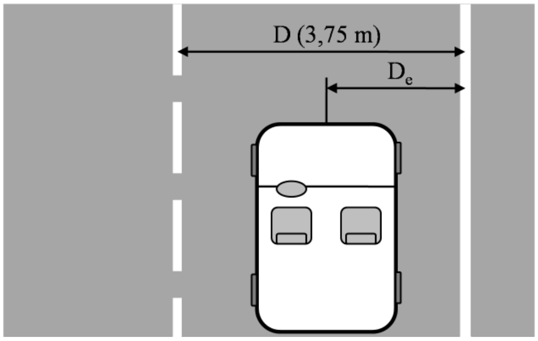


Figure 9 Distance from the edge of the lane, as measured on the simulator. The measure was taken from the middle of the car bumper to the virtual white line on the right side of the street.

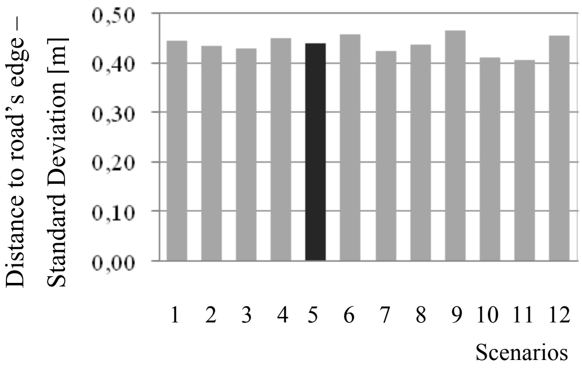


Figure 10 Values of $\sigma(D_e)$ in relation to lighting scenarios. With number 5 is highlighted the scenario without ambient lighting.

This data (shown in Table 5 and Figure 10) has been analysed through one-way ANOVA for the lighting scenarios. The results showed no significant dependency of the driving performance from the lighting situation in the car (F= 0.226 α=0.996).

However, since this measure was not the primary goal of the research, it is difficult to assess its importance. For sure the driver’s performance has not been influenced either way by the lighting scenarios.

Table 5 Mean values of $\sigma(D_e)$ in meters for each lighting scenario.

Lighting Scenario	**(D_e) [m]**
Everything on – bright level with accents	0.45
Series	0.44
Doors – bright level	0.43
Doors – low level	0.45
Without lighting	0.44
Everything on – bright level	0.46
Everything on – low level	0.43
Everything on – middle level	0.44
Foot space – bright level	0.47
Foot space – low level	0.41
Centre console	0.41
Everything on blue – low level	0.46

CONCLUSIONS

The presented study showed significant influences of ambient lighting on driver’s perception. In particular the advantages of ambient lighting concerning space perception, functionality and perceived interior quality were clearly stated, even with low luminance levels. These advantages do not grow by simply using more brightness or by employing more light sources.

In the following the main conclusions which can be drawn by this experiment are listed.

- The whole perception of the car interior is improved through the use of ambient lighting while driving. It intensifies the space perception, enhances the perceived quality of materials and design, facilitates the finding of controls and the orientation in the car, and gives an improved perceived safety.
- A small number of light sources placed in order to cover the whole field of view can give equal results, in terms of perceived space and quality, as many overlapping light sources. Thus an aimed ambient lighting can use fewer components and reduce the production costs and though create a welcoming pleasant atmosphere in the car interior.

- A higher luminance level (mean values of 0.04cd/m²), while increasing the chance of creating discomfort glare and distraction during the driving, does not bring improvements to the driver's perception of the car interior or a better orientation and functionality. This means that darker, less expensive light sources can achieve the same comfort effects.
- The influences of different colours affect more criteria in different way. This has several causes: the diverse field of view and intensity of perception for each colour in the mesopic adaptation level (blue is perceived more intensively and on a wider angle as orange or red), the various emotional values and the different interaction with interior materials through reflection. Thus the choice of colour for ambient lighting has to meet more requirements, nonetheless brand identity and design compliance.
- Influences on the emotional state could not be verified, probably due to the short time available for the evaluation and the focus that the test-persons gave to the primary driving task. In other research studies, where the light stimuli constituted the main focus and the test was longer, such effects could be verified. Probably in order to discover more on this particular aspect, a different experimental design has to be employed.
- The driver's overall performance resulted to be uninfluenced by the ambient lighting, although this measure did only assess how the test persons followed the lane line. No measurements were made on the visual performances, since these have been already verified in other studies.

These results can be considered and used in the future development of such illumination systems, in order to optimize their design, reducing costs and energy consumption and though achieving an optimal subjective perception by the drivers.

On a practical level, from the investigated scenarios a guideline for developers and manufacturers, suggesting luminance levels and their tolerance ranges for ambient lighting systems will be derived.

Further researches should enlarge the spectrum of the investigated colours, which in this research were limited to only orange and blue. This comparison alone, although juxtaposing short wave and long wave colours, cannot describe completely the possible effects that different lighting hues have on the driver's perception of space and quality. In this perspective also the influence of the interior materials is important. Indeed, the most part of ambient lighting comes to the eye after the reflection on completely different kinds of material (e.g. from black plastics to beige or white leather). Thus the perceived situation should be considered not only in function of the lighting colour but also of the combination lighting-material. This topic is currently being investigated.

Moreover, dynamic interior lighting changes (in brightness, position and colour) and their effects have to be investigated. A further step in this direction will be the connection of these changes with inputs from the environment, the car and the passengers. This will provide on one hand adaptation of the interior lighting to the surrounding conditions and to the vehicle settings, enhancing safety and possibly giving a visible feedback of the car status. On the other side, flexibility and compliance to the customers' individual tastes will be ensured. The advantages and problems arising from such systems, as well as theirs acceptance by the drivers have still to be tested and verified. Nevertheless, they offer a new, interesting, emotional and much more coloured way of understanding and developing vehicle interior lighting.

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The Effects of Lighting on Atmosphere Perception in Retail Environments

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ABSTRACT

The present study's objective was to investigate the contribution of lighting in evoking an atmosphere in naturalistic environments, among the extensive set of other environmental cues. In a field study involving 57 clothing stores, lighting attributes (e.g., brightness, contrast, glare and sparkle) and context (i.e. the shop interior) were assessed and quantified independently. These data were then used to predict four dimensions of perceived atmosphere of these stores in multiple regression analyses. A hierarchical procedure was chosen, with context variables entered in the first block and lighting attributes in the second block. We were thus able to determine the effects of lighting on perceived atmosphere, while controlling for context effects. Both lighting attributes and interior qualities were successfully related to perceived atmosphere. Our most important finding was that, even given the substantial contribution of design elements in retail environments, lighting does play a significant role in evoking atmospheres.

Keywords

Lighting, environmental assessment, atmosphere perception, retail environments, Multiple regression, card-sorting

INTRODUCTION

As any light designer, light researcher, and even layperson will confirm, lighting and ambiance are intimately related. Literature indicates that lighting characteristics can influence emotions, mood and cognition, and atmosphere and spatial impressions, although at times the collected findings are inconclusive. With respect to emotions for instance, some studies report more pleasant emotions with higher light intensity levels [1], whereas others report no significant effects [2,3]. Fleisher et al. [1] demonstrated that a combination of high illuminance levels and a relatively large indirect lighting component resulted in higher feelings of dominance. Cool white light was shown to be arousing [1], while a more complex pattern emerged in a second study, reporting positive effects of colour temperature on male participants' mood, yet negative effects on females' moods [2].

Literature reports of several studies investigating the way people assess lighting directly. Hawkes, Loe and Rowlands [4] suggest that people categorize lighting using the lighting characteristics brightness and interest (or uniformity). Flynn and colleagues [5] added a third dimension (overhead – peripheral). Unfortunately, both studies [4,5] used a sample size too small for a robust factor analysis. Veitch and Newham [6], who tackled this problem working with 292 participants, demonstrated that people categorize lighting in terms of the three dimensions: brightness, visual attraction, and complexity.

Literature also describes how lighting can affect people's environmental impressions (for a review see [7]). As one of the first, Flynn, Hendrick, Spencer and Martyniuk [5] used a realistic interior (i.e. conference room) and found an effect of lighting on subjective evaluations of the environment, perceptual clarity and spaciousness. This research, together with several follow-up studies, summarized in [7], suggests that in the North American society and culture, there are at least six broad categories of human impression that can be influenced or modified by lighting design: perceptual clarity, spaciousness, relaxation and tension, public versus private space, pleasantness, and spatial complexity (sometimes liveliness). After relating the impression dimensions to lighting characteristics, Flynn [7] suggested several design guidelines: For perceptual clarity, the designer should apply bright and peripheral lighting. An impression of spaciousness (i.e., the space is perceived as large) is achieved when applying uniform and peripheral lighting. Pleasant and relaxing impressions are the result of peripheral and non-uniform lighting. And lastly, to establish a 'private' impression, the designer can select non-uniform and dimmed lighting.

Houser, Tiller, Bernecker and Mistrick [8] varied the direct/indirect lighting ratio and concluded that walls and ceiling contribute to the perception of overall brightness when work plane illuminance is held constant. Also, rooms appear more spacious with higher ratios of indirect lighting, and rooms with relatively high levels of indirect lighting are favoured over light settings with less than 60% indirect lighting. Literature thus establishes that lighting is able to influence environmental impressions.

Yet although literature reports of studies indicating that lighting characteristics influence moods and emotions, cognition, and environmental impressions, there are hardly any studies that have established these effects outside the laboratory. Although it is one thing to prove that variations in lighting in an otherwise controlled environment have an impact on environmental impressions, showing that lighting actually contributes to atmosphere perception in naturalistic environments, i.e., in the real world is quite another, let alone ascribing this to specific lighting attributes. This is exactly what the current study set out to do. And it did so in a type of environment with substantial variations in interior design, and where atmosphere has been proven to matter significantly: retail environments.

Retail Environments

Retail environments communicate the stores' image and purpose to customers [9], they can evoke emotional reactions [10], impact the customers' ultimate satisfaction with the service [11], and even the money and time spent in the store [12]. Therefore, creating the right environmental setting is of prime importance for shop owners. To create the desired ambiance, lighting may have its contribution, but it is only one of the numerous elements, such as furnishing and finishing of the shop's interior, size, crowdedness, and music, that play a role.

Different categorizations for these environmental characteristics are proposed. Bitner [9] suggested three groups: ambient conditions; spatial layout and functionality; and signs, symbols and artefacts. Berman and Evans [13] included the exterior of the shops and came to four groups: general interior; the layout and design; the point-of-purchase and decoration; and the exterior of the shop. Turley and Milliman [14], in turn, added a fifth category: human variables. Most recently Baker, Parasuraman, Grewal & Vos [15] proposed a model in which the environmental cues were divided into three categories: design, ambient, and social variables.

Since environments include such an extensive variety of stimuli, while on the other hand consumers perceive environments holistically [16] it is essential to seek general variables as descriptors that grasp the main influence of the environment [17]. Kaplan [18] suggested that four environmental dimensions can predict preference for an outdoor environment: complexity, mystery, coherence and legibility. Environmental complexity refers to visual richness, ornamentation, information rate, diversity and variety in an environment [19], and is shown to have a linear relationship with interest (arousal) and a curvilinear (inverted U) relationship with preference (pleasure) [19,20,21], meaning that moderate levels of complexity are most preferred. Another important environmental dimension is order [20], which is related to the extent of coherence, legibility, organization, and clarity of an environment [19]. In studies of urban environments (summarized by Nasar [22]) order has been shown to have a positive impact on pleasantness and a negative impact on arousal. Except for the inverted U relationship between complexity and pleasantness, all these relationships are confirmed for retail environments [23].

We conclude that lighting has a potential contribution to perceived ambiance, but is only one of the numerous elements that may play a role. Our question was whether lighting would play a role that was measurable, and if yes, which lighting attributes would have the most substantial contribution.

METHOD

Design

Fifty-seven clothing stores participated in a field study, exploring the contribution of lighting to environmental impressions, controlling for other contextual influences. For each of these stores the three categories of variables – perceived atmosphere, lighting attributes, and context (i.e., the shop's interior design) – were assessed and quantified. Assessments were made independently of each other, by different groups of experts (lighting) or lay people (atmosphere, context). We then performed multiple regression analyses on perceived atmosphere dimensions with lighting attributes and context as independent variables.

Participants & Shops

For this field study 57 shops were selected. The stores were all located in the city centre of Eindhoven, a mid-size Dutch city, to enable participants and experts to visit all the shops in one morning or afternoon. In order to prevent statistical confounds caused by the type of product sold, only fashion shops were selected to participate[1]. Low and high-end shops were avoided for the same reason. Within this selection of shops, which still presented a wide variety of shop interiors and fittings we expected that structural confounds between lighting configuration and interior design would be limited. Nonetheless, in order to control for this eventuality we also assessed and quantified the style of the shops' interiors.

To assess context, i.e., the interior design of the stores, twenty participants were recruited from a participant database of the university. The group consisted of ten males and ten females, ranging in age between 19 and 44, with an average of 28 years. The respondents were not familiar with the shops participating in the study.

Seven lighting experts participated in the assessment of the lighting and lighting fixtures in the stores. Their ages ranged between 29 and 58, with an average of 46, five were male and two female.

For quantifying perceived atmosphere, six participants were recruited from the university's database. The participants did not have specific affinity to lighting or the shops participating in this study. Three participants were male and three were female. Their ages ranged between 22 and 29, with an average of 24.5 years.

Measurements & Procedure

Context Characterization

A card-sorting experiment was performed to characterize the shops' interior designs. Pictures of these interiors were printed on A5 photo paper and served as cards. The photographs were all taken inside the shop, from the same position at which participants rating the atmosphere (see below) would be standing. In taking the pictures, we avoided photographing ceilings and lighting fixtures where possible. Initially two pictures were taken per shop. After a pilot study we reduced the number of cards to 87, by removing one picture per shop if both pictures were always categorised in the same groups. The participants performed the experiment individually to assure independence of grouping strategies [24].

Participants were instructed to think of a discriminating quality they felt could serve as a base for sorting the shops, e.g. 'cluttered'. They then sorted the pictures of the shops into five piles[2] (ranging from totally not applicable to totally applicable), based on the chosen quality. This was repeated, until the participant could not come up with another discriminating quality.

In total the 20 participants performed 59 categorizations. Multiple correspondence analysis was then performed on these data, yielding two dimensions on which the shops varied (inter-dimensional correlation -.006). We labelled them 'legibility' (order-disorder) and 'warmth' (warm-cold), based on the labels participants had given for their categorizations. Each shop's scores on these dimensions were used in the multiple regression analyses reported below, to account for the variability of shop interiors.

Lighting Attributes

A panel of experts assessed the lighting in the shops during a site visit. For this they used a questionnaire developed also in cooperation with lighting experts. The questionnaire consisted of 31 items, probing established lighting attributes such as brightness, contrast (i.e., uniformity), colour temperature, glare and sparkle, and modelling, as well as the relative contribution of different types of lighting (i.e. general, accent, architectural, decorative) and the lighting installation (see Table 1). Each of the seven experts filled out one questionnaire per shop (i.e., 7 times 57 in total) individually. They visited the shops between ten o'clock in the morning and half past noon, avoiding the busiest hours. Also, their visits were scheduled within a period of three weeks, to minimize the chance of interiors being redecorated. Order effects, e.g. as a result of learning, tiredness or boredom, were controlled by varying the order in which each expert visited the stores.

Inter-rater reliabilities were computed to determine the level of agreement among the experts. Cronbach's alpha's between experts' scores for each individual item ranged from .635 to .940, with an average of .804 (see Table 1). These reliabilities were more than satisfactory, indicating a high level of agreement among the experts in scoring the lighting attributes of the shops. The scores of the experts were averaged to compute each shop's score.

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[1] Since the type of lighting often differs with the type of product, yet product class may also influence atmosphere perception, this could result in structural relations between lighting and ambiance not really attributable to the lighting per se.

[2] Although a division over five piles was desired, the participants were instructed to first create three piles – not applicable, neutral or applicable. Then they were asked to divide the neutral pile into three piles again – less applicable, neutral or more applicable. This resulted in 5 piles in total. This procedure was followed because the pilot study pointed out that this procedure would lead to the most evenly spread division of the pictures over the five piles.

Table 1. Inter-rater reliabilities of lighting questionnaire items

Item	Cronbach's alpha	Item	Cronbach's alpha
General lighting	.940	Accent lighting	.942
Decorative lighting	.805	Architectural lighting	.933
Brightness back walls	.870	Brightness horizontal plane	.823
Brightness ceiling	.820	Brightness floor	.819
Brightness side walls	.892	Brightness overall	.915
Colour temperature light	.759	Colour temperature total space	.813
Glare	.889	Sparkle	.822
Luminance ratio back walls	.789	Luminance ratio horizontal plane	.825
Luminance changes back walls	.691	Luminance changes horizontal plane	.719
Luminance ratio ceiling	.635	Luminance ratio floor	.765
Luminance changes ceiling	.677	Luminance changes floor	.638
Luminance ratio side walls	.816	Luminance ratio overall	.766
Luminance changes side walls	.775	Luminance changes overall	.773
Conspicuous lighting installation	.628	Patterned lighting installation	.778
Amount of fittings	.906	Different fittings	.841
Modeling	.865	***Mean***	**.804**

Factor analyses (Principal Component with Varimax rotation) of the data resulted in six dimensions qualifying attributes of the lighting configuration: contrast, brightness, glare and sparkle, contrast on the ceiling, aesthetics of lighting installation, and decorative lighting. The score for each of the dimensions was determined by averaging the scores of the items contributing to that particular dimension. For instance the score for the factor glare was calculated by averaging the scores for accent lighting, glare and sparkle. Correlations between the six factors are reported in Table 2.

Table 2. Lighting attributes correlation matrix

	bright ness	glare & sparkle	contrast of ceiling	lighting install.	decor. Lighting
contrast	.402	.620	-.056	-.092	.089
bright ness		.399	.165	.206	-.198
glare & sparkle			-.051	.041	.047
contrast of ceiling				.202	-.111
lighting install.					.043

Each shop's scores on these lighting attributes were used in the multiple regression analyses reported below, to account for the variability of the shop lighting.

Atmosphere Perception

In the third phase, six (new) participants also visited all the shops (following different routes, to vary the order in which shops were assessed) and rated the ambiance in each of them. For measuring perceived atmosphere a short version of Vogels' [25] instrument was used. This questionnaire measures perceived atmosphere in four dimensions: cosiness, liveliness, tenseness and detachment. After deliberation with Vogels, 18 of the original 38 items were selected (4 or 5 per dimension), with seven-point Likert scales ranging from totally not applicable to totally applicable. Participants scored each shop on each of these items. They were not aware that the study was focused on lighting and were not instructed to pay particular attention to lighting or lighting fixtures.

Internal consistencies of these atmosphere dimensions were determined by calculating Cronbach's alpha for each of the six participants (see Table 3). Averaged values indicated acceptable (>.60) to good (>.80) reliabilities. The level of agreement between participants was determined by calculating inter-rater reliabilities (Cronbach's alpha) per dimension. The values are reported in Table 3. Correlations between the scores on the different atmosphere factors are displayed in Table 4.

Table 3. Internal consistencies and inter-rater reliabilities of the atmosphere scales

	Average internal consistency*	Inter-rater reliability**
Cosiness	.83	.65
Liveliness	.77	.76
Tenseness	.79	.42
Detachment	.61	.84

*: averaged over 6 participants' individual internal consistency scores; **: between the 6 participants' scores on that dimension.

Table 4. Correlations between scores on atmosphere dimensions

	Liveliness	Tenseness	Detachment
Cosiness	.330	-.613	-.309
Liveliness	1.000	-.340	-.789
Tenseness		1.000	.310

RESULTS

Multiple regression analyses were performed predicting perceived atmosphere dimensions with the two context variables and the six lighting attributes as predictors. Note that in these analyses, the 57 shops were the cases (they made up the rows in the statistical database). Four separate analyses were performed - one for each atmosphere dimension.

We first performed multiple regression analyses on atmosphere dimensions, exploring only lighting attributes as candidate predictors in a stepwise procedure. The obtained significant beta-weights are displayed in Table 5. Brightness contributed significantly to three atmosphere dimensions: cosiness (negatively), tenseness and detachment. Contrast significantly decreased perceived tenseness. Glare & sparkle contributed significantly to liveliness and negatively to detachment.

Table 5. Significant beta coefficients of regression analyses without context variables

Lighting characteristics	Not controlled for context effects			
	Cosy	Lively	Tense	Detached
R²	.336**	.312**	.180	.249*
Brightness	-.588***		.484**	.354*
Contrast			-.362*	
Glare & Sparkle		.469**		-.382*

Note: Results of 4 separate regression analyses, with the 4 atmosphere dimensions as respective dependent variables. N=57. * p<.05, ** p<.01, *** p<.001

Controlled Regression Analyses

We then repeated the analyses, yet this time controlling for contextual variables. A hierarchical procedure was chosen, with context descriptors comprising the first block and lighting attributes the second block. We could thus determine the effects of lighting on perceived atmosphere while controlling for context effects. In the first block, context variables were entered (Table 6). Adding the lighting attributes after this first block generally improved the predicted variance. Moreover, for three atmosphere dimensions, at least one lighting attribute had a significant beta-weight. Brightness significantly and substantially decreased perceived cosiness, and increased perceived tenseness. Glare and sparkle contributed to the perceived liveliness of fashion stores. Furthermore, the shops' legibility was shown to significantly decrease perceived liveliness and increase perceived detachment.

Table 6A. Hierarchical regression predicting cosiness

Cosiness	**β coefficients**		**R²**	**R² change**
	Step 1	**Step 2**		
Block 1 (context)			.105	
Legibility	-.158	-.132		
Warm	.281 *	.246		
Block 2 (lighting)			.384**	.279 **
Contrast		.058		
Brightness		-.499 **		
Glare & Sparkle		-.007		
Contrast of ceiling		-.206		
Lighting installation		.039		
Decorative lighting		-.153		

Note: * p<.05, ** p<.01, *** p<.001

Table 6B. Hierarchical regression predicting liveliness

Liveliness	**β coefficients**		**R²**	**R² change**
	Step 1	**Step 2**		
Block 1 (context)			.407 ***	
Legibility	-.590 ***	-.496 ***		
Warm	-.247 *	-.146		
Block 2 (lighting)			.522 ***	.115
Contrast		.093		
Brightness		-.128		
Glare & sparkle		.293 *		
Contrast of the ceiling		-.123		
Lighting installation		.158		
Decorative lighting		-.026		

Table 6C. Hierarchical regression predicting tenseness

Tenseness	**β coefficients**		**R²**	**R² change**
	Step 1	**Step 2**		
Block 1 (context)			.059	
Legibility	.119	.051		
Warm	-.212	-.116		
Block 2 (lighting)			.189	.130
Contrast		-.298		
Brightness		.445 *		
Glare & sparkle		.043		
Contrast of the ceiling		-.059		
Lighting installation		-.157		
Decorative lighting		.102		

Note: * p<.05, ** p<.01, *** p<.001

Table 6D. Hierarchical regression predicting detachment

Detachment	**β coefficients**		**R²**	**R² change**
	Step 1	**Step 2**		
Block 1 (context)			.652 ***	
Legibility	.806 ***	.765 ***		
Warm	.056	.033		
Block 2 (lighting)			.682 ***	.030
Contrast		.013		
Brightness		.170		
Glare & sparkle		-.175		
Contrast of the ceiling		-.003		
Lighting installation		-.064		
Decorative lighting		.033		

DISCUSSION

Light and ambiance are intimately related, yet we know of very few studies that have attempted to measure how much lighting actually contributes to atmosphere perception in naturalistic environments. The current study attempted to do just that. Also, we hoped to attribute any contribution we might find to more or less specific lighting attributes. And indeed we did manage to verify that lighting contributes a measurable part to atmosphere assessments. This contribution was modest, and we did not establish significant effects for each dimension of atmosphere, but in view of the challenges we met, our findings were certainly satisfactory.

Measuring light's contribution in naturalistic settings proved to be quite a complex exercise. For one, one is dependent on the natural range and variance of lighting used in 'real' settings, and has to find a way of categorising or even quantifying that. In the current study, experts scored the lighting in each of the 57 shops, using a questionnaire specially developed to this end. Inter-rater reliabilities between these experts indicated that this produced a reliable and robust measure, which was more detailed and comprehensive than what could have realistically been possible with objective measurements.

A second obstacle in natural settings is accounting for the substantial variance and contribution of intervening variables. Based on the literature, we expected that especially the shop's interior and social variables would play an important role in defining the atmosphere. The social setting we tried to control by selecting time slots that were not too long and avoided the busiest hours. The shops' interiors were controlled first by limiting them to a certain type of product (clothing) and excluding the extreme ends of the price levels. Second, since this still left us with a huge range of different interiors – e.g. cluttered to spacious, old-fashioned to trendy, warm wooden furniture to cool metal racks and stands – we made an attempt to characterise and quantify these interior styles using the card-sorting method. These data enabled us to characterise all 57 shops by their location in a two-dimensional space stretching from orderly to disorderly and from warm to cold. We were not able to control the soundscapes (e.g., the music playing in the shop) or the shops' exteriors.

A third obstacle in the present research was measuring ambiance or atmosphere. We were not aware of existing standardized instruments for measuring atmosphere in retail environments, or other types of environments for that matter. Instruments most often used are probably the sets of semantic differentials, similar to the one we used in the present study. We preferred this measure [25] to other ones, for instance the well-known set developed by Russell, Mehrabian, and colleagues (e.g., see [17]), since it was specifically targeted to atmosphere perception, and its dimensions appeared closer to what we intended to measure than the dimensions typically coming from those sets (generally something like evaluation, arousal and potency). The current instrument worked well in terms of the internal consistencies of its subscales, yet in hindsight it does not necessarily cover all relevant aspects of atmosphere. Also, it could have been interesting to also have probed characteristics such as 'spaciousness' or 'perceptual clarity' directly. This would have made it easier to compare the present study's findings to those reviewed earlier, for instance by Flynn [7]. However, we felt the current measure was closer to the 'atmosphere' concept, and we had to restrict the number of items, since each participant would have to fill out the questionnaire 57 times (!), one for every shop.

However, we feel that with these 57 shops, we have managed to create a large enough sample to guarantee a good variance in our core dependent and independent variables: lighting attributes and atmospheres, and to perform the multiple regression analyses on. We were in fact quite happy and proud to have been able to recruit that many shops to participate in the study. This potentially also illustrates the interest of these shops' owners in the role that lighting plays in the success of their business.

The first set of regression analyses showed how several lighting attributes were related to atmosphere dimensions. The most important attributes were brightness, contrast, and glare and sparkle. At least one, and sometimes two of these attributes significantly predicted each of the four dimensions.

In the second set of regression analyses, context variables were entered first, before entering the lighting attributes. This way we minimised the chance of confounds caused by naturally occurring relationships between interior design and lighting attributes, which might otherwise lead us to overestimate light's contribution to atmosphere perception. In fact, since the lighting in the shops was also recorded on the photographs used for the context quantifications, the present results are probably an underestimation of the impact of the lighting on perceived atmosphere.

Although some correlations decreased or disappeared, others remained, showing a consistent contribution for instance of brightness to the cosy-dimension (the brighter the impression of the shop, the less confined/intimate/romantic/relaxing was the atmosphere). Glare and sparkle added most to liveliness (the more glare and/or sparkle, the more energising/lively/stimulating was the atmosphere). Brightness contributed positively to the tenseness dimension (the more brightness, the more threatening, tense, uneasy and unfriendly the atmosphere). This was in fact quite unexpected, and not in line with earlier findings, which generally relate brightness to more positive evaluations. This may be specific to this type of environment and definitely calls for more research. No specific lighting attribute was related to detachment. This dimension was largely predicted by the contextual variable 'legibility' (running from disorder to order). The more legible the environment was, the more formal and businesslike the atmosphere. This same legibility characteristic contributed negatively to the liveliness of the shop.

Conclusion

This study provides a better understanding of the impact of lighting on perceived atmosphere in a retail environment. Lighting attributes and interior qualities were successfully related to perceived atmosphere. Granted, the amounts of variance predicted for each of the dimensions of atmosphere are generally modest, and typically only one of the lighting attributes had a significant individual contribution. However, considering the wide variety of shop interiors, clothing collections, music played et cetera, we nonetheless consider the findings striking and encouraging for light designers and researchers: even in the enormous set of visual environmental cues present in retail environments, lighting does play a significant role in creating an ambiance.

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Effect of Lamp Spectrum on Perception of Comfort and Safety

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ABSTRACT

In addition to improving visibility and providing orientation, public lighting is expected to contribute to the perception of comfort and safety of people outside after dark. At present, high-pressure sodium (HPS) lamps are widely used in outdoor applications due to their high efficacy and reliable lifetime. Their use however, comes at the expense of good color rendering and accurate color appearance. Recently developed ceramic metal halide (CMH) lamps provide many of the advantages of HPS in addition to natural white light and significantly better color rendering.

In this paper, results of quantitative research conducted in three European countries on the effect of lamp spectrum on visual performance and the perception of safety and comfort outdoors are presented. The results consistently show that at comparable light levels, the same people perceive areas illuminated with high quality white light to be brighter, safer and more comfortable than the same neighborhood illuminated with yellowish high-pressure sodium lighting.

Keywords

Perception of safety and comfort, outdoor lighting, street lighting, white light

INTRODUCTION

Artificial outdoor lighting can play several important roles. In addition to enabling safe movement, improving visibility and providing orientation, public lighting is increasingly used to contribute to the perception of safety and comfort of people outside after dark. The perception of safety, comfort and appreciation of an outdoor area can be strongly influenced by the lighting used to illuminate it.

Without conditions that ensure safe movement, it would not be possible for people to walk on the street, and without conditions that ensure a general perception of safety, people might choose not to walk on the streets. Factors contributing to safe movement after dark include visual orientation and the ability to detect obstacles on the pavement which may otherwise be a trip hazard. Factors contributing to the perception of safety include absence of glare, perception of brightness in the area and the ability to recognise the expression or faces of other road users at a distance sufficient to take avoiding action if necessary. Previous investigations have suggested that people want to be able to recognize strangers from a distance of 4 m in order to feel comfortable [1]. However it is extremely likely that this "comfort zone" distance varies significantly from one person to another and also depending on the familiarity of the environment. Improving the distance for and ease of facial recognition might contribute to increasing the feeling of safety and security of pedestrians and especially for those who feel most vulnerable. There is certainly interaction between these factors. In general a lighting scheme designed to meet one of these needs, such as recognition of faces and expressions may well go some way to meeting all of them [2].

At present, high-pressure sodium (HPS) lamps are widely used in outdoor applications due to their high efficacy and reliable lifetime. Their use however, comes at the expense of good color rendering (CRI of HPS ~25) and accurate color appearance. Recently developed ceramic metal halide (CMH) lamps provide many of the advantages of HPS in addition to natural white light and significantly better color rendering (CRI > 60). Related benefits of these lamps for the residents and pedestrians in the areas illuminated by them might include greater ease of facial recognition and color identification. Indeed, an earlier laboratory study conducted by Raynham et al. [3] concluded that twice the illuminance level of HPS is required to achieve the same facial recognition distance as with white compact fluorescent light sources at typical nighttime outdoor lighting levels. The advantages of high quality white light for facial recognition is already taken advantage of in the British standard for road lighting, BS5489:2003, which allows a lower lighting level to be used in residential areas if the color rendering index (CRI) of the source used is over 60 [4,5]. Color provides important visual information. Color differentiation and identification can contribute to one's ability to recognize faces or identify one's car, for example. Moreover, in the case of reporting a criminal act, accurate color naming can provide key information about the color of the suspected person's clothing or automobile.

Research conducted by Boyce et al. in New York City and Albany, NY suggests that there is a link in the public mind between the perception of safety of an area after dark and the perception of brightness of that area [6]. Of course the perception of safety in an area depends on many factors which are not related to lighting. Nevertheless, there is a need for residential areas to appear appropriately brightly illuminated at night to support the perceived safety of people in the area at night.

Fotios and Cheal used brightness ratings, brightness rankings and brightness matching to compare the effect of lamp spectrum on the perceived brightness in a variety of laboratory tests. Their results showed that at equal illuminance, lighting from white metal halide (MH) and compact fluorescent light sources were perceived to be significantly brighter than from yellowish HPS. Moreover, they found that at the typical illuminance levels encountered on urban streets (2 – 15 Lux), the same perception of brightness was achieved when the illuminance ratio of metal halide to HPS (MH/HPS) was ~0.73 [7,8]. These results were consistent with early laboratory studies conducted by Rea et al. in which subjects were asked to adjust the illuminance on a scale model scene illuminated with a HPS source until it matched the brightness of the same scene illuminated by a MH source. At illuminance of 0.1 and 1 cd/m^2, the illuminance ratio (MH/HPS) found to achieve an equal perception of brightness was 0.71 [9]. This means that people perceived scenes illuminated with metal halide sources to be equally bright as scenes illuminated with HPS sources when the measured illuminance was ~29% lower for the MH scene. In more recent field tests conducted by Rea et al.[10], respondents stood in the middle of a street between two luminaires and compared the perception of brightness of opposite ends of the street by alternatively looking at the street scenes illuminated by each luminaire. Subjects compared a variety of scenes where one part of the test street was illuminated with HPS at levels between ~5 – ~15 Lux and the opposing direction of the street was illuminated with CMH source also between ~5 – ~15 Lux. Subjects were given written questionnaires and for each pair of lighting conditions, they were asked to make a forced choice for the lighting condition, under which they would feel safer to walk at night and under which the street and surroundings as well as objects placed on the pavement appeared brighter. The test included pairs of lighting conditions where the ratios of illuminance on the scene illuminated with CMH to the illuminance on the scene illuminated with HPS (CMH/HPS) varied between 0.33 – 3. Interpolation of the results suggested that an illuminance ratio of CMH/HPS of 0.79 was required to create an equal perception of brightness and a ratio of 0.66 was required to create an equal perception of safety [10]. This opens up the opportunity to maintain the same perception of safety with CMH lamps while reducing the light level.

In this paper, results of field tests conducted in actual urban streets in the Netherlands, Spain and the United Kingdom on the effect of lamp spectrum on the perception of safety and comfort are presented. The goal of the research was to determine how end-users evaluate the outdoor lighting in their neighborhoods before and after it was changed from yellow high pressure sodium (~2000K) to warm white CDO 2800K or neutral white CDO 4200K street lighting and vice versa, as well as how this change affected their perception of safety and comfort and their appreciation of the neighborhood. At the same time, objective measurements of the performance for facial recognition and color identification were compared under yellow and warm or neutral white light. Altogether, over 300 residents participated in the experiments under both yellow and white light.

TECHNICAL PROPERTIES OF LAMPS USED

The lamps used in the experiments were based on high pressure sodium (HPS) and ceramic metal halide (CMH) technologies. Some properties of the lamps are listed in Table 1.

Table 1: Correlated color temperature (CCT) and color rendering index (CRI) of HPS and CMH sources used in experiments

Technology	Commercial Name	CCT (K)	CRI
HPS	SON T	2000	25
CMH	Master City White 2800 CDO-TT 2800K	2800	83
CMH	Master City White 4200 CDO-TT 4200K	4200	90

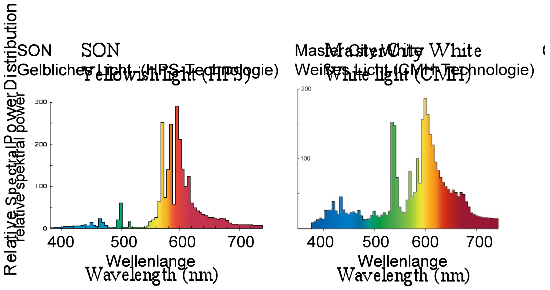


Figure 1: Spectrum of SON (based on HPS technology) and Master City White 2800K (CMH technology)

RESEARCH SET-UP

Research was conducted in Eindhoven, NL, Navalcarnero, Spain and St. Helens, UK by IPM International as part of a large quantitative study commissioned by Philips Lighting to evaluate how residents experienced the street lighting in their neighborhoods before and after it is changed from yellow HPS (~2000K) to warm white (~2800K) light as well as how this change affects their perception of safety and comfort and their appreciation of their neighborhoods.

As evident from Table 2, the tests in the UK were conducted after those in the NL and in Spain. Additional tests were conducted in different streets in St. Helens, UK, where the lighting was changed from (1) HPS to neutral white light (CDO 4200K), (2) from neutral white light (CDO 4200K) to warm white light (CDO 2800K) and (3) from warm white light (CDO 2800K) to HPS. The latter was done to check whether or not changes seen were due to the fact that residents expected certain changes due to a change in lighting. In the UK, each participant performed the test under both lighting conditions in one area. Different participants performed the tests in the different areas.

The people responsible for public lighting in the respective cities identified possible locations where the lighting could be changed according to the research schedule. One of our requirements of the test areas was that they were safe. This was necessary to ensure that the researchers could conduct interviews and tests at night with minimal risk. The residents were sent or shown a letter informing them that tests were being conducted to evaluate the perception of safety of the area after dark. There was no mention of lighting or the commissioner (i.e. Philips) in the letters.

The number of different respondents who participated in the tests in each area is shown in Table 2. The respondents were recruited from people living in the vicinity, but not in the actual streets in the experimental area. The split over gender and age group (below and above 40 years) is shown in table 3. One of the recruitment criteria was that the respondents walked or biked outside after dark at least three times a week.

The test involved individual face-to-face interviews during which a detailed questionnaire was filled in. In addition, objective measurements of visual performance were conducted. Each test lasted ~45 minutes. A *mixed research design* was used in Eindhoven and Spain, meaning that some of the respondents (55 and 60 in the case of the Netherlands and Spain respectively) participated in the test both under the initial lighting condition as well as after the lighting had been changed (i.e. "before and after") while others only participated in the subjective evaluations after the lighting had been changed (see Table 2). This *mixed design* enabled the detection of artifacts since people might become more sensitive to lighting after they have been interviewed about it the first time. The lighting was changed soon after the first set of interviews ("before" interviews) were completed and the "after" interviews were started at least 3 weeks after installation of the new lighting. There was no extra maintenance (e.g. cleaning) when the lamps were changed.

During the face-to-face interviews, the respondents were asked to

1. Rate their perception of safety and comfort in the test area on a 5-pt scale
2. Rate the importance of street lighting to their perception of safety and comfort
3. List the most important aspects of lighting for them and to evaluate the street lighting in the test area against these and other aspects

Subsequently, the respondents were explicitly asked to

4. Make various comparisons using a 7-point scale with respect to the previous lighting condition.

Visual performance was evaluated on the basis of the distance to recognize faces and colors. During the facial recognition test, the researchers stood with their back towards the closest pole so that the picture was only illuminated from the distant neighboring pole. The researchers held pictures with the faces of well-known personalities for the particular country in front of themselves. The pictures were printed on non-glossy A4 paper so that the size of the face was approximately life-sized. A total of 8 different pictures were used. The pictures were divided into two groups of 4 pictures. Half of the residents were shown one group of 4 pictures under the initial lighting, and the second group of pictures after the lighting had been changed. The other half of the participants was shown the pictures under the reverse lighting conditions so that all pictures were observed under both lighting conditions. The order of the 4 pictures shown was randomized among the different participants. Only the respondents in the "before + after" group did the facial recognition test, and a within-subject analysis was done to compare the performance under the different light sources.

The poles used and the position at which the researcher stood relative to the pole was chosen under the initial lighting. The vertical illuminance at the position of the pictures was measured under both lighting conditions.

The protocol for the facial recognition test was as follows. As shown schematically in figure 2, the test person started walking slowly from a distance of ~15 m towards the researcher holding the picture. They were instructed to stop and say as soon as they were close enough to

1. Identify the gender of the person on the picture
2. See the picture well enough to guess the identity of the person and
3. See the person well enough to be sure of their identity

It was stressed that the focus was on seeing the picture well enough to guess or be sure of the identity of the person on the picture even if the respondent did not know the person or remember their name. All three distances were recorded.

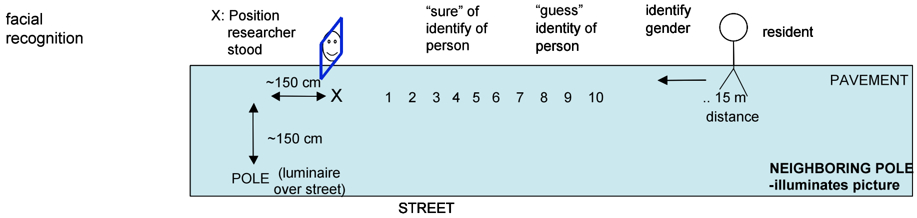


Figure 2: Schematic of set-up used in facial recognition and color identification tests

Table 2: Summary of the number of respondents and timing of evaluations done in 3 European cities

		Installed Lamps and Test Dates				Evaluations Done	
Location	Nr. different respondents	Initial Lighting Condition	Test Date 1 Initial Condition	Lighting after Lamp Change	Test Date 2	Comparison of Visual Performance	Subjective Evaluation
Eindhoven, NL	55	SON	March 2006	CDO 2800K	April 2006	√	√
	56			CDO 2800K	April 2006		√
Navalcarnero, Spain	60	SON	April 2007	CDO 2800K	May 2007	√	√
	60			CDO 2800K	May 2007		√
St. Helens, UK	30	SON	November '08	CDO 2800K	January '09	√	√
	33	SON	November '08	CDO 4200K	January '09	√	√
	31	CDO 2800K	November '08	SON	January '09	√	√
	31	CDO 4200K	November '08	CDO 2800K	January '09	√	√

Table 3: Summary showing split over gender and age group

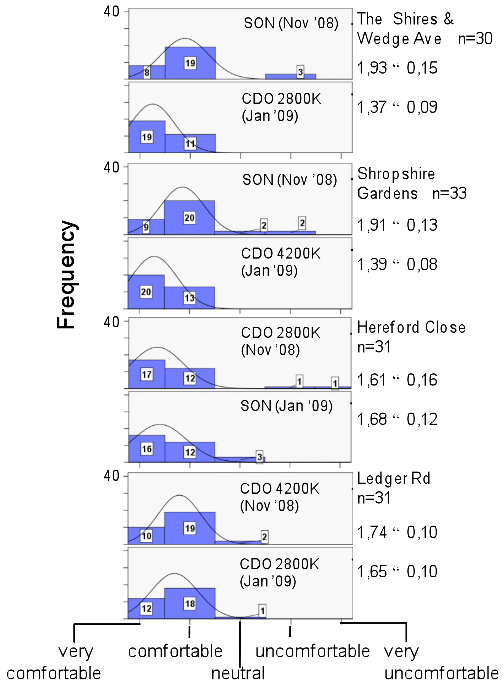
	Eindhoven, NL (n=111)		Navalcarnero, Spain (n=120)		St. Helens, UK (n=125)		All 3 countries (n=356)	
	% male	% female	% male	% female	% male	% female	% male	% female
≤ 40	15	12	24	27	21	20	20	20
> 40	50	24	27	20	24	35	33	26

RESULTS

The results were analyzed separately for each country. In all three countries, the most important aspect of street lighting given by the respondents was the "brightness" of the illuminated area. Consistent with studies referenced in the introduction, a higher perceived brightness of the street and pavement contributes to a higher perception of safety. Since one of the requirements of the areas chosen was that it was safe, it is not surprising that independent of the lighting, people felt relatively safe in all test areas.

As illustrated by the histograms of the results from the UK, substantially more people felt *very* comfortable when the same area was illuminated with warm or neutral white light compared to with SON (see figure 3). This trend was also seen in Eindhoven and in Navalcarnero. The mean and standard error of the mean is written next to the plots in figure 3 and also by similar plots in later figures.

Table 4 summarizes how respondents in the UK answered various questions on a 5-point scale regarding their perception of comfort in the area, the quality of the lighting and the effect of the street lighting on their perception of safety and brightness of the area. The mean for the above evaluations are given. Paired-sample T-tests (confidence interval 95%) were used to evaluate if the mean of the ratings were different or not under the first and second lighting condition. There is a difference when the corresponding value in Sig.(1-2) column in Table 4 is less than 0,05.



Question: How do you feel about the area here? After sunset, please rate how you feel on a 5 point scale from very comfortable/very much at ease to very uncomfortable/ very uneasy. very comfortable = 1, very uncomfortable = 5

Figure 3: Plots showing how respondents in St. Helens, UK rated the perception of comfort before and after the lighting had been changed.

The respondents were asked the same questions under both lighting conditions. Moreover, at the point where they were asked these questions under condition 1, there was no discussion that the lighting would be changed and under condition 2, there was no mention that the lighting had been changed.

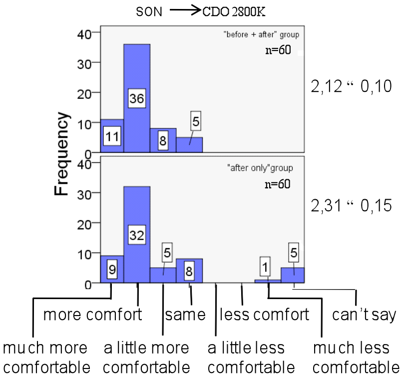
As seen in table 4, there were no statistically significant differences regarding how the same people rated the area and effect of the street lighting on their perception of safety when the lighting was changed from CDO 4200K to CDO 2800K. However, when the lights were changed from SON to either CDO 2800K or CDO 4200K, the perception of safety, comfort, brightness and light quality was improved.

When the lights were changed from CDO 2800K to SON, there was a statistically significant reduction in the rated light quality, brightness of the area and the effect of lighting on the perception of safety. In particular, the brightness of the area was rated to be "just right" with CDO 2800K and CDO 4200K, whereas it was rated to be "too dark" with SON. Even when the lighting in Hereford Close was changed from CDO 2800K to new SON lamps, the area with the new SON lamps was evaluated to be "too dark" (table 4). Even though a statistically significant difference in the perception of comfort was found when the lighting was changed from SON to CDO 2800K, there was no statistically significant difference found regarding the perception of comfort of the area when the reverse change was made (i.e. from CDO 2800K to SON). This might suggests that there is an enhancement in the subjective ratings after changing the street lighting. Nevertheless, the results taken together consistently indicate that for pedestrians, streets illuminated with white light are perceived to be brighter and safer and at least equal but often more comfortable than the same streets with SON.

Table 4: Summary of ratings for different lighting conditions in St. Helens

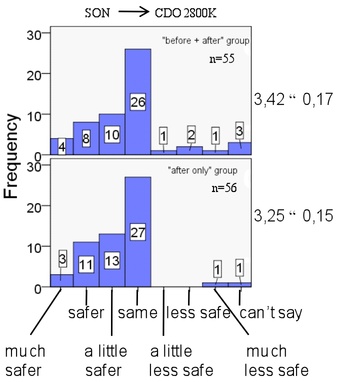
		Mean Rating			
Questions:	Cond. 1 → Cond. 2	Cond. 1	Cond. 2	Diff. (1-2)	Sig. (1-2)
How do you feel about this area here? After sunset, do you feel: very comfortable / at ease (1) ⇔ very uncomfortable / uneasy (5)?	SON → CDO 2800K	1,93	1,37	0,567	0,001
	SON → CDO 4200K	1,91	1,39	0,515	0,000
	CDO 2800K → SON	1,61	1,68	-0,07	0,861
	CDO 4200K → CDO 2800K	1,74	1,65	0,097	0,374
Now I would like you to tell me what you think of the lighting in terms of its quality: By quality I mean nice light, good color. Do you feel that it is: 1 (very pleasant) ⇔ 5 (very unpleasant)	SON → CDO 2800K	2,40	1,67	0,733	0,000
	SON → CDO 4200K	2,61	1,30	1,303	0,000
	CDO 2800K → SON	1,94	2,58	-0,645	0,009
	CDO 4200K → CDO 2800K	1,77	1,94	-0,161	0,258
And now I would like to know whether the lighting here makes you feel safe or not. Does it make you feel: 1 (very safe) ⇔ 5 (very unsafe)	SON → CDO 2800K	2,20	1,33	0,867	0,000
	SON → CDO 4200K	2,06	1,33	0,727	0,000
	CDO 2800K → SON	1,52	2,06	-0,548	0,003
	CDO 4200K → CDO 2800K	1,65	1,68	-0,032	0,572
And how do you rate the brightness of the area. For you personally, is it: 1 (much too bright) ⇔ 5 (much too dark). 3 = just right.	SON → CDO 2800K	3,38	2,90	0,483	0,000
	SON → CDO 4200K	3,34	3,00	0,345	0,016
	CDO 2800K → SON	3,00	3,61	-0,613	0,000
	CDO 4200K → CDO 2800K	2,97	3,03	-0,065	0,489

After answering the questions shown in table 4, the respondents were asked during the second condition if they had noticed any recent changes in the test area. As mentioned in the research set-up, the respondents in general did not live in the streets where the lighting had been changed, but in the vicinity. About 50% of the Dutch respondents in the “before + after” group spontaneously mentioned the street lighting had been changed, as did about 40% in the Dutch “after only” group. By comparison, in Spain, ~77% of the respondents in the “before + after” group and ~50% of the respondents in the “after only” group spontaneously mentioned that the street lighting had been changed. In St. Helens, ~85% of the respondents noticed the change from SON to CDO and ~55% still noticed the change from CDO 4200K to CDO 2800 K. When triggered to look at the street lighting, the majority of respondents, including those in the “after only” groups in the Netherlands and Spain who had not spontaneously mentioned the street lighting, eventually reported that the color of the street lights had changed or that brighter street lights had been installed. Since the street lighting in the Netherlands and Spain was changed on a commonly used connecting road in the residential area, even those respondents who did not do the test under the first condition (i.e. “after only” group) were familiar with the test area. In the UK, where smaller residential streets were used, all of the respondents did the test under the initial as well as the second lighting condition. Thus the vast majority of respondents could make an evaluation as to whether or not they felt equally comfortable (or safe etc.), or less or more so than before. The comparison was done using a 7-point scale, where “no difference” was assigned a value of 4. A one-sample T-test was used to check the difference between the mean of the distribution and the test value “4” (no difference). In figures 4 – 6, results of some of the responses are graphically shown and in Table 5, a wide range of data is summarized.



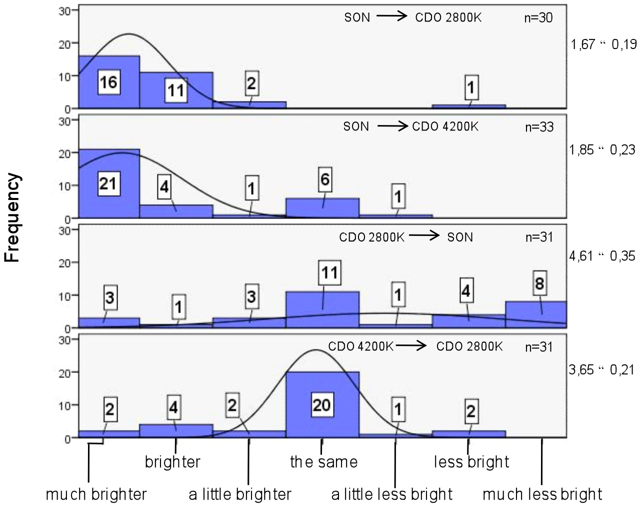
Question: How comfortable is the current street lighting, compared to the street lighting before?
(SON →CDO 2800K, CDO is the “current” lighting)
much more comfortable = 1, the same = 4, much less = 7

Figure 4: Plots showing how respondents in Navalcarnero, Spain, compare the perception of comfort after the lighting was changed to CDO. Mean and std. error of mean is listed.



Question: How does the present lighting compare with the lighting before? Does it make you feel much more safe, the same or much less safe?
(SON →CDO 2800K, CDO is the “present” lighting)

Figure 5: Plots showing how respondents in Eindhoven, NL compare the perception of safety in the test neighborhoods after the lighting had been changed to CDO. much safer = 1, the same = 4, much less safe = 7



Question: How does the present lighting compare with the lighting before in terms of brightness, quantity of light?

Figure 6: Plots showing how respondents in St. Helens, UK compare the brightness in the test neighborhoods after the lighting had been changed as shown on the plots.
much brighter = 1, the same = 4, much less bright = 7

When specifically asked to compare the lighting, the majority of respondents in all three countries rated the white street lighting to be equally or more comfortable than the yellowish SON street lighting. There were no statistically significant differences between the “before + after” and the “after only” group in either the Netherlands or Spain. The most common reasons given for the increased comfort were related to the ability to see clearer, better and further. The reason most often given by the few respondents who rated the area to be less comfortable after the change to white light was that the area was too brightly lit in their opinion.

Moreover, when the street lighting is changed from yellowish HPS to warm or neutral white CDO, the perception of safety is significantly improved. In the test street in St. Helens, where the lighting was changed from warm white CDO to yellowish SON, the majority of respondents did not report any change in the perceived safety in the area – albeit a few more respondents reported that it had deteriorated. The fact that there was no significant difference in this “before vs. after” test when white CDO was offered first and yellowish HPS offered subsequently might indicate that there is a positive enhancement in the rating of the second lighting condition since respondents might automatically expect an improvement when street lighting is changed. Nevertheless even with this “expected improvement”, yellow HPS is not rated better than white light regarding the ambience of perceived safety created. No difference was found between the perceived safety under warm and neutral white light in St. Helens. CDO 4200K was not evaluated in the Netherlands and Spain in this test.

The main reason given in all three countries for the increased perception of safety under white light is related to the higher perception of brightness of the whole area. The majority of respondents perceive the area illuminated with white light to be brighter, even though the measured illuminance level was not increased (Table 6). This is consistent with previous laboratory studies referenced in the introduction.

When the area appeared brighter, most respondents felt that their clarity of sight was improved and this was linked to an improved perception of safety. Though not the subject of this paper, it should be noted that many respondents clearly expressed that they want the area at night to appear “bright”, but not “*too* bright”. The lighting levels used in the different test locations were typical for the type of urban streets in the particular country and were not perceived as being “*too* bright” by most respondents in the specific area. As seen subsequently in Table 6, the installed lighting levels varied significantly in the different countries, with the highest level being in the Spanish test location.

In summary, in all three test locations, most respondents appreciated the increased perception of brightness achieved by using white CDO street lighting. This was achieved at the same installed power and comparable illuminance levels.

Table 5: Summary of various evaluations comparing the second to the first lighting condition

Question	Land	Group	Cond. 1 → Cond. 2	Mean	Std. Error Mean	Test Value =4 Sig. (2-tailed)
Now I would like to ask you how comfortable and pleasant the present lighting is in your personal opinion? Compared to the lighting before, is it? 1 = much more comfortable 4 = the same 7 = much less comfortable	NL	b+a[1]	SON → CDO 2800K	3,28	0,24	0,004
		a only[2]	SON → CDO 2800K	3,24	0,19	0,000
	Spain	b+a	SON → CDO 2800K	2,12	0,10	0,000
		a only	SON → CDO 2800K	2,31	0,15	0,000
	UK	b+a	SON → CDO 2800K	1,77	0,20	0,000
		b+a	SON → CDO 4200K	1,94	0.17	0,000
		b+a	CDO 2800K → SON	4,06	0,37	0,861
		b+a	CDO 4200K → CDO 2800K	3,45	0,21	0.013
And how about safety? How does the present lighting compare with the lighting before? Does it make you feel 1 = much safer 4 = the same 7 = much less safe	NL	b+a	SON → CDO 2800K	3,42	0,17	0,002
		a only	SON → CDO 2800K	3,25	0,15	0,000
	Spain	b+a	SON → CDO 2800K	2,41	0,11	0,000
		a only	SON → CDO 2800K	2,63	0,13	0,000
	UK	b+a	SON → CDO 2800K	2,07	0,21	0,000
		b+a	SON → CDO 4200K	1,97	0,16	0,000
		b+a	CDO 2800K → SON	4,32	0,28	0,258
		b+a	CDO 4200K → CDO 2800K	3,71	0,18	0,119
And what about the brightness of the area? Does it look 1 = much brighter 4 = the same 7 = much less bright	NL	b+a	SON → CDO 2800K	3,17	0,21	0,000
		a only	SON → CDO 2800K	2,76	0,18	0,000
	Spain	b+a	SON → CDO 2800K	2,08	0,96	0,000
		a only	SON → CDO 2800K	2,35	0,12	0,000
	UK	b+a	SON → CDO 2800K	1,67	0,19	0,000
		b+a	SON → CDO 4200K	1,85	0,23	0,000
		b+a	CDO 2800K → SON	4,61	0,35	0,087
		b+a	CDO 4200K → CDO 2800K	3,65	0,21	0,102

[1] b+a = “before + after”group, [2] a only = “after only” group

In each area, respondents in the "before + after" group performed facial recognition tests under 2 lighting conditions.

In Spain and the Netherlands, the distance at which residents were sure that they could recognize faces on the picture was increased by more than 20% under white light. This objective measurement was consistent with subjective evaluation that faces were easier to recognize under white light.

In tests conducted in the UK, independent of whether the test was first done under white or yellow light, respondents consistently expressed the perception that the clarity of their visibility and ability to see expressions, faces and details was improved under white light sources. However, this was not consistently reflected in the results from the facial recognition tests done in St. Helens. In Hereford Close where the test was first done under CDO 2800K and then under SON, the mean distance for facial recognition was longer under SON. It should also be noted that in Hereford Close, the mean distance for facial recognition under CDO was lower than in other test locations in St. Helens where the vertical illuminance on the pictures were comparable. The reason for this is unclear. Compared to the initial CDO condition, the difference in the mean under the second lighting condition (SON) was just statistically significant. This result might indicate that there was a "learning effect" which contributed to the respondents identifying the pictures from further away in the 2nd lighting condition (even though they were shown different pictures). However, this "improvement" attributed to a learning effect is less than the improvement generally seen when CDO 2800K or CDO 4200K is used instead of SON.

Table 6: Average Distance for Facial Recognition Measured in Tests done in Eindhoven, Navalcarnero and St. Helens

Cond.		Vert. illuminance on picture (Lux)	Dist. to identify person. Mean ± std. Err. Mean (m)	Diff. Mean Cond1-Cond 2 (m)	Sig. Cond 1_2
	Eindhoven, The Netherlands (55 respondents)				
1	SON (yellow)	3.3 ± 0.6	5.4 ± 0.5	-1,2	0,000
2	CDO 2800K (warm white)	1.4 ± 0.4	6.6 ± 0.4		
	% higher with CDO 2800K rel to SON		+ ~22%		
	Navalcarnero, Spain (60 respondents)				
1	SON (yellow)	10 ± 0.7	8.5 ± 0,26	-2,4	0,000
2	CDO 2800K (warm white)	~10	10.9 ± 0,21		
	% higher with CDO 2800K rel to SON		+ ~28%		
	The Shires and Wedge Avenue, St. Helens, UK (30 respondents)				
1	SON (yellow)	~1.6	8.7 ± 0.5	-1,1	0,015
2	CDO 2800K (warm white)	~1.6	9.8 ± 0.4		
	% higher with CDO 2800K rel to SON		+~13%		
	Hereford Close, St. Helens, UK (31 respondents)				
1	CDO 2800K (warm white)	~1.6	7.6 ± 0.5	-1,2	0,047
2	SON (yellow)	~1.6	8.9 ± 0.7		
	% higher with CDO 2800K rel to SON		- ~14%		
	Shropshire Gardens, St. Helens, UK (33 respondents)				
1	SON (yellow)	~0.6	5.7 ± 0.5	-1,8	0,003
2	CDO 4200K (neutral white)	~0.6	7.1 ± 0.6		
	% higher with CDO 2800K rel to SON		+ ~25%		
	Ledger Road, St. Helens, UK (31 respondents)				
1	CDO 4200K (neutral white)	~1.6	9.8 ± 0.5	-1,4	0,040
2	CDO 2800K (warm white)	~1.6	11.3 ± 0.5		
	% higher with CDO 2800 rel to 4200K		+ ~13%		

CONCLUSION AND DISCUSSION

The results presented in this paper are based on quantitative research exploring the effect of lamp spectrum on people's perception of street lighting after dark. The results show that people experience several benefits when high quality white light is used instead of yellowish street lighting. In particular, the perception of brightness, comfort and safety is significantly enhanced in the same area as judged by respondents in three European countries who conducted the tests in areas where the street lighting had been changed from yellowish SON to warm or neutral white CDO lighting. The results of these field tests together with other published results [11, 12] illustrate the limitations of the current practice of using the photopic luminous efficiency function V(λ) at mesopic light levels (i.e. between 0,001 – 3 cd/m^2). V(λ) is used to transform the spectral power distribution of a light source into a single measure of the light level (luminance and illuminance). V(λ) characterizes the spectral sensitivity of foveal cones, which peak at 555nm under photopic lighting conditions (i.e. > ~3 cd/m^2). However, many of the lighting levels encountered on residential streets at night fall within the mesopic range. At mesopic light levels, both rods and cones in the retina may be active. This leads to changes in the spectral sensitivity with changing light levels since the contribution of rods and cones vary with changing light levels in the mesopic region. The peak of the spectral sensitivity of rods is at ~507nm. Therefore for lighting applications at night, the effectiveness of lamps with relatively more short wavelength emission (i.e. white light sources compared to yellow light sources) can be underestimated by the current system of photometry. This is currently being addressed by various technical committees (TC) within the CIE. In particular, CIE TC 1-58 is working to establish the appropriate mesopic sensitivity functions which can serve as the foundation of a system of mesopic photometry based on visual task performance (e.g. detection of objects, speed of detection, identification of the objects). This system is not expected to correlate well with visual assessment of brightness in the mesopic region [13]. However, another technical committee (TC 1-37) is developing a supplementary system of photometry for evaluation of lighting at all lighting levels in terms of brightness.

The use of a more appropriate system of mesopic photometry for the mesopic range can encourage the use of more visually effective and thereby energy efficient lighting and eventually contribute to a safer, more comfortable and pleasant feeling for people outside at night.

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Light and Corporate Identity;
Using Lighting for Corporate Communication

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ABSTRACT

The central focus of this study is to investigate what potential exists for brand communication in the lighting of retail outlets. Lighting not only facilitates the visual task, helping to present the merchandise and contributing to the feeling of wellbeing, but can also augment the communication of a brand's appearance. For this study, computer visualisations of retail outlets with different lighting variations are evaluated in terms of light, spatial setting and brand impression by regional and international groups using the semantic differential technique. A comparison between rooms with and without luminaires yet with the same lighting effect demonstrates the effect of luminaires as design objects. From the results it can be deduced that light can be used for brand communication in order to define the image of a company more clearly.

Keywords

Retail design, Perception, Corporate identity, Lighting, Marketing, Brand communication, Brand image

INTRODUCTION

In lighting engineering, the perception of lighting has long been evaluated in the context of safety and efficiency at the workplace. In recent times, however, there has been an increase in the proportion of studies looking at the atmosphere of the room – whether aimed at increasing the motivation at the workplace or at generally improving the feeling of wellbeing on the premises (Loe et al., 2000; McCloughan et al., 1999; Knez, 2000). As a result, quantitative lighting design has been expanded by the addition of an important dimension, that is to say, by the inclusion of this qualitative perspective. In the context of brand communication, the question raises itself as to what qualitative messages can be conveyed via architecture or architectural light, respectively, and how is this aspect incorporated in the marketing.

From the semiotics perspective, the architecture can be seen as a symbol (Nöth, 1985). A window, for instance, not only fulfils the practical function of allowing the permeation of light, but also communicates meaning depending on its shape and position. Accordingly, many symbols in architecture have an intentionality and can be deciphered if the observer knows the code – maybe using architectural history for instance. Thus, for example, Krampen and Kotler (1979) used the semantic differential analysis to identify the factors of meaning that connect people and buildings; and Eco (1972) developed his semiotic model in which he distinguished between *denotation* as a physical function and *connotation* as a socio-anthropological function. Hence, the interest of brand communication is primarily directed at the secondary function of architecture, the connotation. Richter (2008), in his architectural psychological work, describes how, for instance, consumer worlds now make use of insignia from the sphere of religion in their spatial symbolism.

Conversely, the findings of brand management form an important framework for dealing with the concept of brand communication. The analysis of the consumer market and buying behaviour creates an essential pre-condition for developing new strategies (Kotler, 2000). Cultural, social, personal and psychological factors make a considerable contribution to the decision to buy. Knowing the preferences of the respective target group will simplify the propagation of brand messages aimed at transmitting the image of a brand from the company to the customer (Foscht et al., 2008).

The American Marketing Association defines the term "brand" as follows: "A brand is a name, term, sign, symbol or design, or a combination of them, intended to identify the goods or services of one seller or group of sellers and to differentiate them from those of competitors." The dimensions of meaning embodied by the term "brand" can go off in six directions: attributes, benefits, values, culture, personality or user (Kapferer, 1992). In addition to the service, which reflects the brand values, the atmosphere in the particular retail outlet also plays a significant role and must fit the target group (Kotler, 1973).

To investigate an effective communication strategy, marketing uses image analysis, which in turn is often measured using the semantic differential (Osgood et al., 1957; Florack et al, 2007). Kotler explains that image "is the set of beliefs, ideas and impressions a person holds regarding an object." Conversely, Stern defines the term "image" more in terms of communication theory, when she writes: "Image is generally conceived of as the outcome of a transaction whereby signals emitted by a marketing unit are received by a receptor and organized into a mental perception of the sending unit" (Stern et al., 2001). In this present study, the term "image" is related to the external environment when the consumer evaluates photographs of retail outlets – in the sense of store image. "Psychologically-orientated definitions locate image in the consumer's mind and treat it as a cognitive and/or emotional construct based on consumers' feelings" (Stern et al, 2001). Brand image and brand awareness together form the two components of brand knowledge (Keller, 1993). In this context, the architecture of stores can be categorised as a non-product-related attribute. It achieves a symbolic benefit which is appreciated by the customer because it corresponds to his or her self-concept. When making the decision to buy, the emotional dimension can even be greater than the functional aspect (Pawle, 2006). Consumers and their emotions, social standing and value orientation are classified using milieu studies (Florack et al., 2007). The value orientation theory in social psychology was developed by Kluckhohn and Strodtbeck and assumed that understanding and communication could be facilitated by analysing people's orientation in a cultural context (Kluckhohn et al., 1961). A survey consisting of different situations with associated questions served as a basic assessment instrument. Silberer drew the value orientation more into the context of companies and consumer behavior (Silberer, 1991). The allocation into groups within this study makes use of the Sinus milieu, which plots the value judgement on the Y-axis and social standing on the X-axis (Florack et al., 2007).

Lighting in the form of neon advertisements has long been used for brand communication (Schivelbusch, 1992). Luminous texts or company logos have increased a brand's presence in the urban area and, as a luminous feature at a shop's entrance, have made it easier to identify a brand-name store. Seen in terms of semantics, light is directly used as a sign. Yet when consumers enter the store, they are no longer confronted by the brand's luminous signage but are standing in the light of that brand, experiencing a specific atmosphere that is deliberately linked with the brand via the lighting. The consistent use of a uniform lighting concept for all the retail outlets of a brand helps a company to build up a uniform image for a clear brand identity. From the marketing point of view, the lighting not only fulfils the function of facilitating vision and of creating a hierarchy of perception using differentiated brightness levels for the presentation of special products, but also reflects a brand identity. Within the corporate architecture, the lighting then becomes an information medium for the corporate identity (Messedat, 2007). The value of a lighting system for salesrooms is therefore no longer seen solely in terms of how attractive it is in the sense of a good general sales lighting for generating more sales turnover (Cuttle et al., 1995), but also in terms of how well it conveys the brand image. The existence of uniform design guidelines for store lighting is evidence of how light has now become a strategic component of companies' corporate design manuals (Scheer, 2001). The study sought to demonstrate how the lighting can create different brand images within the same room. The qualitative lighting design approach helps to consider the principles of perception-oriented lighting design as well as how luminaries are integrated into architecture (Ganslandt et al., 1992).

METHOD

To investigate the hypothesis that solely changing the lighting concept is sufficient to change the brand identity of a retail outlet, an empirical consumer investigation was conducted. It was further assumed that the appearance of the ceiling in a standard shop can produce a prestigious impression all on its own. The background for this assumption lies in the observation that heterogeneous merchandise below eye level dominates the visual field, whereas – speaking of architectural lighting design - the ceiling is mainly influenced by the architecture itself and thereby the ceiling could contribute significantly to the appearance of a store and likewise to the corporate lighting image. An additional assumption was that light on its own makes classification in the sense of social milieus possible and that luminaires are not absolutely necessary. This aspect could clarify the role of the lighting concept in relation to the product design of the luminaries within corporate lighting design guidelines. A further hypothesis was that a high-class store impression does not necessarily equate to simply increasing the brightness.

The sample group was selected from volunteers who had mainly little to do with architectural lighting professionally. To analyse global differences, part of the study was conducted with an international sample group. To obtain an evaluation of different lighting situations, the test participants were asked to give their judgement on the light, spatial setting and brand. The psychophysical method of "semantic differential" for quantifying stimulus and subjective reaction, which is frequently used in lighting research, was reduced to just a few dimensions in order to reveal clearer relationships (Houser et al., 2003). Eleven pairs of adjectives covered the different dimensions. The light was evaluated via the following factors: "bright – dark", "high-contrast lighting – diffuse lighting", "cold – warm". The room's characteristics were rated using the paired adjectives "spacious – defined". The adjective pair "attractive – unattractive" directly rated the subjective emotional impression in the sense of an affective evaluation (Schierz, 2004). Attributive components, representing a cognitive evaluation of mental concepts, were rated using: "natural – technical", "dramatic – relaxed", "uniform – differentiated" and "unobtrusive – expressive". The dimension of the brand was evaluated relative to the social milieus of the consumers and to the possible allocation of brand fields to the attributive adjective pairs "traditional – modern" and "low budget – high class". The spectrum of evaluative tasks for the participants ranged from photos depicting real architecture, combinations of photography and graphic art through to lighting visualisations that enabled different lighting concepts to be created for the same location. The test participants were surveyed online to keep the workload and costs within appropriate limits, especially for the international survey. The results were evaluated using descriptive statistics and correlation analysis.

Experiment 1:
Evaluating the photography of real projects

Experiment one aims at existing projects and reveals for an outdoor and indoor situation that the lighting design can influence the mood and brand appearance even if the building structure appears similar. Surveying several architectural situations in real environments is a highly complex process, especially regarding the proximity of the buildings to each other, the influence of the surroundings, the architectural differences and the coordination of a sufficiently high number of participants. As an initial step, therefore, an image evaluation was conducted using photographs in an online survey. Because petrol stations have been using uniform lighting design principles for quite some time now (Stichting Prometheus, 1994), night-time photos of petrol stations were used, whereby all the specific brand information in the form of text and logos had been deleted using image processing (Figure C1, Situation A).

Furthermore, to test what effect the luminaires have on the appearance of the ceiling within a store, two outline perspectives of the room with the cut-out in the ceiling were first given to the observer for evaluation, followed by the complete photos. In this way, an integrated lighting approach was set over and against an additive concept with spotlights (Figure C2, Situation B). The personal details collected not only included age, sex and experience in lighting design but also the participant's value orientation, the size of their hometown and their current mood (Table T1).

The online survey (n=101) used the Limesurvey software, which worked with a seven-point scale for the semantic differential for each question. The two ends of the scale corresponded to "very much"; the middle was labelled "neutral". The first image evaluation used an image format of 500 x 375px and the second series used 600 x 390px so that the design and the scales could be viewed together on one monitor.

Table T2 summarises the descriptive statistics for both series of tests. Figure 1 provides a graphic overview of the mean values of the eleven scales. First of all, from the petrol-station situations A1 and A2, it can be seen that the architecture combined with the two different lighting concepts does indeed have an effect on the components relevant for the social milieu since it affects both the basic orientation of "traditional – modern" and the value rating of "low budget – high class". In contrast, the scales of "attractive – unattractive" and "dramatic – relaxed" only show marginal differences.

For situation B showing the interior of two stores, figure 2 shows that a strong analogy is evident within each of the situations B1 and B2 when it comes to the evaluation on the emotional and cognitive levels. Although a large spatial area can only be recognised from its contour and only the ceiling permits a statement about light it reveals a clear similarity to the evaluation of the total shop image. Striking features can be identified not only with the attributes "traditional – modern" and "low budget – high class" but also with "dramatic – relaxed" and the spatial perception "spacious – defined". These points produce a greater contrast than the light attributes "bright – dark" and "high-contrast lighting – diffuse lighting".

In contrast to situation A, where it could perhaps be noted that the petrol stations differed in design and size, a comparable differentiation of the social milieu is evident with situation B where the perspective and proportion are identical. The examples chosen here illustrate how the differences with the petrol stations largely concern the "low budget – high class" scale, whereas the two stores differ more in the "traditional – modern" scale (figure 3). The strong to very strong correlation (0.6-0.8 to 0.8-1 respectively) between the ceiling cut-out on its own and the entire room (Table T3) justifies the assumption that the appearance of the ceiling alone can be taken as an indicator for the appearance of the store as a whole.

Table T1 Test groups for experiments 1, 2, 3

Group	1	2.1	2.2	3
N	101	18	22	99
Female %	48	38	50	67
Male %	48	50	45	31
Age average	28	28	25	31
Light experience %	18	28	41	60
No light experience %	79	61	50	38

Table T2 Descriptive statistics for experiment 1: Mean (M) and standard deviation (S). Situations A1 and A2 petrol-stations, situations B1 and B2 Retail shop with a for ceiling detail and b for total shop image.

Situation	A1		A2		B1a		B1b		B2a		B2b	
	M	S	M	S	M	S	M	S	M	S	M	S
attractive | unattractive	-0,2	1,6	-0,2	1,6	0,4	1,7	0,4	1,6	-0,1	1,8	-0,7	1,8
dramatic | relaxed	-0,2	1,4	0,0	1,4	0,0	1,4	-0,4	1,3	0,4	1,3	0,9	1,4
spacious | defined	-0,5	1,4	0,0	1,5	-0,4	1,5	0,0	1,4	-0,6	1,5	-1,2	1,4
uniform | differentiated	-1,5	1,3	0,1	1,6	-0,8	1,8	-0,1	1,7	-0,6	1,7	-0,7	1,5
natural | technical	1,7	1,4	1,2	1,3	0,7	1,5	0,4	1,5	0,9	1,5	0,6	1,6
bright | dark	-1,0	1,3	-0,1	1,6	-0,9	1,3	-0,7	1,3	-0,4	1,3	0,0	1,3
cold | warm	-1,5	1,4	-0,2	1,4	0,6	1,4	0,3	1,4	0,6	1,5	0,8	1,5
high-contrast lighting | diffuse l.	-0,5	1,5	0,1	1,5	0,2	1,4	0,0	1,4	0,2	1,5	0,5	1,4
traditional | modern	0,6	1,8	1,3	1,4	0,1	1,6	0,0	1,6	1,5	1,3	1,4	1,5
low budget | high class	0,3	1,4	0,7	1,5	0,1	1,7	-0,3	1,3	0,8	1,4	1,4	1,3
unobtrusive | expressive	0,7	1,5	0,4	1,4	0,2	1,5	0,4	1,4	-0,1	1,5	-0,6	1,5

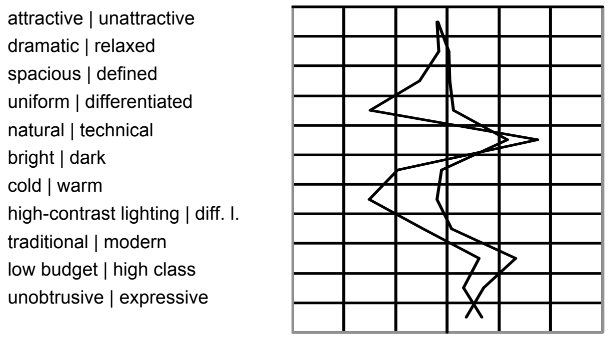

Figure 1 Comparison of mean semantic differential appearance for situations A1 and A2

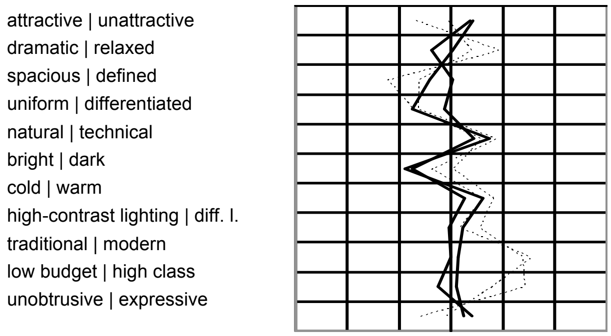

Figure 2 Comparison of mean semantic differential appearance for situations B1 (line) and B2 (dashed line) each with ceiling detail and total shop image

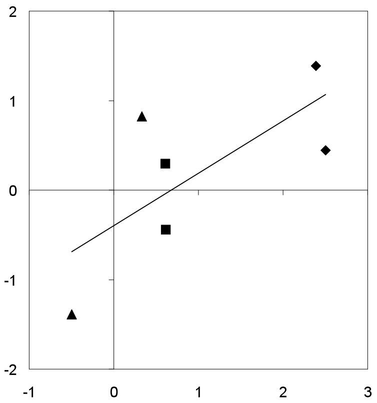

Figure 3 Relation traditional – modern (x-axis) and low budget – high class (y-axis): ■ Situation A, ◆ Situation B1, Situation B2

Table T3 Correlation between ceiling detail and total shop image for situation B retail shop.

Situation	B1a	B1b	B2a
B1a			
B1b	,758**		
B2a	,634*	,191	
B2b	,398	-,208	,871**

Table T4 Descriptive statistics for experiment 2: Mean (M) and standard deviation (S). Situations 1a-8a shop with luminaries (Group 2.1) and situations 1b-8b shop with erased luminaires (Group 2.2)

Situation	1a		2a		3a		4a		5a		6a		7a		8a	
Shop with luminaires	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
attractive | unattractive	0,4	1,8	0,1	1,5	0,3	1,9	-0,2	2,0	0,5	1,9	-0,2	1,8	-0,1	2,2	1,1	1,6
dramatic | relaxed	-0,1	1,4	-0,3	1,4	-0,8	1,8	0,2	1,6	-1,5	1,7	-0,3	1,3	-0,9	2,0	-0,8	1,5
spacious | defined	0,2	1,3	-1,5	0,9	1,0	1,0	0,3	1,5	-0,1	1,7	-1,6	1,1	1,3	1,1	-1,2	1,8
uniform | differentiated	0,1	1,3	-0,3	1,5	1,5	1,2	-0,1	1,4	-0,1	1,8	-1,3	1,4	0,8	1,8	-1,9	1,5
natural | technical	0,9	1,6	1,2	1,4	1,5	1,6	0,8	1,5	1,4	1,5	0,9	1,8	2,7	0,6	1,7	1,4
bright | dark	0,9	1,4	-1,4	1,5	1,2	1,3	0,8	1,5	1,1	1,5	-2,0	0,8	2,6	0,5	-2,2	1,0
cold | warm	-0,8	1,6	-0,1	1,8	-0,1	1,7	0,8	1,5	1,1	1,2	-0,5	1,7	-0,4	1,8	-1,7	1,4
high-contrast lighting | diffuse l.	0,5	1,7	-1,2	1,5	-0,8	1,7	0,6	1,9	-0,4	1,6	-0,1	1,4	-0,2	2,2	0,3	1,6
traditional | modern	0,6	1,6	0,7	1,4	1,7	0,9	0,4	1,3	1,4	1,2	0,6	1,8	1,6	1,7	-0,3	0,9
low budget | high class	-0,2	1,4	0,6	1,6	0,0	1,6	0,3	1,4	0,4	1,8	0,7	1,5	0,5	2,0	-0,5	1,5
unobtrusive | expressive	-0,4	1,6	1,3	1,3	1,2	1,6	0,1	1,5	2,1	1,3	0,9	1,4	1,6	2,0	0,3	1,7

Situation	1b		2b		3b		4b		5b		6b		7b		8b	
Shop with erased luminaires	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
attractive | unattractive	0,9	1,3	-0,2	1,8	-0,1	1,6	-0,3	1,6	0,7	1,7	-0,2	1,8	0,2	2,1	1,2	1,4
dramatic | relaxed	0,2	1,4	-0,9	1,2	-1,0	1,6	0,6	1,5	-2,1	0,8	-0,5	1,0	-1,9	1,3	-0,7	0,8
spacious | defined	0,0	0,8	-0,4	1,2	0,9	1,2	0,1	1,2	0,0	1,6	-1,5	1,4	1,1	1,6	-0,4	1,8
uniform | differentiated	-0,6	1,6	-0,1	1,4	1,7	1,2	0,3	1,4	0,0	1,7	-0,9	1,7	1,3	2,0	-1,2	1,6
natural | technical	1,2	1,2	1,6	1,3	1,9	0,8	-0,3	1,4	1,5	1,3	0,4	1,8	2,4	1,0	1,4	1,6
bright | dark	0,7	1,6	-1,9	0,9	1,2	1,1	0,8	0,9	1,1	0,8	-2,2	1,0	2,7	0,6	-2,0	1,0
cold | warm	-0,8	0,9	-0,6	1,3	0,4	1,5	1,6	0,9	1,4	1,4	-0,7	1,2	-0,6	1,8	-1,9	1,0
high-contrast lighting | diffuse l.	1,2	1,3	-1,1	1,2	-1,2	1,4	0,4	1,3	0,4	1,2	-0,4	1,4	-1,0	1,9	0,3	1,7
traditional | modern	0,4	1,6	1,3	1,1	2,1	0,8	0,1	1,4	2,1	1,0	0,2	1,6	2,3	0,8	-0,7	1,6
low budget | high class	0,2	1,1	0,2	1,5	0,0	1,4	0,6	1,2	0,1	1,1	0,4	1,3	0,7	1,3	-1,0	1,6
unobtrusive | expressive	-1,3	1,1	1,3	0,8	1,8	1,1	-0,5	1,3	2,3	0,8	-0,1	1,4	2,3	1,0	0,2	1,6

Table T5 Correlation analysis for situations 1a-8a shop with luminaries (Group 2.1). *Indicates correlations coefficients that are significant at the 5% level. **Indicates correlations coefficients that are significant at the 1% level.

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10
P01 attractive | unattractive										
P02 dramatic | relaxed	-,531									
P03 spacious | defined	-,134	-,196								
P04 uniform | differentiated	-,310	-,146	,846**							
P05 natural | technical	,192	-,616	,477	,307						
P06 bright | dark	-,226	-,238	,950**	,838**	,439					
P07 cold | warm	-,424	-,123	,296	,432	-,182	,471				
P08 high-contrast lighting | diffuse l.	,079	,400	,141	-,318	-,212	,081	-,209			
P09 traditional | modern	-,304	-,498	,687	,853**	,455	,758*	,527	-,506		
P10 low budget | high class	-,792*	,053	-,114	,150	-,005	,084	,552	-,461	,424	
P11 unobtrusive | expressive	-,108	-,738*	,127	,307	,502	,261	,502	-,712*	,710*	,602

Experiment 2: Evaluating the lighting visualisation

To evaluate one and the same room with different lighting situations, the study used lighting visualisations based on Dialux Renderings. Various investigations have shown that the comments made about computer simulations compare favourably with observations made about the real space and that the comparison is therefore valid and acceptable. (Newsham et al., 2005; Mahdavi et al., 2002; Rohrmann et al., 2002). The aim of the visualisations was to show how the appearance of the same interior changes solely due to the lighting. Refitting a room or constructing several otherwise identical salesrooms would be logistically and economically highly impractical and therefore simulations were used here. The simulated salesroom measured approximately ten by fifteen by three and a half metres. Items of clothing were shown on shelves and tables. The shop window and the background featured decorative points with mannequins, which also gave an idea of the room's size. As the viewing angle, the view looking into the room through the shop window was chosen as the central perspective. This is a perspective that consumers would be familiar with when walking past a store and standing in front of the entrance. Two on-line questionnaires were conducted in order to assess what influence the design of the luminaires has on the appearance. Group 2.1 (n=18) were given visualisations with luminaires (800 x 294px); group 2.2 (n=22) received visualisations in the same format in which the luminaires were erased. As in experiment 1, the same semantic differential was used with both groups. Eight different lighting scenes were given to each of the two groups for evaluation. The paired questions for each lighting situation were randomly put in a new order each time to avoid the effects of repetition.

Table T4 presents the results of groups 2.1 and 2.2 showing the mean and standard deviation. Where the spatial situation is the same but the lighting is different, great differences between the light scenes are apparent not only with the scales for light, but also with the attributes for the allocation to brand fields, i.e. with "traditional – modern", "low budget – high class". For group 2.1, for instance, the relationship between the "traditional – modern" scales and the adjective pairs "spacious – defined" and "bright – dark" shows strong to very strong correlations. The latter has a two-tailed significance of 0.05 (Table T5). The "low budget – high class" attribute shows a middle correlation to the "cold – warm" parameter.

The analysis of the mean values from the two series of situations, 2.1 and 2.2, vividly demonstrates that a strong correlation exists with the four factors "attractive – unattractive", "natural – technical", "high-contrast lighting – diffuse lighting", "low-budget – high class" and all other factors have a very strong correlation (Table T6). In seven cases the correlation on the level of 0.01 has two-sided significance, in three others it is 0.05.

The comparison of store situations with and without luminaires but with the same lighting effect demonstrates that, in the examples presented, the significant impression can be made just with the light alone. The luminaires take on a subordinate role. This aspect can be quite different in real surroundings because the luminaires appear bigger in the room due to the perspective as the observer moves around. Nevertheless, for building a brand image, the importance of the lighting concept compared to the choice of luminaires should not be underestimated.

Table T6 Correlation analysis for Group 2.1 and 2.2.

Scales	Light-Luminaires
attractive | unattractive	,743*
dramatic | relaxed	,860**
spacious | defined	,886**
uniform | differentiated	,910**
natural | technical	,638
bright | dark	,995**
cold | warm	,952**
high-contrast lighting | diffuse lighting	,718*
traditional | modern	,907**
low budget | high class	,772*
unobtrusive | expressive	,891**

* Significance at 5% level. ** Significance at 1% level.

Experiment 3: Evaluating the lighting visualisation in the international comparison

To analyse cultural differences in the context of global marketing strategies, group 2.2, which originated from Germany, was set in relation to group 3, which had an international composition (n=99): group 3.1 = Europe (n=24); group 3.2 = America (n=20); group 3.3 = Middle East (n=26) and group 3.4 = Asia (n=17). Table T7 lists the mean and standard deviation for the entire group 3.

Using the correlation coefficient, table T8 shows the relationship of how greatly the different regions distinguish themselves from each other or resemble each other. The strongest analogies are present in Middle East – Europe, followed by Europe – Asia and America – Europa. If the values are compared with respect to the attributes, it is shown that the strongest correlation exists for "bright – dark", followed by "traditional – modern" and "uniform – differentiated". If the mean of the correlation coefficients is considered, overall there is a very strong correlation between the regions.

If, for instance, only the parameters "traditional – modern" and "low budget – high class" are considered, it then becomes clear, as figure 4 shows, that the geographical areas each receive a similar evaluation yet can still be delineated from each other, and the extent to which regional differences can arise also becomes apparent. By dividing into groups 3.1-3.4 and 2.2, the graphic reflects how the salient points of the evaluations arise for the various lighting situations.

If all the data of group 3 is considered in terms of the evaluation of "spacious – defined" and "bright – dark" in relation to the brightness of the image (Table T9), then it becomes evident from table T10 that the measurement of the overall image brightness correlates very strongly with these two factors and has a two-tailed significance level at 0.01. However, a stronger indicator for the impression of brightness and expanse is the brightness of the vertical surfaces in the image. These account for 70% of the image area and produce a higher correlation coefficient than that obtained with the overall image brightness.

If the "bright – dark" parameter is set in relation to "low budget – high class", it then becomes apparent that the evaluation of the attribute for the price image remains largely constant despite changing brightness (Figure 5). The use of light to generate a high-price brand identity is therefore not dependent on higher luminous flux and thus higher energy consumption.

Table T7 Descriptive statistics for experiment 3: Mean (M) and standard deviation (S). Situations 1b-8b shop with erased luminaires (Group 3)

Situation	1b		2b		3b		4b		5b		6b		7b		8b	
Shop with erased luminaires	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
attractive | unattractive	0,6	1,7	0,1	1,7	-0,8	1,6	-0,4	1,6	0,0	2,0	0,0	1,7	-0,6	2,2	1,1	1,8
dramatic | relaxed	0,0	1,4	-0,8	1,4	-1,5	1,3	0,0	1,7	-2,0	1,2	0,6	1,5	-2,2	1,4	0,5	1,2
spacious | defined	0,3	1,6	-0,2	1,7	0,7	1,6	0,3	1,4	0,5	1,7	-1,2	1,7	1,4	1,7	-1,0	1,8
uniform | differentiated	-0,4	1,7	-0,3	1,8	1,5	1,3	0,8	1,5	1,0	1,7	-1,0	1,4	1,6	1,6	-1,8	1,5
natural | technical	0,9	1,7	1,6	1,2	1,9	1,1	0,1	1,6	2,1	1,0	-0,2	1,6	2,5	0,7	0,4	1,7
bright | dark	1,0	1,5	-1,8	1,2	0,4	1,4	0,5	1,4	0,9	1,5	-2,2	0,9	2,5	0,9	-1,8	1,1
cold | warm	-0,8	1,5	-0,4	1,5	-0,1	1,5	1,4	1,4	0,5	1,8	-0,1	1,8	-1,1	1,8	-1,4	1,4
high-contrast lighting | diffuse l.	0,8	1,5	-1,0	1,5	-1,5	1,3	-0,7	1,7	-1,0	1,7	-0,1	1,6	-1,6	1,9	0,8	2,0
traditional | modern	0,5	1,7	0,6	1,7	2,1	0,9	0,2	1,4	2,1	1,1	0,1	1,8	2,5	0,9	-0,5	1,9
low budget | high class	-0,4	1,6	0,3	1,5	0,9	1,4	0,7	1,5	0,6	1,5	-0,1	1,7	1,2	1,5	-1,1	1,8
unobtrusive | expressive	-0,6	1,4	0,7	1,3	1,8	1,3	0,5	1,5	1,7	1,3	-0,4	1,7	2,0	1,4	-0,8	1,5

Table T8 Correlation analysis for different regions within Group 3 (Situations 1b-8b shop with erased luminaries).
* Significance at 5% level. ** Significance at 1% level.

Scales	Region										Mean
	America-Asia	America-Europe	Europe-Asia	Middle East-America	Middle East-Asia	Middle East-Europe	Germany-America	Germany-Asia	Germany-Europe	Germany-Middle East	
attractive | unattractive	,745*	,779*	,826*	,714*	,654	,927**	,529	,592	,818*	,763*	,735
dramatic | relaxed	,911**	,800*	,937**	,956**	,961**	,924**	,698	,800*	,799*	,734*	,852
spacious | defined	,826*	,883**	,740*	,912**	,806*	,942**	,922**	,949**	,826*	,865**	,867
uniform | differentiated	,952**	,983**	,979**	,941**	,922**	,938**	,814*	,884**	,827*	,879**	,912
natural | technical	,926**	,930**	,972**	,938**	,923**	,960**	,674	,828*	,859**	,721*	,873
bright | dark	,931**	,983**	,965**	,981**	,966**	1,000**	,964**	,942**	,984**	,985**	,970
cold | warm	,918**	,957**	,930**	,879**	,882**	,853**	,896**	,836**	,854**	,969**	,897
high-contrast lighting | diffuse l.	,928**	,842**	,862**	,910**	,895**	,872**	,579	,650	,921**	,643	,810
traditional | modern	,939**	,991**	,945**	,937**	,858**	,920**	,955**	,950**	,931**	,927**	,935
low budget | high class	,763*	,914**	,924**	,678	,831*	,864**	,501	,677	,627	,755*	,754
unobtrusive | expressive	,949**	,936**	,940**	,870**	,822*	,940**	,797*	,806*	,912**	,776*	,875
Mean	,890	,909	,911	,883	,865	,922	,757	,810	,851	,820	,862

Table T9 Image brightness (Minimum 0, Maximum 255) of situations 1b-8b: Total brightness, horizontal surfaces (30%), vertical surfaces (70%)

	Total		Horiz.		Vert.	
	M	S	M	S	M	S
1b	123,0	35,9	156,2	28,4	109,2	29,1
2b	136,7	62,8	160,1	67,7	127,1	57,9
3b	135,2	62,8	134,3	53,8	135,6	66,7
4b	108,7	57,2	126,8	61,8	102,4	54,1
5b	112,6	65,4	116,3	62,0	111,0	66,8
6b	153,6	63,3	151,5	58,5	154,7	65,7
7b	56,5	37,2	52,8	37,2	58,3	37,0
8b	152,3	66,4	134,9	51,0	159,5	70,6

Table T10 Correlation analysis for image evaluation factors and image brightness within Group 3.

Scale	spacious | defined	bright | dark
spacious | defined		
bright | dark	,930**	
brightness total	-,850**	-,874**
brightness horizontal	-,678	-,715*
brightness vertical	-,861**	-,877**

* Significance at 5% level. ** Significance at 1% level.

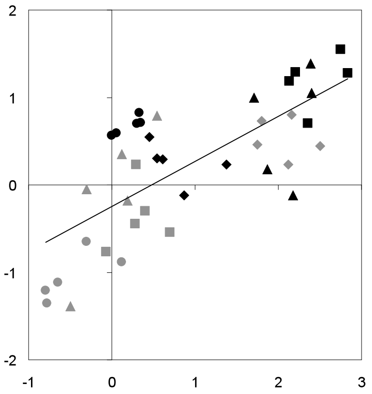

Figure 4 Relation traditional – modern (x-axis) and low budget – high class (y-axis). Situation 1b-8b for Group 3 and Group 2.2 with separate marks for five regions: America, Asia, Europe, Middle East, Germany

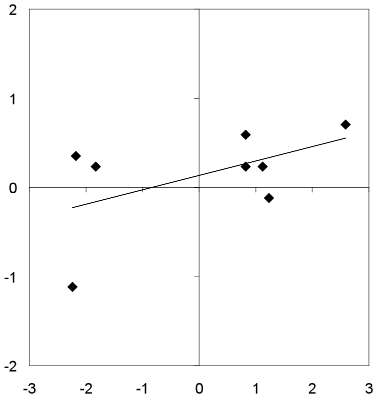

Figure 5 Relation low budget – high class (x-axis) and bright – dark (y-axis). Situation 1b-8b, Group 3

RESULTS

The different image analyses permit the conclusion that various relationships exist between the architectural lighting and the brand identity of a retail outlet. Groupings for strategic marketing can undertaken based on the attributes for social milieu in order to analyse the image of lighting designs for target groups via aspects such as value orientation and social standing. The evaluation of the surveys shows that the rooms can convey a very different image in terms of brand identity simply through having different lighting. This phenomenon can be used for brand communication in order to clearer define the image of a business at the point of sale. The aspect of brightness, although much discussed in lighting research, actually only plays a subordinate role. A possible advantage of this is that using light to construct a striking brand image does not necessarily entail higher energy consumption. The comparison of situations with and without luminaires for the same lighting effect demonstrates that the essential impression is already reached via light and that visible luminaires are not strictly necessary. The appearance of the ceiling can give an indication of the store's image simply by virtue of its lighting effect and design pattern. The international comparison reveals that different groups evaluate the brand image differently, although there is still strong correlation. Uniform lighting concepts could be implemented as global design guidelines for international markets if global variance is included. Lighting concepts that are able to augment the brand identity can generate added value for the business. The financial value of a lighting system would then no longer only consist of investment and running costs but also of the contribution to brand communication.

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Figure C1 Situation A.

Outdoor photos. Petrol station A1 and A2

(Ralf Peters, Tankstelle, 1998. Foto: Courtesy Bernhard Knaus Fine Art, Frankfurt a.M., Germany.)

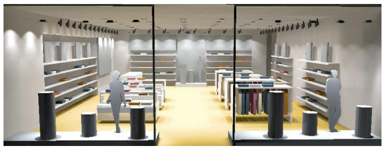
Figure C2 Situation B.

Ceiling visualisations and photos. Shop B1 and B2

Figure C3 Situation C. Retail space visualisations

1a. Shop with luminaires

1b. Shop without luminaires

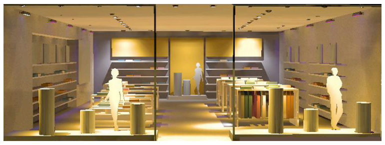


2a. Shop with luminaires

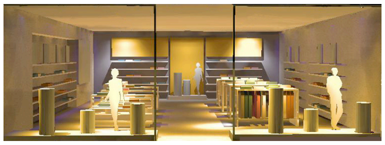
2b. Shop without luminaires

3a. Shop with luminaires

3b. Shop without luminaires



4a. Shop with luminaires



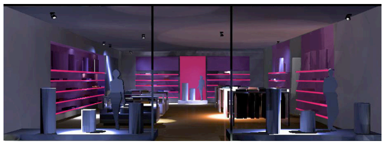
4b. Shop without luminaires

5a. Shop with luminaires

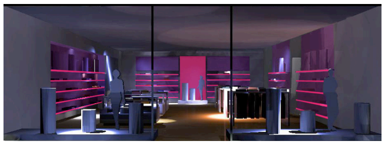
5b. Shop without luminaires

6a. Shop with luminaires

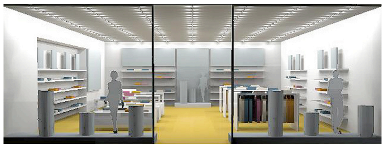
6b. Shop without luminaires



7a. Shop with luminaires



7b. Shop without luminaires



8a. Shop with luminaires

8b. Shop without luminaires

Tuning the Spectrum of Lighting to Enhance Spatial Brightness: Investigations of Research Methods

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ABSTRACT

In this paper we describe research of spatial brightness at photopic levels and how this is affected by the spectral power distribution of the light source. Our research of experimental methods has identified strategies for best practice in experimental design; ignoring these leads to results which can give a misleading estimate of the effect of lamp spectral distribution on spatial brightness. This article reports the on-going meta-analysis of previous work and new experimental data pertinent to research methods. A preliminary set of reliable data are proposed for use with modelling to extrapolate the relationship between SPD and spatial brightness.

Keywords

Spatial brightness, spectral power distribution, research methods, evaluation mode, visual field.

INTRODUCTION

Spectral power distribution (SPD), along with spatial distribution, temporal modulation, and illuminance, is one of the fundamental variables available to the lighting designer. This article discusses the effect of SPD on impressions of spatial brightness at photopic levels typical of interior lighting.

The term *spatial brightness* is used to imply a subjective evaluation of the amount of light in a space. It is distinct from object brightness - the brightness of an illuminated surface or object - although brightness may be the term used by naïve observers, and may be considered akin to the visual clarity judgements investigated in some previous work [1-4]. Spatial brightness is a dominant perceptual attribute. Boyce and Cuttle asked test participants to describe the lighting in a room in their own words and found that they used mainly terms of brightness and clarity; pleasantness and colourfulness were among those also mentioned, but these very infrequently [5].

Interior electric lighting is a significant energy consumer. Within the EU, lighting in the commercial sector consumes 30% of total electricity consumption [6]; lighting accounts for up to 40% of energy costs in a typical UK office [7] and an average of 39% of the energy use in US office buildings [8]. Lighting recommendations are based almost entirely on ensuring visibility and the data on which these recommendations are based have not taken into account any possible effects of the spectral content of the light source. Visual performance models [e.g. 9] imply that virtually all tasks done in offices and schools could be done just as well at much lower illuminances than those currently used. However, illuminances have not been reduced because people like an interior to appear bright. Dim, gloomy lighting can induce a sense of visual discomfort which may change the observer's mood and motivation to carry out a task, particularly if the work is prolonged [10]. Thus, if a perception of brightness could be maintained at a lower illuminance, energy consumption and carbon emissions could be reduced.

There is evidence that light source SPD affects the perception of spatial brightness [e.g 11,12] and this provides a means for reducing illuminances whilst maintaining the same perception of brightness. To do this requires a tool for predicting how lamp SPD affects spatial brightness and hence reliable and appropriate evidence with which to develop the tool.

There is much ongoing work to investigate effects of SPD within the lighting community. The Illuminating Engineering Society of North America (IESNA) has established the Visual Effects of Lamp Spectral Distribution committee to investigate SPD effects on spatial brightness and visual effort at photopic levels, and new research was presented by several groups at the 26th Session of the CIE in Beijing, 2007.

The spatial brightness section of the IESNA committee has two stages of work. The first stage is to identify reliable empirical evidence that demonstrates an effect of lamp spectrum on spatial brightness at photopic levels; the objective of this article is to provide evidence to support decisions necessary when identifying reliable evidence. *Reliable* is here intended to mean data which are unbiased by the experimental procedure and through this are more consistent. Through experimentation, critical analysis of experimental data and literature survey, the authors have identified features of experimental design that might be considered best practise for research of subjective evaluations of lighting. The second stage is to identify a method for predicting the magnitude of the lamp SPD effect on spatial brightness, hence using the set of reliable data to test and develop prediction tools.

Around sixty studies have previously investigated lamp SPD effects on spatial brightness (or visual evaluations considered similar to spatial brightness), some reporting a significant effect while others report a negligible effect. The problem encountered when comparing the outcomes of these different studies is that each has tended to use a unique combination of independent variables and methods - lamp SPD, response task, stimulus size, illuminance and evaluation mode [13]. A first step in interpreting these data is an exploration of research methodologies to identify how these differences in methodology matter, hence to identify those methods giving reliable and appropriate estimates of lamp SPD effects on spatial brightness.

A problem within the body of previous work is that much of it must be considered unreliable, frequently because of incomplete reporting. There are three reasons for considering work to be unreliable. Firstly, the published work either reveals an experimental or subjective bias, or does not present sufficient data to check whether an expected bias has been successfully countered. Secondly, there are insufficient data to allow the results to be analysed; one common problem is that the mean value of the dependent variable is reported but without a measure of dispersion, and there are no raw data or references to further publications. Finally, descriptions of the apparatus and methodology are insufficient.

RESPONSE TASKS

The assessment of brightness is a psychophysical task that requires the test participant to make sensory responses to physical stimuli. These assessment tasks are usually one of three types:

- *adjustment*, where the participant is required to adjust the magnitude of one dimension of a stimulus (e.g. illuminance) toward a given sensation, such as matching the visual sensation of a reference stimulus;
- *discrimination*, where the test participant is required to make simple ordinal discrimination judgements of stimuli, e.g. which of two stimuli is brighter; and
- *category rating*, where the participant is required to assign numbers to stimuli to represent the sensation magnitude.

Matching

In the side-by-side matching task, two stimuli differing in illuminance and SPD are presented simultaneously, illuminating adjacent, identical spatial locations (Figure 1). The illuminance of one stimulus is adjusted by the test participant until the two appear, as near as possible, equally bright. If the ratio of the illuminances of these stimuli is different from unity then the brightness judgement must in some way be affected by differences in light source SPD. The authors recently reported on sources of experimental bias in the matching task [14] and these tend to exaggerate apparent differences between stimuli.

Figure1. Identical side-by-side rooms used in a matching task. This is a simultaneous evaluation.

There are three elements of the matching procedure that can affect the results. The first relates to the process of adjustment itself. There is a tendency toward conservative adjustment, whereby the variable stimulus is set to a lower level than expected [15]. This can most easily be seen in null condition data (matching using stimuli of identical SPD), where the mean illuminance of the variable stimulus is significantly less than that of the fixed stimulus at equal brightness, but is also evident in matches made between different types of lamp. When matching tests are carried out at a range of reference illuminances, there is a tendency for response contraction bias [16]; matches made at the higher illuminances are set to a lower than expected illuminance, whilst matches made at the lower illuminances are set to a higher than expected illuminance. Bias due to dimming can be countered by applying the dimming action to alternate stimuli on successive trials.

The second bias in the matching task relates to the stimulus position; whether a particular stimulus is located in the left-hand (LH) or right-hand (RH) field. Thornton & Chen [4] used side-by-side matching to compare visual clarity under different lamps. Their trials included four null conditions for which an illuminance ratio (RH/LH) of unity would be expected at equal clarity if there were no positional bias. Subsequent analysis [17] of these null condition data suggested a mean illuminance ratio (RH/LH) of 1.145 at equal clarity, although there are insufficient data to determine whether this is a statistically significant departure from unity. A positional bias has also been reported when using smaller fields; this was an observer who consistently reported the top half of a horizontally split field to be brighter than the bottom half, even when the top and bottom stimuli were reversed [18]. Positional bias can be countered by using lamps to illuminate alternate spatial locations in successive trials. Some studies do analyse their data for positional bias and in these it has been shown to have negligible effect [e.g. 19], but the majority of studies do not make this analysis, do not employ counterbalancing, and a positional bias must therefore be considered possible.

In many matching studies, possible effects of conservative adjustment bias and positional bias are compounded. Table 1 shows the results from Aston & Bellchambers' matching tests [1]. In these tests, *Kolor-rite* lamps illuminated the left-hand booth and three test lamp types alternately illuminated the right-hand booth. Test participants adjusted the illuminance of the *Kolor-rite* booth until the visual clarity of the two booths appeared equal, the test lamps being set to one of three reference illuminances. Neither dimming application nor spatial location were counterbalanced. In every case, the median illuminance of the *Kolor-rite* lamp is lower than the illuminance of the test lamp; it is not possible to say whether these differences in illuminance is due to lamp SPD or to experimental bias.

Illuminance of test lamps	**Median illuminance (lux) of Kolor-rite lamp at equal visual clarity with three test lamps**		
(lux)	Daylight	Warm White	White
200	170	130	145
400	270	230	270
800	560	460	435

Table 1. Results of Aston & Bellchambers' side-by-side matching test [1]. In every case the variable stimulus (Kolor-rite) in the left-hand booth was set to the lower illuminance.

The third bias relates to the initial illuminance of the variable stimulus, as set by the experimenter prior to each trial. This can be set to an illuminance either higher or lower than that of the reference stimulus, which may modify the observer's internal brightness reference. An effect of initial illuminance can be seen when an adjustment task is used for preference judgements, an absolute judgement carried out in the absence of a reference stimulus. Ray asked observers to adjust the illuminance of lighting to a level clear and comfortable to read at [20]. This was carried out under two types of tungsten filament (GLS) lamp, having either a clear-glass or blue-glass envelope. Eighteen observers repeated this twice for each type of lamp, once each starting from a high illuminance and a low illuminance. The results are shown in Table 2. It can be seen that the lamps were set to a higher illuminance when the initial illuminance was high than when the initial illuminance was low, and these differences are statistically significant ($p<0.05$, t-test).

	Clear-glass GLS lamp		**Blue- glass GLS lamp**	
Initial illuminance of stimulus	high	low	high	low
Mean preferred illuminance (lux)	1123	645	806	419

Table 2. Mean illuminances of lamps set to a level clear and comfortable to read at [20]. Note: unpublished undergraduate thesis, raw data analysed by Fotios [17].

For the side-by-side matching task, this suggests a trend for the variable stimulus to be set to a higher level at the matched condition when starting from a high initial illuminance and a lower level when starting from a low initial illuminance. This trend can be seen in the results from two studies [21,22] although it is not always a significant trend, but a significant effect in the opposite direction has also been found [23], i.e. the variable stimulus was set to a higher level when starting from the lower initial illuminance. It is clear that the initial illuminance of the variable stimulus can affect the outcome of a matching task, although the evidence is not conclusive as to the direction of the effect, but this is sufficient to warrant the precaution of counterbalancing the initial illuminance of the variable stimulus.

Many studies have not employed sufficient steps of counterbalancing, and did not include null condition trials with which to quantify the magnitude of any bias effects. Thus, of 18 brightness matching studies carried out at photopic levels only five were considered to be reliable [4,19,22,24,25]: nine were suggested to be unreliable due to lack of counterbalancing and four studies failed to provide sufficient data with which to make this analysis [14]. It has been shown that in the matching task there is negligible difference in outcome (illuminance ratio) when using different visual objectives (e.g. equal brightness, equal clarity or equal appearance) [26] and this conclusion enables the findings from the five reliable studies to be collated.

Discrimination

In the discrimination task, two stimuli of different SPD are presented at a range of different illuminances; at each presentation, the test participant reports which is the brighter. Previous work has used rapid sequential presentation of the two stimuli at the same spatial location (Figure 2) [e.g. 12,27] or simultaneous evaluations (Figure 1) [28]. Whilst judgement of the brighter of a pair of stimuli is a more precise and repeatable task than is adjustment for equal brightness, the discrimination task can be biased through the range of stimulus magnitudes selected. Identification of relative illuminances for equal brightness demands the discrimination task is repeated at a range of illuminances, and two studies have shown stimulus range bias is sufficient to affect the outcome of discrimination tasks [29,30].

Figure 2. A single spatial location illuminated using two different sources of light in rapid succession. This is a sequential evaluation.

Fotios & Cheal examined stimulus frequency bias, the distribution of illuminances above and below that which produces the same brightness as the reference stimulus [29]. *Biased* here means there are, for example, more cases when the test stimulus is dimmer than the reference than when it is brighter. Consider the observation of two lamps of different SPD at the illuminances at which they are expected (perhaps as according to parallel studies) to appear equally bright; a biased stimulus frequency causes identification of *brighter stimulus* to be unfairly biased toward the stimulus which has been less frequently identified as brighter in preceding trials. This can suggest a statistically significant difference between two stimuli when none exists. This may arise from subjects' preconceptions of chance, that each of a pair of stimuli must be correct (brighter) on an equal number of trials. To counter stimulus frequency bias, the number of stimulus magnitudes should be equally divided about that giving equal brightness.

Teller, Pereverzeva & Civan [30] sought brightness judgments of small red and blue targets presented on a white monitor screen. For each colour, a range of targets varying in luminance were presented in random order, and observers reported whether the target was brighter or dimmer than the surround. Three ranges of target luminance were used in successive trials – for the red target these ranges had mid-point values of -0.6, -0.3 and 0.1 log luminance relative to the white surround. Typically 11 target stimuli were used in each range, increasing in steps of 0.05 log units. It was found that a stimulus judged brighter than the surround on 100% of trials with a target range of lower mid-point luminance, was also judged dimmer than the (identical) surround on 100% of trials with a higher mid-point range of luminances. Thus, the stimulus range affected the brightness judgment; a stimulus was made to appear brighter or dimmer than the reference by changing the range of luminances in which it was presented.

Investigation of the discrimination task in research of lamp SPD and spatial brightness is on-going. It has been used in only a few studies, and these have not tended to use null-condition trials (stimuli of identical SPD and illuminance) which would otherwise provide evidence to validate the method.

Category Rating

In the category rating task different lighting conditions are evaluated separately (Figure 3) and attributes of the visual environment are rated using a scale that gives only a limited range of fixed numbers. Poulton [31] discusses many potential causes of bias within this task. A recent review applied Poulton's ideas to research using the category rating method, and found that this method can understate the effect of lamp spectrum [32].

Figure 3. A single space is illuminated by one type of lamp. Judgements are made of this in isolation before proceeding to the next stimulus. This is a separate evaluation.

Previous lighting studies have tended to use seven-point rating scales, for example a scale ranging from 1 (dim) to 7 (bright). There is some evidence that test participants are able to reliably distinguish between approximately seven categories of a uni-dimensional stimulus, and this is apparent for a broad range of sensory judgements, but with more than seven categories confusions become more frequent [33]. Green and Rao [34] demonstrated that a response range of around seven categories is able to adequately represent intended responses; fewer categories (2 or 3) lead to poor recovery and there are diminishing returns beyond six categories. The seven-point response range has commonly been used to define the semantic differential rating task, e.g.;

- *The semantic differential consists of a set of bipolar, seven-category rating scales* [35].
- *Semantic differential rating scales – a seven category range between the extremes* [36].

There is a tendency for respondents to avoid using the ends of a scale, to underestimate large sizes and overestimate small sizes, and this response contraction is enhanced if the response range has an obvious middle value such as with the seven-point scale [31]. Such an outcome can be observed in the findings of previous lighting research: Wake et al [37] used 7-point scales, and for their brightness rating they concluded "*the differences among lamps are extremely small*"; Akashi & Boyce [11] used 5-point scales (-2 to +2) with a middle neutral point marked '0' and found "*The mean ratings ... do not indicate any strong opinions, i.e. all mean responses are around neutral*". Because of potential response contraction bias it is not clear whether there really is no difference of brightness between the lamps used in these studies, under the particular conditions used, or if the mid-point value in the response range contributed to the test failing to reveal a difference. This bias can be countered by using a response range with an even number of response points.

The rating task is affected by the relative numbers of response categories and stimulus magnitudes [31]. If the response scale has fewer categories than there are stimuli, several stimuli will need to be grouped within each category, and this may hide the difference between two stimuli when this difference may be small but is nonetheless real. Consider the study by Boyce & Cuttle (their Experiment 1) which used 22 stimulus conditions, including four types of lamp and four illuminances, and a five-point response range [5]. Their participants would thus need to group several of the 22 stimuli within each response category. Their results reveal that only one of the 19 rating items (dim) was found to be significantly affected by lamp type, and this at $p<0.05$ may be a Type I error (i.e. erroneous rejection of the null hypothesis). Differences in brightness due to illuminance were significant; these may be more prominent than differences due to SPD and would thus dominate the response category decision. The use of too few response categories does not give observers the opportunity to report whether two SPDs are differently bright. This response grouping bias can be countered by using similar numbers of stimulus magnitudes as there are response categories.

Response contraction in the category rating task can also be induced by failure to randomise or balance the order in which stimuli are presented and by failure to anchor the response range to the stimulus range by visual demonstration [32].

In a recent review of 17 studies using category rating at photopic levels to compare brightness effects of lamp spectrum, only three were considered to provide reliable data, the remainder having suspected experimental bias or provided insufficient data to check for such bias [32].

STIMULUS SIZE

Three further aspects of experimental design pertinent to all psychophysical methods in lighting research are discussed below: stimulus size, evaluation mode and design of the illuminated field.

Previous studies have used visual stimuli of a wide range of sizes, from remote viewing of a bipartite field subtending 2° at the eye [38] or booths subtending around 40° at the eye [4], to tests placing subjects within lit rooms [5] and thus giving stimulation of the whole retina - full-field stimulation. Stimulus size is expected to matter because the relative distribution of the long, medium and short-wavelength sensitive photoreceptors varies with retinal location [10]. Whilst full fields are representative of most real world conditions, it is often easier to set up and characterise smaller fields in laboratory trials.

Experimental evidence demonstrates that a 10° field produces different colour matching judgement to a field of size 102° wide and 50° high [39]; that the difference in sensitivity between fields of size 9° and 64° is small relative to the difference between 3° and 9° fields [40]; and that the average luminance of the horizontal band 40° wide centred at normal eye height relates well to subjective ratings of spatial brightness [41]. These data suggest that subjective evaluations of lighting for full field vision can be made using scale models, and that the minimum size is somewhere in the region of 10° to 40°. This proposal will be examined in further work.

EVALUATION MODE

There are two primary modes of evaluation, joint and separate [42]. In the separate mode (Figure 3) stimuli are presented individually, whilst in the joint mode two or more stimuli are presented in juxtaposition. The joint mode can be subdivided into simultaneous and successive modes. In the simultaneous mode (Figure 1), two stimuli are presented at the same time in adjacent spatial locations; in the successive mode (Figure 2) the two stimuli are presented in temporal juxtaposition at the same spatial location.

Chromatic adaptation

Joint and separate modes of evaluation lead to different degrees of chromatic adaptation. Chromatic adaptation is the neutralisation of activity in the opponent colour channels as the eyes acclimatise to the stimulus. Activity in the opponent colour channels contributes to brightness [43] and thus the degree of chromatic adaptation will affect the size of this contribution.

The time course of chromatic adaptation has been measured using colour appearance judgements following a change in adaptation. The data suggest two stages of adaptation. The initial rapid stage gives approximately 60% chromatic adaptation in the first five seconds, and is followed by the slower stage where approximately 90% chromatic adaptation is reached after 60 seconds; it takes almost two minutes to reach 100% chromatic adaptation [44,45].

In separate evaluations which allow adaptation to a single stimulus for two minutes or more, an observer's white point becomes the chromaticity of the stimulus. This complete chromatic adaptation reduces the chromatic contribution to brightness although experimental results suggest it does not completely eliminate any effect of SPD [32,46].

In simultaneous evaluations the chromatic adaptation state of the observer is difficult to define. The observer does not adapt to the individual stimuli but to the mixed spectrum, giving a white point somewhere between the chromaticities of the two adapting conditions being considered [47]. In sequential evaluations the same spatial location is illuminated by different stimuli in rapid sequential presentations. Berman et al [12] illuminated a wall alternately by two different sources, presented for 5 seconds each, and with three alternations between the two sources. Vrabel et al [27] illuminated a room for three seconds per source, with a two second dark interval between them, this cycle being repeated as many times as required by the observer. With each stimulus presented for approximately five seconds before alternating to the second stimulus, the observer's white point would move toward the chromaticity of the first stimulus, without actually reaching it, then towards the chromaticity of the second stimulus when that is presented, again without reaching it, and so on. The white point would therefore eventually lie somewhere between the chromaticities of the two individual stimuli and the state of chromatic adaptation would be similar to that for the side-by-side presentation. Hence the simultaneous and sequential modes of evaluation will yield similar results when other parameters are also similar. Studies using joint modes of evaluation tends to exaggerate differences between stimuli compared to findings using separate evaluation [46].

Interval bias

While simultaneous evaluations may suffer from positional bias, the preference for one spatial location over another, successive evaluations may be affected by interval bias [48], the preference for one temporal interval over the other. In brightness discrimination judgements this would be a tendency to report a particular interval as being brighter when it is not. Yeshurun et al present experimental data exhibiting large interval bias in visual judgements, some favouring the first interval and some the second interval [48]. Needham defines interval bias as the overestimation (negative time-error) or underestimation (positive time-error) of the second of two stimuli presented in succession [49] and suggests that it changes with variation of the time interval, or pause, between presentations of the stimuli: intervals of up to approximately three seconds tend to result in an underestimate of the second stimulus, whilst intervals above approximately three seconds tend to result in an overestimate of second stimulus.

In their detection task, Jäkel and Wichmann [50] found a strong bias to the second interval from three of their five observers, including the expert observer, when using successive evaluation whilst the simultaneous evaluation task was virtually unbiased. In their discrimination task, Jäkel and Wichmann found similar sensitivity with simultaneous and successive tasks but each of their four naïve observers was still better at the simultaneous discrimination task than the successive discrimination task after 20,000 detection trials [50]. Uchikawa and Ikeda found that matching and discrimination tasks using side-by-side brightness comparisons gave more precise results than did successive presentations [51]. Doubts about the successive discrimination task lead a recent study to report that it should be used with caution, if at all [48].

There are two issues regarding use of sequential and simultaneous evaluation modes that need further investigation before discussions of previous lighting research can be resolved. The first relates to the dominant visual mechanism though which lamp SPD affects spatial brightness. If this is through the opponent colour channels [43] then chromatic adaptation is of interest and the sequential and simultaneous evaluation modes lead to similar states of chromatic adaptation. Alternatively, it has been suggested that the spatial brightness response is mediated by control of pupil size [12] in which case the sequential evaluation is preferable to the simultaneous mode because it would allow the pupil to respond to the SPD of the individual stimuli rather than to the mixed SPD of both. The second issue is that of interval bias in sequential evaluation tasks. It is unfortunate that previous studies of lamp SPD and brightness using discrimination between successive stimuli have tended not to include a null condition trial so there are no data with which to quantify the magnitude of any such bias.

Further research has been carried out at Sheffield University and Pennsylvania State University to compare the simultaneous and sequential modes of evaluation and preliminary results are reported below.

Experimental data: Sheffield

Fotios & Cheal previously reported the results of brightness matching and brightness discrimination tests, both using simultaneous evaluations [21]. This work is currently being repeated using sequential evaluation.

The simultaneous evaluations [21] used a pair of side-by-side booths, with separate light sources simultaneously illuminating each booth. Light was transported to the top of each booth through a light pipe, using an iris in the pipe to adjust illuminance and avoid any effect on the SPD or spatial distribution of light in the visible chamber. The sequential evaluations used only one of these booths, presenting a visual field of approximately 37° high and 36° wide. Light from two different lamps was transported to the top through separate light pipes, again using irises to adjust the illuminance. Luminance measurements show negligible differences in spatial distribution between lamps, between light from the two light pipes and between levels of dimming.

The two stimuli were presented in rapid succession: stimulus A (5s); dark interval (300ms); stimulus B (5s); dark interval (300ms); stimulus A (5s) etc. These durations were chosen to repeat the conditions used by Berman et al [12]. For the matching test this procedure was followed until the test participant was satisfied with their brightness match. For the discrimination test the number of repeats was limited to three.

Four lamps were used; a standard high pressure sodium (HPS 70W), a compact fluorescent (CFL) and two types of metal halide (MH1, MH2), as defined in Table 2, these being the lamps used in previous work [21]. Using the HPS as the reference source gave four lamp combinations including a null condition. The order in which lamp pairs were presented was balanced between subjects.

Lamp		**CCT (K)**	**CRI**
HPS	*70W/150W SON-T Pro*	2000	25
CFL	*55W PL-L*	3000	82
MH1	*70W CDO-TT*	2800	83
MH2	*70W CDM-T*	4200	92
MH3	*150W CDM-TT*	4200	92

Table 2. Lamps used by Fotios & Cheal in brightness matching and discrimination tests.

In sequential brightness matching trials one of the two lamps in a pair was set by the experimenter to the reference illuminance. The test participant used the dimming control, a three-turn rotary dial, to match the lighting as-near-as-possible for equal brightness. This procedure was repeated by each test participant to counterbalance dimming application and dimming direction. When the HPS lamp in a pair was used as the stimulus of fixed illuminance the reference illuminance was 7.5 lux, measured at the centre of the floor of the booth, this being a pilot study for further research of street lighting. When the MH and CFL lamps were used as the stimulus of fixed illuminance the reference illuminance was 5.0 lux, this expected to be approximately equally bright as the HPS at 7.5 lux and thus maintain a similar state of adaptation in both cases.

In sequential brightness discrimination trials, lighting from one lamp in each pair was set to the reference illuminance and lighting from the other lamp was set to a range of illuminances. At each presentation the test participant reported which interval appeared brighter, a forced choice task. This procedure was repeated by each test participant to counterbalance lamp nomination as reference and variable stimulus. When the HPS lamp in a pair was used as the stimulus of fixed illuminance, this being 7.5 lux, the CFL and MH lamps were presented at 2.0, 3.0, 5.0, 7.5, 10.0 lux. When the MH or CFL lamps in a pair was used as the stimulus of fixed illuminance, this being 5.0 lux, the HPS lamp was presented at 3.0, 5.0, 7.5, 10.0 and 15.0 lux. These ranges were chosen with expectation that the middle value would tend to appear equally bright as the fixed illuminance stimulus, thus avoiding a stimulus frequency bias [29].

Results from the ten test participants used to date are shown in Table 3, in comparison with results from the previous trials using simultaneous evaluation [21]. The four-parameter logistic equation was used to derive the illuminance ratio for equal brightness from the results of the discrimination tests.

Evaluation mode	**Illuminance ratio at equal brightness**			
	HPS/ HPS	**CFL/ HPS**	**MH1/ HPS**	**MH2/ HPS**
Brightness matching				
Sequential	0.99	0.68	0.74	0.70
Simultaneous	0.99	0.72	0.73	0.71
Brightness discrimination				
Sequential	1.01	0.67	0.69	0.66
Simultaneous	1.00	0.59	0.68	0.64

Table 3. Comparison of illuminance ratios for equal brightness determined using matching and discrimination tasks with simultaneous (n=21) and sequential (n=10) modes of evaluation. Simultaneous data as previous reported [21]; sequential data not previously reported.

Two observations are drawn from Table 3. Firstly, there appears to be little difference in illuminance ratio for a particular lamp pair between sequential and simultaneous evaluation modes, for both the matching and discrimination tasks, and thus that the evaluation mode does not significantly affect operation of the visual mechanism(s) responsible for SPD effects on spatial brightness. Secondly, brightness discrimination appears to suggest illuminance ratios that depart slightly further from unity than those from the matching task. Data from the null condition trials, the HPS/HPS lamp pair, suggest negligible experimental bias.

Results of the sequential brightness judgements and comparison of these with results of the simultaneous tests will be submitted for peer reviewed publication upon completion of the trials. In addition to using illuminance ratios to compare the size of any SPD effect upon spatial brightness, this analysis will also analyse precision and interval bias.

Experimental data: Penn State

Brightness judgements at photopic levels were made using side-by-side and rapid sequential discrimination tasks. The visual field in each case was one, or both, of a pair of identical empty rooms with approximate dimensions of 3.0m (wide) x 3.6m (deep) x 2.7m (height). All surfaces within the subject's field-of-view were neutral gray. The rooms were fitted with indirect luminaires, suspended about 400mm from the ceiling, and these had continuous rows of RGB LEDs. Four stimulus conditions were used, these being the four possible combinations of two correlated colour temperatures (3000K, 7500K, both on the blackbody locus) and two luminances (24 and 30 cd/m^2) as measured at eye height on the surface of the wall directly in front of the subject. The ten paired combinations of these four stimuli included four null conditions and the left/right stimulus position (simultaneous evaluations) and the first/second stimulus interval (sequential evaluations) were counterbalanced for the between-stimulus pairs, giving sixteen paired comparisons.

In the simultaneous evaluations the rooms were observed from a seated position just outside of the rooms, with the partition between the rooms aligned with the subject's sagittal plane. In the sequential evaluations the subject was seated within the left-hand room, In all cases a chin/forehead rest was used to maintain consistency in the viewing field across trials and subjects. For the simultaneous evaluations, presentation durations were not limited. For the sequential presentations each stimulus was presented for 5s with a 25ms dark interval and subjects were instructed to view at least three sets of alterations (i.e. ABABAB) before making their choice about which light setting was brighter. This is comparable to the method employed by Berman et al [12].

The tests were carried out by 47 participants using a repeated measures procedure. Full results will be submitted for publication in a peer reviewed journal and here we focus on the comparison of results from the sequential and simultaneous evaluations.

Stimulus pair		**Distribution of judgements of brighter stimulus**			
		Simultaneous evaluation		**Sequential evaluation**	
1	*2*	*1*	*2*	*1*	*2*
A	D	6	88	4	90
B	C	72	22	90	4
A	C	28	66	39	55
B	D	31	63	49	45
C	D	2	92	0	94
A	B	2	92	0	94

Table 4. Comparisons of brightness discrimination judgements obtained using sequential and simultaneous modes of evaluation. (n=94). These stimuli are A (3000K, 24 cd/m^2), B(3000K, 30 cd/m^2), C(7500K, 24 cd/m^2), D (7500K, 30 cd/m^2).

Table 4 summarises the results. The frequency with which the stimulus in a pair was reported to be brighter is similar for both the sequential and simultaneous evaluations. McNemar's test suggests the difference is significant ($p<0.01$) only for the BC and BD lamp pairs. Conclusions drawn about statistical significance related to effects of SPD and luminance were identical with both methods. The room with the higher luminance was selected as brighter irrespective of CCT, and at equal luminance CCT was unrelated to brightness perception. There are subtle differences in some of the contrasts that were studied and these are presently under further investigation, but the general conclusion is that both experimental methods will lead to comparable results. This is not unexpected since both methods place the subject in a state of mixed adaptation. Preliminary analysis suggests that any bias between the right-hand and left-hand rooms in the simultaneous evaluation, or between the first and second intervals in the sequential evaluation, was negligible.

VISUAL FIELD

In previous work, visual fields have ranged from uniform, neutral surfaces, to interior spaces with coloured surfaces and containing objects. Whilst the neutral field enables analysis of brightness effects purely due to differences in SPD, the coloured environment better represents most real world interiors. Two questions are raised. Firstly, are results obtained in studies using coloured environments transferable to other settings? Secondly, are test participants attracted to objects in the observed field such that their response is dominated by foveal vision rather than full field vision? Brightness matching trials were carried out using four different field designs to explore the transferability of results from one setting to another [52]. These tests were carried out at mesopic levels, this again being a pilot study for work investigating lighting for residential streets.

Method

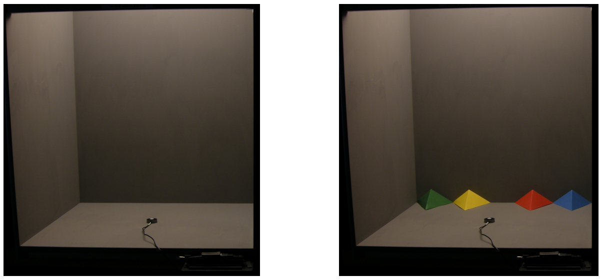
The four illuminated fields are shown in Figure 4. These are:

Achromatic: These are two side-by-side booths. The interior surfaces of the booth were painted matt grey (Munsell N5, r = 0.2).

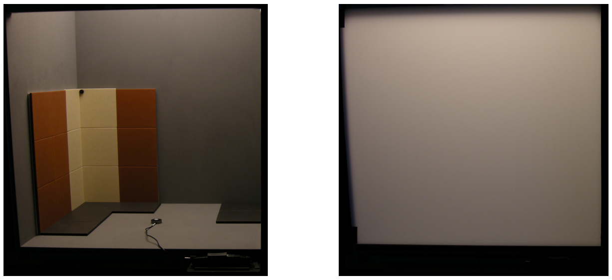
Coloured Objects: Pyramids made from coloured card (red, green, blue and yellow) were placed on the floor of the achromatic environment. This is the field design used in previous work [21].

Coloured Surfaces: Approximately one third of the visible interior surfaces of the achromatic booths were lined with unglazed quarry tiles in three colours (red, beige and black) simulating brick, stone and asphalt surfaces. The proportion of colour was determined from a brief survey of residential streets in Sheffield, a city in the UK.

Uniform Field: The front openings of the achromatic booths were covered with two sheets of acrylic diffuser of neutral transmittance. This provided a neutral and uniform stimulus field.



Achromatic Coloured Objects



Coloured Surfaces Uniform Field

Figure 4. Visual fields used to compare effect of colour and objects on the results of brightness matching tests. Note: only the left-hand field is shown; the right-hand field was a mirror image.

The test participant's task was to adjust the illuminance in one booth to match the brightness produced by the reference illuminance (7.5 lux) in the other booth. For the uniform field design the reference illuminance was set to achieve an average luminance of the front surface of the reference field equal to the average luminance (0.38 cd/m^2) of the walls in the other field designs. In trials, both sides were of identical design, the left-hand booth being a mirror image of the right-hand booth.

Four lamps were used, these being similar to the lamps used in previous work [21]. These were high pressure sodium (HPS 150W), compact fluorescent (CFL), and two types of metal halide (MH1, MH3) as defined in Table 2. Lamp MH1 was used as the reference stimulus, and thus there were four lamp pairs including a null condition.

Each of the four lamp pairs were matched four times, counterbalancing the initial illuminance of the variable stimulus (set by the experimenter to be obviously higher or lower than the fixed stimulus) and counterbalancing the designations of fixed and variable booth. Each trial was repeated twice. The order in which the four lamp pairs were used and the booth in which the reference lamp (MH1) was located were balanced across the ten test participants (age range 25-54 years; 7 female, 3 male). Each participant saw all experimental conditions, a repeated-measures procedure, and hence made 128 brightness matches.

Results

The mean illuminance ratios for the four lamp combinations and the four field types are shown in Table 5. Within these treatments, data for each subject are the mean of the eight trials carried out per lamp pair and field design.

Field design	**Mean illuminance ratio for each lamp combination**			
	HPS/ MH1	**CFL/ MH1**	**MH1/ MH1**	**MH3/ MH1**
Coloured surfaces	1.35 *(0.13)*	0.93 *(0.09)*	0.99 *(0.08)*	0.92 *(0.08)*
Coloured objects	1.24 *(0.11)*	0.90 *(0.09)*	0.96 *(0.07)*	0.92 *(0.07)*
Achromatic	1.24 *(0.14)*	0.88 *(0.12)*	0.98 *(0.06)*	0.93 *(0.14)*
Uniform field	1.22 *(0.27)*	0.90 *(0.08)*	0.96 *(0.08)*	0.90 *(0.12)*

Table 5. Mean illuminance ratios (and standard deviations) from side-by-side brightness matching trials (n = 10) using four different visual fields.

The effect of field design can be seen by comparing illuminance ratios for the four field designs under each lamp combination. The mean illuminance ratios in Table 5 suggest all four field designs yield similar illuminance ratios under the MH1/MH1, MH3/MH1 and CFL/MH1 lamp pairs; under the HPS/MH1 lamp pair there appears to be a difference between the coloured surfaces field and the other three field designs. Two-way repeated measures ANOVA (lamp pairs x field design) suggests that the effect of field design is not statistically significant, although it is close (p=0.082). Differences between field-designs were examined using paired t-tests on all combinations of field design within each lamp pair. Of these 24 analyses, only two differences are significant, and both of these are for the HPS/MH1 lamp pair; coloured surfaces vs. coloured objects (p=0.003), and coloured surfaces vs. achromatic (p=0.008).

Effects of field design on brightness judgements were considered using the current results and also the results from two previous studies at photopic levels [5,19] in which surface colour and the presence of an object were varied. Three conclusions were drawn:

1. Brightness matching using illuminated achromatic interior environments produces the same outcome (illuminance ratio at equal brightness) as brightness matching using illuminated flat surfaces of neutral spectral reflectance.
2. The insertion of coloured objects into an achromatic environment does not affect the outcome.
3. An environment with coloured surfaces produces the same outcome as an achromatic environment, and there is no significant effect with the level of colourfulness.

These findings will be submitted to a peer reviewed journal for publication.

SUMMARY

All experimental methods contain bias. This is not necessarily a problem if there are data, such as null-condition data, that enable bias effects to be estimated. Robust conclusions demand the same stimuli are compared using a variety of psychophysical methods and if these tend to agree then greater confidence can be placed in the results. Whilst a few studies have done this [11,19,24,27], most do not, hence the meta analysis being carried out by the authors.

The consideration of research methods discussed in this article suggests that much of the previous work provides an unreliable estimate of lamp SPD effects on brightness. Frequently, this is because the reported method reveals experimental error, or because there are insufficient data reported to determine whether a potential experimental error has been countered. At present, the analysis suggests that data from only 14 of 60 previous studies are reliable; these are shown in Table 6.

The next stage of this research is to develop a tool to enable prediction of lamp SPD effects on spatial brightness, hence to guide the selection of lamp type and illuminance. A common limitation of the experimental work is that lamps are selected from those commercially available using coarse indicators of lamp spectral characteristics, such as Colour Rendering Index, Correlated Colour Temperature or the ratio of scotopic to photopic lumens (S/P). It is less common for researchers to create custom illuminants that have spectra intentionally designed to manipulate an underlying mechanism of vision; only two studies appear to have done so [12,28].

Three categories of prediction tool are colour appearance models; the S/P ratio, e.g. consideration of the intrinsically photoreceptive retinal ganglion cell (ipRGC); and lamp colour characteristics, e.g. relative values of CCT, CRI, and gamut area. Allied discussions include consideration of how the effect of lamp SPD might be applied in practice and comparison with effects on visual effort and circadian response.

Study	Response task	Field size	Evaluation mode
Akashi & Boyce, 2006 [11]	Yes/No response to statements.	Full field	Separate
Berman et al, 1990 [12]	Discrimination	Full field	Sequential
Boyce, 1977 [19]	Matching	Full field	Simultaneous
Boyce, Akashi, Hunter & Bullough, 2003 [53]	Yes/No response to statements.	Full field	Separate
Boyce & Cuttle, 1990 (Experiment 2) [5]	Category rating	Full field	Separate
Flynn & Spencer, 1977 [54]	Category rating	Full field	Separate
Fotios & Gado, 2005 [26]	Matching	40^o high, 72^o wide	Simultaneous
Fotios & Levermore, 1997 [22]	Side-by-side Matching	22^o high, 38^o wide	Simultaneous
Houser, Tiller & Hu, 2004 [28]	Discrimination	Full field	Simultaneous
Hu, Houser & Tiller, 2006 [24]	Matching	Full field	Simultaneous
Ray, 1989 [20]	Adjust to preferred illuminance	Full field	Separate
Thornton & Chen, 1978 [4]	Matching	30^o high x 50^o wide	Simultaneous
Vrabel, Bernecker & Mistrick, 1998 [27]	Discrimination	Full field	Sequential
Vrabel, Bernecker & Mistrick, 1998 [27]	Category rating	Full field	Separate

Table 6. Tests suggested to give reliable demonstration of SPD effect on brightness at photopic levels

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Ecological Measurements of Light Exposure, Activity, and Circadian Disruption in Real-world Environments

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ABSTRACT

Presented is an overview of the recently developed Daysimeter, a personal measurement device for recording activity and circadian light-exposure. When the Daysimeter is worn on the head, two light sensors near the eye are used to estimate circadian stimulus (CS_A) exposures over extended periods of time. Phasor analysis combines the measured periodic activity-rest patterns with the measured periodic light-dark patterns to assess behavioral circadian entrainment/disruption. As shown, day-shift and rotating-shift nurses exhibit remarkably different levels of behavioral circadian entrainment/disruption. These new ecological measurement and analysis techniques may provide important insights into the relationship between circadian disruption and well-being.

Keywords

Circadian rhythms, phasor analysis, circadian disruption, Daysimeter, circadian light, phototransduction

INTRODUCTION

The synchronization of the endogenous master clock to local time on earth is governed by a robust and regular 24-hour pattern of light and dark on the retina. If the light-dark pattern is not above threshold, or if its period is something other than 24-hours, human biology is disrupted, from single cells to overt behavior [6, 14]. Circadian disruption can manifest itself in poor sleep, digestion, reduced attention and performance [8, 9, 15]. Over time this disruption can lead to serious maladies such as cardiovascular disease [24], diabetes and obesity [1], and cancer [17, 19, 20]. Despite the plethora of animal and epidemiological research demonstrating the negative impact of circadian disruption on health, surprisingly little is known about the levels of circadian disruption actually experienced by people in different types of living conditions and environments.

This paper describes a measurement tool for collecting ecological data on circadian light-dark stimuli and rest-activity patterns along with methods of analyzing such data so that circadian entrainment and disruption can be assessed. Results of using such techniques to study a cohort of nurses engaged in both day- and rotating-shift work is also presented.

INSTRUMENTATION

The Daysimeter™ was developed as a personal circadian light exposure and activity meter to measure circadian light-dark and activity-rest patterns in the field [3]. It was necessary to develop a sophisticated, small photometer calibrated in terms of the spectral-spatial-intensity response of the human circadian system. Moreover, since light must be incident on the retina to be effective, the Daysimeter had to be designed to place the light sensors near the plane of one cornea. Extending from a number of basic studies on circadian phototransduction [2, 4, 21], and physiological optics [22], a model was developed for human circadian phototransduction [12], and this model forms the basis of the Daysimeter's photometric response characteristics. To measure activity, the Daysimeter incorporates accelerometers that respond to head movements and orientation with respect to Earth's gravitational field. Activity and light are measured together at regular time intervals and electronically stored. In addition, the Daysimeter logs its operating temperature. Using practical power management techniques, the Daysimeter can gather light, activity and temperature data for up to 30 days for subsequent analysis.

Two calibrated photosensors are employed to measure optical radiation in close proximity to the cornea. Based upon the spatial sensitivity model of the retina developed by Van Derlofske et al. [22], both sensors have a nearly cosine spatial response meaning that the sensors are most sensitive to light at normal incidence with sensitivity at other angles decreasing proportional to the cosine of the incident angle. One sensor is a conventional glass-filtered silicon photodiode (Hamamatsu model S1286, custom glass filter) having a spectral sensitivity closely matching the standard photopic luminous efficiency function, V(λ) [5]. The other sensor is a short-wavelength (blue) sensor fabricated from a gallium arsenide phosphide (GaAsP) photodiode (Hamamatsu model GA5645), having an intrinsic long wavelength response cutoff at approximately 580 nm, together with a UV blocking glass filter (Schott GG395). This "blue" sensor has a spectral response peaking at approximately 460 nm with an 80 nm full-width-half-maximum (FWHM) bandpass.

Once the optical radiation data obtained by the Daysimeter from both sensors are downloaded to a computer, "circadian light" levels can be approximated using post-processing algorithms based upon the model of circadian phototransduction by Rea et al. [12]. The values of circadian light levels are scaled so that 1000 lux of CIE Illuminant A (an incandescent blackbody radiator at 2856 K) is equivalent to 1000 circadian light units (CL_A). Four spectral sensitivity functions are used in the model: the scotopic luminous efficiency function, V'(λ) [5], based on rod sensitivity, $V_{10}(\lambda)$ based upon the S, M and L cone fundamentals [16], the S-cone fundamental [18], and a standard photo-opsin emulating melanopsin contained within the intrinsically photosensitive retinal ganglion cell (ipRGC; [2]) and having a peak spectral response at 480 nm and a half-bandwidth of 95 nm. Briefly, in the model the cone fundamentals form a spectrally opponent (blue vs. yellow [7]) input to the ipRGC which sends circadian light signals to the SCN. The modeled rod response suppresses output from the ipRGC when the blue-yellow opponent signal is positive, with diminishing suppression at higher irradiance levels as rods become more fully bleached. A negative blue-yellow opponent signal, however, produces a response determined solely by the ipRGC (no cone input and no rod suppression). The Daysimeter system uses its two spectral channels to approximate the four spectral channel input in the model. Discrepancies were minimized between the two-channel estimates and the four-channel model calculation of CL_A for several practical light sources using a conventional least-squares technique. Based upon those results, algorithms were developed to minimize measurement errors of CL_A from the Daysimeter; the results of that analysis are shown in Figure 1. Spectral mismatch errors of the photopic channel for the light sources in Figure 1 are less than 2% except for the 470 nm LED which has a photopic spectral mismatch error of 8%.

The human circadian system response to light (CL_A), as measured by acute nocturnal melatonin suppression [10], follows a logistic function [25]. This response function is used to transform the CL_A values into circadian stimulus values (CS_A). CS_A is considered to be a better measure of the effectiveness of the light stimulus for the human circadian system because it is defined in terms of the circadian system's input-output relationship, including both threshold and saturation.

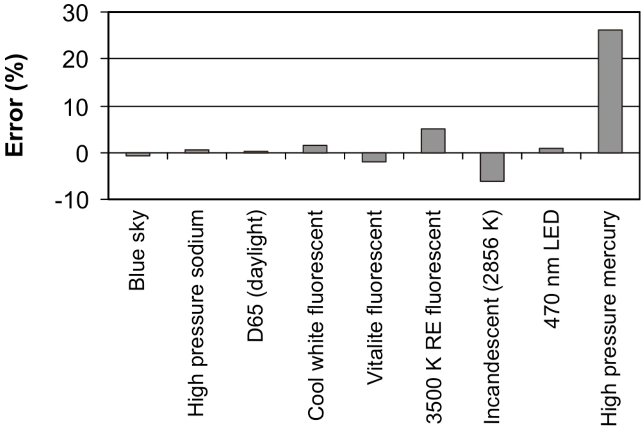

Figure 0. Errors in estimating a fixed level of circadian stimulus (1000 CL_A) from the model of circadian phototransduction by Rea et al. [12] generated by several common light sources using the algorithms applied to the two-sensor data acquired by the Daysimeter.

The Daysimeter model used in the present study had two orthogonally oriented accelerometers contained within a single electronic sensor package (Analog Devices, model number ADXL330) and mounted on the Daysimeter's circuit board. The outputs of the sensor package are voltages that are proportional to the instantaneous acceleration of each accelerometer. These voltages are converted to digital values using the 12-bit analog-to-digital converter of the microprocessor (Texas Instrument MSP430F169) that controls operation of the Daysimeter. The digital data are acquired once per second, and then used to calculate an activity index every 30 s using the following equation:

$$\text{Activity Index} = k\sqrt{\frac{\left(SS_x + SS_y\right)}{n}} ,$$

where SS_x and SS_y are the sums of the squared deviations from the mean digital value for each accelerometer (x and y) over the 30-second logging interval, n is the number of samples (30), and k is a calibration factor converting the measured output voltage of the accelerometers in arbitrary analog-to-digital converter counts to units of g-force (1 g-force = 9.8 m/s²). In other words, the activity index is the root-mean-square (rms) deviation in acceleration in two dimensions measured for every 30-second logging interval.

ANALYSIS METHODS

Phasor analysis, a technique based on signal processing techniques [11], makes it possible to interpret the light and activity data, sampled together over consecutive multiple days (usually seven days for the data presented here), in terms of the phase and magnitude of the joint 24-hour patterns. The correlations between the periodic changes in light and in activity are first determined by calculating the circular correlation function of the light and activity time series. The circular correlation function reveals how the correlation (r, not r^2) between light and activity change as a function of the timing difference, or phase between them (Figure 2). The circular correlation function is then decomposed into its temporal frequencies and phase angles using Fourier analysis techniques, from which the 24-hour frequency component is selected as a measure of circadian rhythmicity. The 24-hour phasor magnitude is used as the metric for behavioral circadian entrainment/disruption; the greater the magnitude, the greater the level of behavioral circadian entrainment of activity to light. The phasor angle reflects the phase relationship between the periodic light-dark exposure pattern and the periodic activity-rest pattern in the correlations (Figure 2). Figure 2 shows examples of

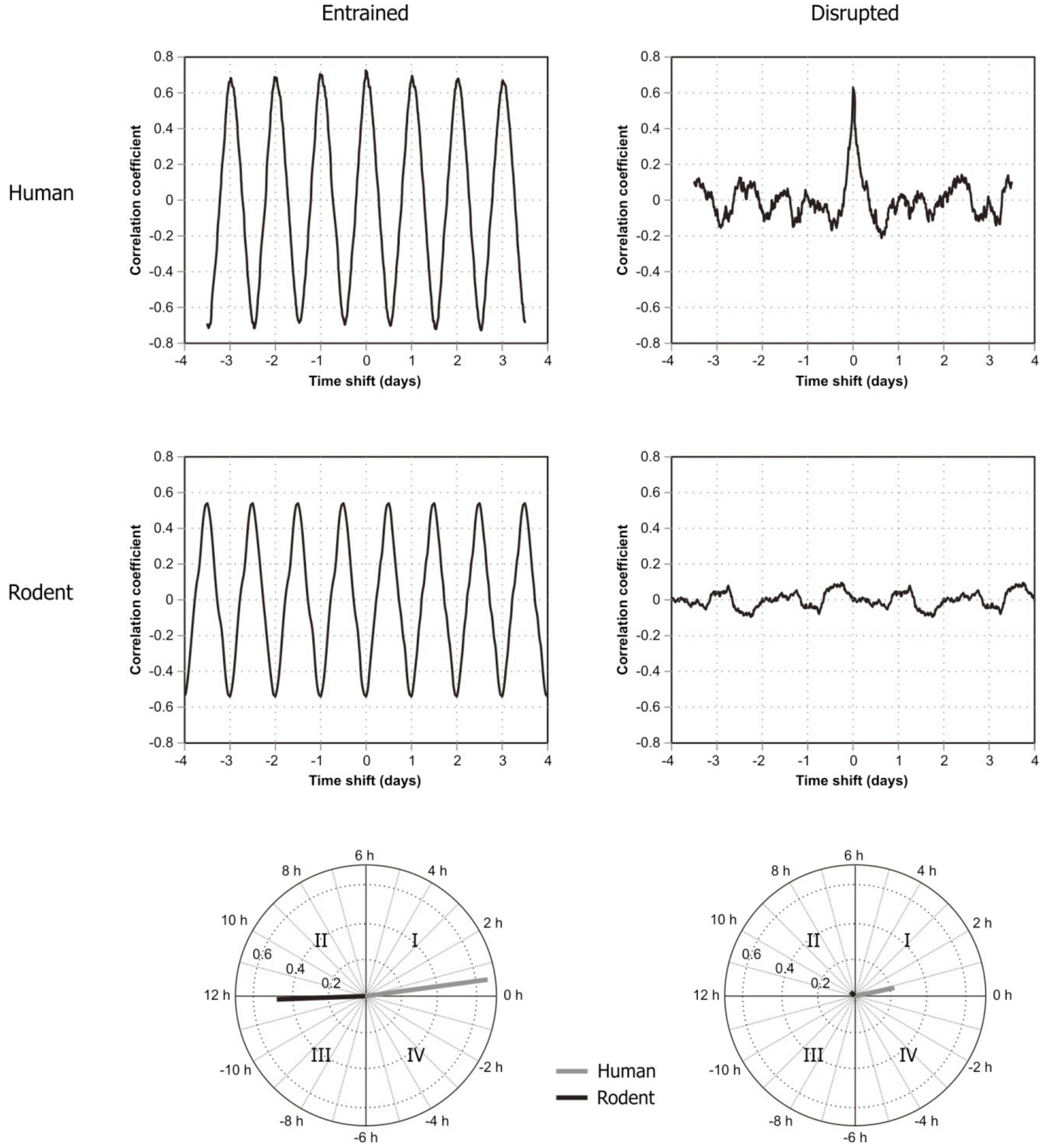

Figure 2: Circular correlation functions and associated phasors for two nurses, one day-shift and one rotating-shift, and for two nocturnal rodents, a rat exposed to a regular pattern of 12L:12D and a rat exposed to a "jet lag" pattern of light and dark (the 12L:12D pattern was reversed every 48 hours).

the circular correlation functions and associated phasors for two nurses, a day-shift nurse and a rotating-shift nurse, as well as for two nocturnal rodents, one exposed to a regular pattern of 12 hours light and 12 hours dark (12L:12D) and one exposed to a simulated "jet lag" pattern (discussed later in the text).

Two techniques of parsing the Daysimeter data can be used for phasor analysis. The "all-at-once" technique computes the circular correlation function of the entire data set (e.g., seven days) in one operation. The resulting circular correlation function provides the correlation coefficients between light and activity for time shifts in activity ranging from zero to the total length of time over which data were collected (usually seven days for the data collected here). Because the circular correlation extends over multiple days, this technique is sensitive to day-to-day variations as well as variations within each day. Fourier analysis applied to the all-at-once circular correlation extracts the magnitude and the angle of the 24-hour component, separating it from the longer, infradian, and shorter, ultradian, variations. If the power in these longer or shorter periods in the circular correlation is large, the magnitude of the 24-hour phasor is reduced. To facilitate Fourier harmonic analysis the time duration, or total length of the data set, is truncated to an integer number of days.

The "sliding-window" technique parses the data into a progression of overlapping 24-hour segments and calculates a circular correlation for every segment. Fourier analysis is applied to each of these circular correlation functions to extract the 24-hour, fundamental component. The resulting 24-hour phasors for each data segment are then averaged (vectorally) to arrive at a phasor representing the entire data collection period. The advantage of the sliding-window technique is that it utilizes all the available data without truncation; therefore, it is better than the all-at-once technique for short collection protocols because it utilizes all of the limited data available. A limitation of this technique, however, is that there is no ability with the sliding-window technique to identify rhythms slightly longer or shorter than 24 hours. Analyzing seven days of data using the all-at-once technique has a precision of approximately 3.4 hours for resolving the expressed circadian periods in the circular correlations, whereas the sliding-window technique cannot reliably resolve periods up to approximately 12 hours. This higher degree of period resolution with the all-at-once technique will necessarily result in shorter 24-hour phasor magnitudes than those obtained for the same data using the sliding-window phasors unless there is no significant power in the infradian or ultradian rhythms. This difference is most evident with disrupted subjects who do not necessarily show a strong 24-hour rhythm but still exhibit relatively large sliding-window phasor magnitudes. Because the period resolution is worse with the sliding-window technique than with the all-at-once technique, the power of the other non-24-hour periods also contribute to the phasor magnitude.

The activity index values can be used to compute two statistics developed by Van Someren et al. [23] to estimate the day-to-day consistency of activity over the recording session (interdaily stability, IS) and the hour to hour consistency of activity over the recording session (intradaily variability, IV). High values of IS indicate that the subject's 24-hour activity and rest pattern was consistent over the entire recording session; high values of IV indicate that the subject's pattern of activity and rest was highly fragmented with intermittent and inconsistent intervals of movement and no-movement. Neither statistic accounts for levels of light exposure or changes in light exposure levels.

DATA COLLECTION

The Nurses' Health Study II is a prospective cohort study that began in 1989, when 116,671 registered female nurses in the United States between the ages 25 to 42 were enrolled. The study was designed to prospectively examine the effects of oral contraceptive use and other life style factors on chronic diseases, particularly cancers and cardiovascular diseases. Surviving nurses within this cohort were contacted to serve as potential subjects between November 2006 and April 2008; 138 nurses volunteered to participate. The study was approved by the Committees on the Use of Human Subjects in Research at the Brigham and Women's Hospital and the Harvard School of Public Health, as well as Rensselaer's Institute Review Board; written informed consent was obtained from each participant.

Reported here are results from Daysimeter measurements for 38 day-shift and 61 rotating-shift nurses; the rotating-shift nurses worked from one to five nights over the recording period. For 16 other nurses in the study who were categorized as rotating-shift, the Daysimeter data indicated that they did not work any nights during the study period, so their data are not included. The larger number of rotating-shift nurses reflects the initial assumption that day-shift nurses would be more homogenous with respect to circadian entrainment than the rotating-shift nurses. Data from 23 of the 138 nurses were unusable due to recording irregularities or non-compliance with the seven-day protocol. It was possible to identify data from those nurses who did not comply with the protocol by using the data from the Daysimeter's on-board temperature sensor; room-temperature readings, as opposed to elevated temperatures when the Daysimeter is in close contact with the body, and extended periods of inactivity were certain signs that the nurse did not wear the device when required. Visual inspection of the temperature and activity data plotted against time was used to identify noncompliance. Only those protocol departures lasting about a day or more could be unambiguously identified and were removed. The data from 13 of the remaining 99 nurses showed non-compliance during only one to three days of the seven-day recording period. For these nurses, only the data for the noncompliant days were removed; 10 nurses provided six days of useful data and three provided five.

RESULTS

Table 1 summarizes the results of the measurements. Two-tailed student t-tests revealed that, on average, day-shift nurses were exposed to statistically higher levels of light (both photopic and CL_A) than rotating-shift nurses during the recording sessions. It is interesting to note, however, that the ratio of the average photopic light level to the average circadian level is similar for both day-shift and rotating-shift nurses. This suggests that the types of light sources, natural and electric, seen by both groups were not remarkably different for both groups. Interesting too, the average activity levels of the two groups were nearly identical. The phasor analysis of the continuous light and activity data provided by the Daysimeter indicated that the synchronization between the light-dark exposures and the activity-rest behavior was much greater for the day-shift nurses than for the rotating-shift nurses based upon the highly significant difference between the two groups in terms of their respective phasor magnitudes determined using either the sliding-window or the all-at-once techniques. There was no difference between the two groups in terms of their phasor angles using the sliding-window technique, but there was a significant difference between the phasor angles of the two groups using the all-at-once technique. Following the earlier discussion, the all-at-once technique is much more sensitive to consistency in the light and activity patterns over the entire recording period than the sliding-window technique. Thus, there is a much larger difference between the two groups in terms of their phasor angles using the all-at-once technique.

Table 1.

	Photopic light (lux)	Circadian light (CL_A)	Activity Index (Δg-force$_{rms}$)	Interdaily Stability (IS)	Intradaily Variability (IV)	Phasors			
						Sliding-window		All-at-once	
						Magnitude	Angle (hours)	Magnitude	Angle (hours)
Day-shift (N=38)*	302 [188]	369 [227]	0.0094 [0.0014]	0.692 [0.144]	0.447 [0.170]	0.50 [0.11]	0.65 [0.74]	0.46 [0.12]	0.68 [0.71]
Rotating-shift (N=61)*	188 [152]	209 [166]	0.0097 [0.0018]	0.252 [0.129]	0.458 [0.135]	0.33 [0.10]	0.64 [0.73]	0.12 [0.10]	2.3 [3.2]
t-test p-value (two-tail)	0.0028	3.9×10^{-4}	0.26	2.1×10^{-24}	0.72	6.4×10^{-11}	0.94	2.7×10^{-24}	2.4×10^{-4}

* – Mean values shown; standard deviation values in [brackets].

Photopic light exposures: *The Daysimeter system utilizes a fully calibrated (spectral, spatial, intensity) photopic light sensor measuring in lux (lm/m²). Group means [standard deviation] are computed from individual subject means of each subject's entire recording session.*

Circadian light exposures: *Using the model from Rea et al. [12], circadian light exposure values are determined from the photopic and blue light sensor data measured in CL_A. Group means [standard deviation] are computed from individual subject means of each subject's entire recording session.*

Activity index: *Values from two orthogonally oriented accelerometers (measuring up/down and forward/back head motions) are used to compute an activity index that is logged at regular time intervals along with the light readings. Each logged measure of activity is the rms combination of the standard deviation of acceleration taken once per second over a 30-second interval of both accelerometers. Group means [standard deviation] are computed from individual subject means of each subject's entire recording session.*

Interdaily stability: *The IS statistic developed by Van Someren et al. [23] measures the consistency of activity among days and ranges from 0 to 1. A value of 1 results when every day's activity is identically to the other days, while conversely a value of 0 results from no similarity among days.*

Intradaily variability: *The IV statistic developed by Van Someren et al. [23] measures the fragmentation of rhythm between rest and activity based on a scale from 0 (no variability from hour to hour) to upwards of 2. A larger value indicates more fragmentation of rest and activity, or conversely, less consolidation of rest/activity patterns.*

Phasor magnitude: *A correlation between circadian light exposure and activity (calculated using either the sliding-window or the all-at-once technique) for the observation period, in this case 5-7 days. A higher magnitude indicates the subject has a consistent, 24-hour schedule with respect to activity and light. Lower magnitudes indicate low correlation between daily cycles of light and activity irrespective of phase differences.*

Phasor angle: *A phase relationship between circadian light exposure and activity (calculated using either the sliding-window or the all-at-once technique) for the observation period, in this case 5-7 days. A positive angle (first quadrant) indicates a delay in activity with respect to light and a negative angle (fourth quadrant) indicates an advance in activity with respect to*

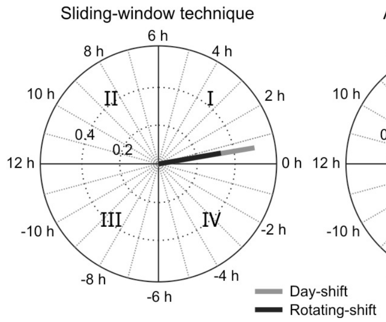

Figure 3. Average phasors for day-shift and for rotating-shift nurses using the sliding-window (left) and all-at-once (right) techniques. See text for discussion of the two methods.

Figure 3 illustrates on polar coordinates the average phasors for both groups using both techniques, sliding-window and all-at-once. For diurnal species the phasors typically plot in the first and fourth quadrants, indicating activity and light exposure are positively correlated. Phasor angles for humans are almost always in the first quadrant, indicating that activity is delayed with respect to light exposure, typically because people become active with the bright, morning light but continue to be active after sunset under dim, electric light; see later discussion on this point.

Figure 4 shows the distribution of the phasor magnitudes for the two groups of nurses on a linear scale, but broken down in terms of the number of night-shifts they worked during the recording period. Obviously the day-shift nurses did not work any nights; two rotating-shift nurses worked five nights. Figure 4 shows that, in general, as the number of working nights increase, phasor magnitudes decrease. This suggests that behavioral circadian disruption increases with the number of nights worked. It should be noted, however, that one of the two nurses who worked five nights had a higher phasor magnitude than all those working three or four nights and most working two nights, and that the highest average circadian disruption was for nurses working three night shifts during the week. This suggests that disruption might be less for people who continually work the night shift compared to those who do so intermittently, but, of course, there are too few samples to reach any reliable conclusions concerning the health of these nurses.

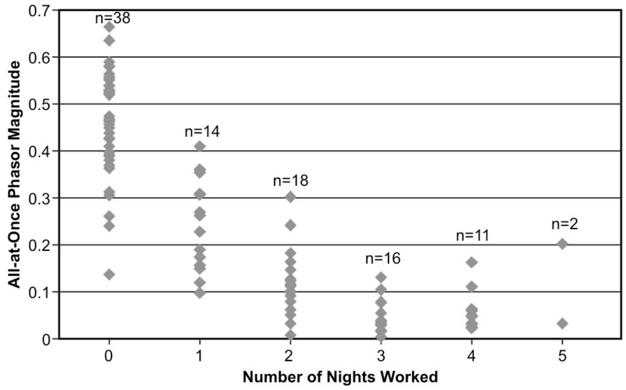

Figure 4: All-at-once phasor magnitudes for day-shift and rotating-shift nurses plotted as a function of the number of nights worked

Figure 5 compares the sliding-window and the all-at-once techniques for computing phasor magnitudes for the day-shift and rotating-shift nurses. For the day-shift nurses, either method returns similar results (r^2=0.91). For the rotating-shift nurses, the similarity is reduced (r^2=0.18). The most obvious explanation being that the day-shift nurses are on a regular schedule with every day similar to every other day. Since their behavior conforms to a stable 24-hour pattern both techniques give the similar phasor magnitudes. Rotating-shift nurses, on the other hand, have variable schedules so they do not have stable 24-hour patterns of light and/or of activity. They exhibit a complex variety of rhythm periods, some slightly shorter and some longer than 24 hours. As previously discussed, the sliding-window technique lumps together a broader range of periods in the 24-hour phasor resulting in relatively larger phasor magnitudes than those obtained by the all-at-once technique.

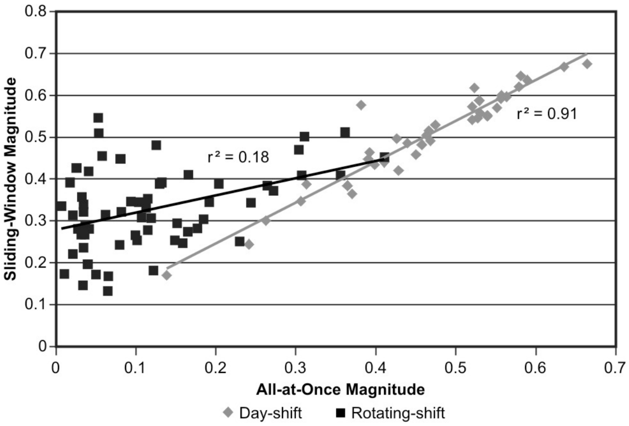

Figure 5: Comparison of phasor magnitudes for the sliding-window and the all-at-once techniques

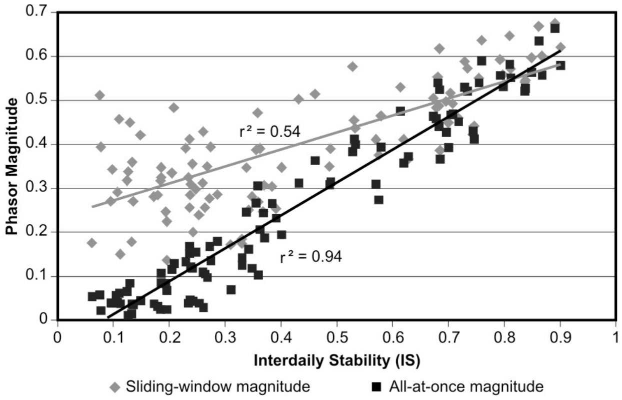

Figure 6: Comparison between the IS statistic based upon activity and the two techniques for determining phasor magnitude based on activity and light exposures

Figure 6 is a comparison of the IS statistic and the phasor magnitudes obtained using the sliding-window and the all-at-once techniques. The all-at-once technique yields results that correlate highly with the IS statistic (r^2=0.94). The IS statistic is inherently based upon an assumed 24-hour activity rhythm, but since it does not depend on light exposures, the high correlation indicates that light exposure maintained a similar pattern with respect to activity throughout the week. The relatively weaker correlation between the IS statistic and the sliding-window phasor magnitude implies that, although light and activity might be highly correlated, the period of oscillation did not conform precisely to a 24-hour period. That is, the 24-hour based IS statistic is low but the sliding-window phasor magnitude is high, relative to the all-at-once phasor magnitude. It is not known at this time which phasor technique is more predictive of health and well-being; must people maintain high regularity across all days (measured with the all-at-once phasor) to be healthy or can people vary behavior (activity) across days (measured with the sliding-window phasor) without consequences to health and well-being?

Figure 7 illustrates sliding-window phasors for four different day-shift nurses paired with their average daily circadian stimulus (CS_A) and activity profiles. Because average activity and average light are plotted independent of one another, they are not strictly comparable to the corresponding phasors. Nevertheless, the paired diagrams do help illustrate how activity and light tend to affect phasor magnitudes and angles. Based upon examinations of a wide range of activity and light exposure profiles from day-shift nurses, the data from nurse A can be considered as “typical.” Generally speaking, a “typical” day-shift person exhibits a delayed phasor angle of between one and two hours with a phasor magnitude between 0.5 and 0.6. “Typical” individuals tend to be consistently active throughout their waking period, but are exposed to relatively higher light

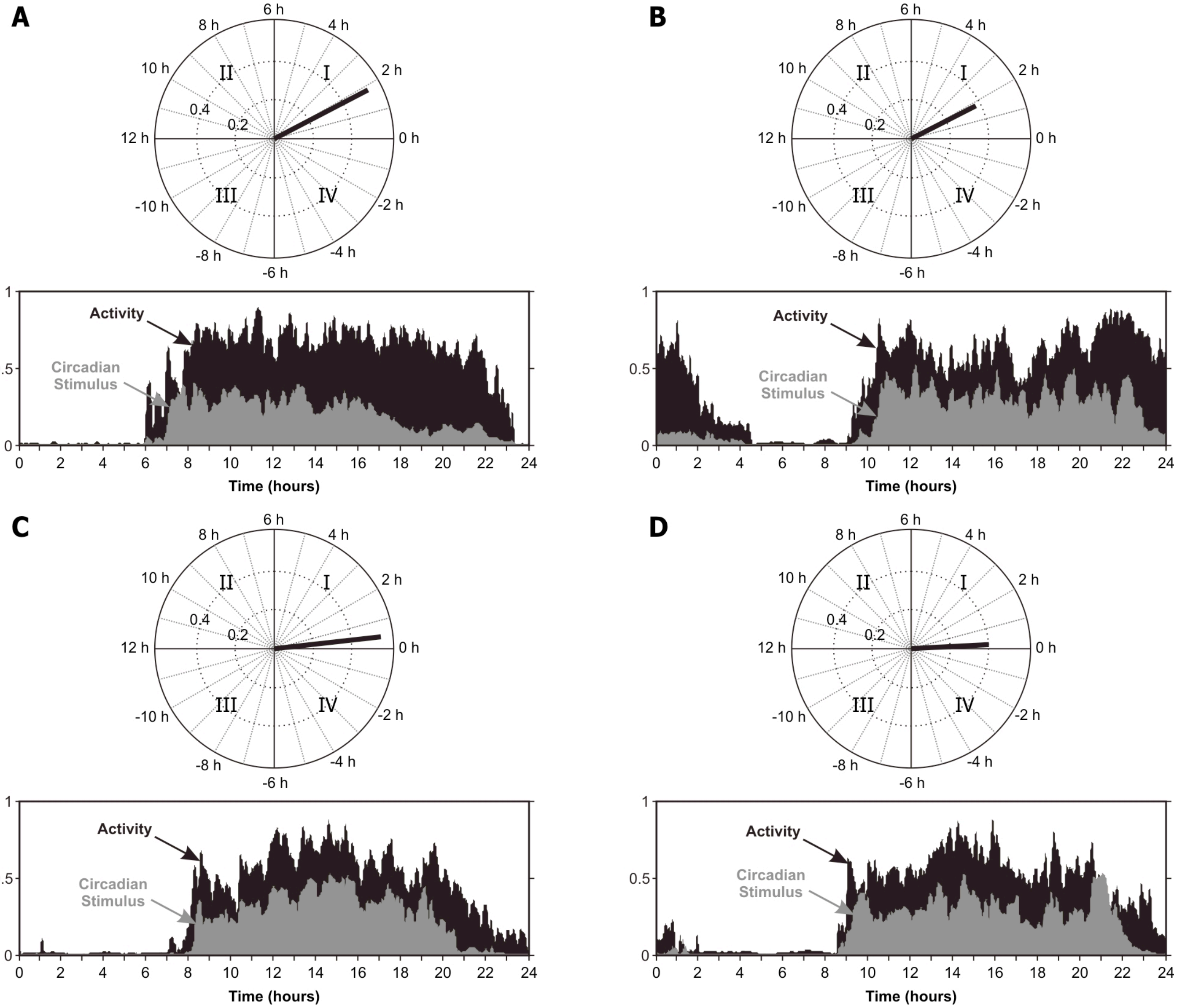

Figure 7: Average activity and average circadian stimulus (CS_A) values across a day with corresponding sliding-window phasors for four different day-shift nurses

levels in the early part of their activity period than toward the end. This asymmetry in relative light exposure from the early to the late part of their activity period, in fact, produces delayed phasor angles in Quadrant I. The phasor angle for the "typical" nurse is nearly the same as that for day-shift nurse B, but the phasor magnitude for nurse B is lower. Comparing the average activity and light exposure data for the two nurses, it is clear that for both nurses light exposures are lower in the late part of the activity period than in the early part of the activity period, thus leading to their nearly identical phasor angles. It is even clearer that activity is more variable and less well correlated with light exposure for nurse B than for nurse A. This yields a shorter phasor magnitude for nurse B than for nurse A. It is important to point out that the absolute time of activity and light do not affect the phasor angle or the phasor magnitude, at least not directly. Again, the phasor is based upon the synchronization between activity and actual light exposure, not between activity and clock time. The phasor magnitudes for nurses A and C are nearly identical, the major difference is in their phasor angles. It can be readily appreciated from this figure that nurse C does not exhibit the relative asymmetry in light exposure from the early to the late activity period as is seen with nurse A. Consequently the phasor angle for nurse C is advanced with respect to nurse A to near 0 hours. The average activity and light exposure data for nurse D are very much like those for nurse C except they are less well correlated, yielding the same phasor angle, but a lower phasor magnitude. Compared to the "typical" nurse A then, nurse D is more variable in her activity and light exposure patterns and does not exhibit the asymmetry of activity from the early to the late parts of her activity period. Of potential interest, nurse D appears to be exposed to bright light toward the end of her activity period relative to any of the other nurses, including the "typical" nurse. Also it should be noted that the period of time with no light and activity (presumably sleep) is less for nurses B and D than for nurses A and C who both have relatively large phasor magnitudes. Again, whether these differences are predictive of health and well-being remains to be studied systematically.

DISCUSSION

It is becoming clearer that human health and well-being are dependent upon the synchronization of biological systems [13]. The master clock in the SCN sets the pace for peripheral systems, but if these complex systems become asynchronous with one another (e.g., following jet lag) we experience poor sleep, indigestion, and performance errors. These, in turn, may lead to chronic problems such as insomnia, diabetes and obesity, and injury.

Since the pattern of light and dark drives the timing of the master clock, it is obviously important for our evolving understanding of human health that we begin to measure the light-dark cycles actually experienced by individuals in their own living environments as affected by electric lighting and modern day work schedules. The Daysimeter was developed for this purpose. Measuring the light-dark patterns experienced by people in their living environments is important, but those data are not particularly valuable unless it is possible to interpret them in the context of human well-being and health. Phasor analysis was developed to quantify the synchronization of oscillating light-dark patterns and activity-rest patterns, thereby giving an individual-specific measure of behavioral circadian entrainment or disruption. In addition to activity, but not examined here, other measures of circadian regulated processes, such as core body temperature, heart rate, and hormone levels, can be made together with light exposure measurements and then analyzed using the phasor analysis technique described here.

It is also readily possible to relate individual-specific measures of circadian disruption to individual-specific measures of performance, affect and fatigue. It is also theoretically possible to develop individual-specific treatments to correct circadian disruption and measure their efficacy through changes in phasor magnitude and angle as they relate to changes in medically meaningful outcomes. Obviously genetic differences as well as differences in environmental stressors must also be considered. In the near future, however, it should be possible, using tools like the Daysimeter and phasor analysis, to begin to bridge ecological measurements of circadian disruption to controlled studies of circadian disruption using animal models for such diseases as cancer, cardiovascular disease, and diabetes.

Recently we were able to show the feasibility of this bridge. Figure 2 shows the circular correlations and associated phasors for a day-shift nurse and a rotating-shift nurse together with the circular correlations and associated phasors for a rat placed on a regular 12L:12D schedule and a rat placed on a regularly reversing (i.e., continuous jet lag) pattern of light and dark. As can readily be appreciated from Figure 2, and despite the differences in two species with regard to their photic niche (i.e., diurnal nurses versus nocturnal rats), it should now be possible to parametrically study the impact of circadian disruption actually experienced by individuals in different living environments with any one of several animal models for human diseases and disorders. These envisioned studies can then serve as the next logical step in understanding the impact of circadian disruption on human health, complementing the pioneering epidemiological studies that raised our collective concern for how circadian disruption might impact human health [17, 19].

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Content-based Adaptation of the Dynamics of Estimated Light Sources

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ABSTRACT

Lighting is a very important aspect in film-making. Using a technique known as light source estimation, it is possible to estimate the color properties of the light sources used while filming scenes of films or television series. One very important—but often unaddressed—aspect of light source estimation is related to temporal control. In this paper, we propose a novel method for temporal control of the estimated light source of a video scene. After describing the method, we will explain the results of a user study which shows that it is superior when compared with traditional temporal control techniques.

Keywords

Movie lighting, content analysis, light source estimation, temporal control.

INTRODUCTION

Lighting is a very important aspect in film-making. In modern movies and television series, film makers and cinematographers carefully use light to accentuate certain aspects of the story, to change the atmosphere that is conveyed, or to establish a certain mood. For example, candlelight suggests romance and harmony, high contrast lighting achieves accentuated dramatization, and moving light can invoke fear, chaos and madness [17]. Colored light is also used to accentuate certain aspects of the story or to help convey certain emotions. Although there are no specific rules on how to associate colors with emotions, red is often found associated with love or hatred, yellow with happiness and joy, and blue with peace and tranquility [18].

For regular film watchers, these lighting aspects usually have an implicit influence: although they are of crucial importance to help convey the story, most people don't actually realize that they are "manipulated" by lighting changes during a movie. On the other hand, the presence and characteristics of these elements have very often been used in the area of video content analysis; interpretation of cinematographic rules — such as information about the lighting of a scene and the color of the light source that illuminates it — can give important semantic information about that scene or even about the entire movie. For example, Rasheed et al. use scene lighting characteristics, along with other visual features, to automatically classify the genre of a movie [11]. Light source estimation can thus be a very important technique to extract high-level, semantic information about a scene.

One particular application of light source estimation is the creation of a lighting atmosphere which is rendered while users watch a movie on a television screen. If the light source is estimated correctly, the rendered atmosphere will resemble the light settings of the scene in the movie and increase the user's immersion in the content.

The topic of light source estimation has been well studied in the past and several well described techniques are in common use. The techniques range from simple MPEG-7-style dominant color extraction [15] to more advanced systems based on white point extraction. In [1,2], some of these methods are reviewed. As we are mostly interested in the dynamic control of the estimated light source rather than the actual light source estimation itself, a full comparison between the different known methods is beyond the scope of this paper. For simplicity reasons, we will only use a single light source estimation algorithm in this paper to test our dynamic filtering technique. For each content frame, we construct an RGB space in which each the color of each pixel is represented by a point. We then use least squares estimation to determine the best fit of the data from the linear RGB color space into a vector in that space. Because the light source is reflected on objects on the screen, this vector has the property that it reflects precisely the color that is reflected on the different surfaces.

For the application mentioned above, the temporal dynamics of the estimated light source are very important. The actual lighting set-up of a mise-en-scène — i.e. the arrangement of actors and scenery on a setting filmed for a motion picture — filmed for a calm movie scene is usually constant for an entire scene. However, light source estimation techniques are not perfect, and camera action and object movement often cause the estimated light source to vary throughout such a calm scene, even though the actual lighting during recording of the scene didn't change at al. If the raw results of light source estimation are used to render a lighting atmosphere, the atmosphere will be much more dynamic than the actual content as the user sees it on the screen. This effect not only reduces immersion, but it might even distract and annoy the viewer. On the other hand, a very dynamic lighting atmosphere might be desirable if scene under consideration is equally dynamic, for example when many special visual effects are used. In that case, a dynamic atmosphere will match the content on the screen and will therefore contribute to the viewer's immersion.

This temporal aspect of lighting has not been so much addressed. This is surprising, as dynamics of lighting and light effects are a fundamental part of the cinematographic experience Most existing work on temporal control of estimated lighting focuses on the use of (advanced) low-pass digital filters which "smoothen" the estimated signal over time. In [16] an advanced implementation of such a system is described, which uses substantial time subsampling and employs the spatial detection of special effects on small regions to reset a low-pass filter. Whereas this system is able to react to very localized visual effects, a drawback is that it will often fail to reflect the global dynamic properties of an entire scene. This drawback actually applies to most filters described in literature: however advanced these filters are, unless they take into account the fact that global and local dynamic properties of the content, on a frame by frame basis, are inherently a very important part of the content itself, they will unavoidably decrease the intensity of these elements for the viewer.

Let's look at two extreme cases as an example. During reasonably static, dialog-based scenes — such as those which occur quite often in soap operas and popular comedy television series like *"Friends"* and *"Will and Grace"* — the resulting estimated light source should be rather static throughout the entire scene. However, at the exact frame this scene ends and a completely different scene starts, the light source should reflect the properties of the new scene immediately and should not be slowly smoothed throughout. At the other extreme, consider a scene in a war movie where the battle takes place at night. Due to the dark lighting conditions, any special effect (small such as a gunshot or intense such as an explosion) should be reflected in the estimated light source. In this case, smoothing with a low-pass filter is simply not acceptable.

In this paper, we propose a novel method for temporal control of the estimated light source of a video scene. The goal is to smooth the estimated light source color when the content is static but to allow special, abrupt effects to be instantly reflected without latency in the resulting estimation. This will allow an atmosphere to be rendered while viewers watch a movie on a television. This atmosphere not only reflects the color of the lighting of a scene but also its temporal dynamics. All of this will help increase the immersive experience.

In the next section we will introduce the algorithm. Afterwards we will describe the test content and objective criteria for characterizing the dynamics of that content. We will then describe the user test that we have carried out to evaluate the proposed algorithm. Finally, we will discuss the results and conclude the paper.

TEMPORAL CONTROL ALGORITHM

In the context of this paper, by "temporal control", we mean the process through which the results of light source estimation are modified or filtered to change its temporal characteristics. An example of a very simple temporal control algorithm is a low-pass filter. When applied to the output of a light source estimator, it simply eliminates (or "smoothes") all abrupt color variations given by that estimator. As can be easily imagined, the resulting colors vary slowly in time, regardless of how dynamic the content might be.

For the reasons explained in the introductory section, it is not always desired that the estimated light source follows the changes in the content on a frame-by-frame basis. Particularly for the application described earlier where an atmosphere is rendered in real-time along with a movie being watched by the viewer, the rendered light source should only change significantly when the same happens with the content. With the approach described in this paper we attempt to let the dynamics of each scene dictate how "smooth" the variations of the resulting light source color should be. Very dynamic scenes will lead to fast variations in the light, whereas static, slowly varying scenes will lead to results that are calm and smooth in time.

It should be noted that the temporal control algorithm proposed in this paper does not depend on the light source estimation algorithm used. In fact, it is suitable for any kind of raw color signal input, for example expressing an approximation of the color properties of the dominant light source in a scene. The method described in this section can be used without loss of generality for any such input.

To achieve automatic smoothing as described above, we need to characterize the dynamics of the content in a feature which is simple to use. As physical light sources that illuminate the scene during recording naturally influence both the colors and the luminance of that portion of the motion picture, we will estimate the dynamics based on color- and illumination-based features. From these features, we then compute the dynamics for each frame of the content.

To calculate these features, we make use of a so-called "combined HSV histogram". HSV is a relatively simple three-component color space, characterized by the hue (H), saturation (S) and brightness (value, V) [6]. We use an HSV color space here, rather than the simpler RGB color space, because HSV more accurately describes perceptual color relationships than RGB. On the other hand, it is still computationally simpler to implement than real perceptually uniform color spaces like CIE 1976 La*b*. However, because the HSV color space is not completely perceptually uniform, in particular in the low brightness colors, we need to use a non-trivial distance measure as we will define below.

We define a 256-bin HSV histogram as follows:

- The 256 bins are ordered in a cube of dimensions 16×4×4. The first dimension corresponds to the hue values (discretized in 16 bins), the second dimension corresponds to the saturation (discretized in 4 bins), and the third dimension corresponds to the value (discretized in 4 bins). We use more bins for the hue component than for the saturation and value components because we want to give more importance to the differences in hue than to differences in saturation or brightness.

- For each video frame, we calculate the HSV values for each of the pixels and fill each bin of the histogram with the number of pixels that have an HSV value in the corresponding range.
- If the hue value is expressed as a number in [0,360) and the saturation and value are numbers in [0,1], the first bin will thus contain the number of pixels that have an hue between 0 and 22.5 (=360/16), a saturation between 0 and 0.25, and a value between 0 and 0.25.

Mathematically, we can express this as follows:

$$\begin{aligned} HSV[h,s,v] = \mid \{ (\mathrm{i},\mathrm{j}) : & \\ & \frac{360}{16}h \le H_{\mathrm{ij}} < \frac{360}{16}(h+1) \\ & \wedge \frac{1}{4}s \le S_{ij} < \frac{1}{4}(s+1) \\ & \wedge \frac{1}{4}v \le V_{ij} < \frac{1}{4}(v+1) \\ \} \mid & \end{aligned} \tag{1}$$

where i and j correspond to the rows and columns of pixels in each video frame, and H_{ij}, S_{ij}, and V_{ij} are the hue, saturation and value components, respectively, of the pixel at position (i,j).

The histogram is then normalized by dividing each value by the total number of pixels in the video frame, in order to make the feature independent of the dimensions of the video frame.

The HSV histogram is created for each frame in a video sequence. Next we define a distance measure Δ between two of such histograms

$$\Delta = \sum_{h=0}^{15}\sum_{s=0}^{3}\sum_{v=0}^{3}\left|HSV_t[h,s,v] - HSV_{t-1}[h,s,v]\right| \tag{2}$$

as the sum of the absolute differences between corresponding bins in two consecutive frames. As the histograms are normalized, this definition of the distance measure Δ will always yield a value between 0 and 2.

However, large parts of video frame often have very low brightness. Whenever such dark regions are present in two consecutive frames, the distance between the corresponding HSV histograms will also be very small. This is caused by the fact that HSV is not perceptually uniform as explained before. For our application, this is undesirable for two reasons:

1. Dark regions of an image do not convey much information about the light settings of a scene, other than the fact that the light source did not strongly illuminate that area;
2. A small difference between the histograms of two dark video frames might hide the fact that the light settings captured on those two frames are completely different. For example, consider the situation in which a very dark scene is illuminated by a small green light in the first frame, and that that light suddenly changes to red in the next frame. In that case the light condition as determined by the histograms should clearly be very different, even though the majority of the pixels are black or very dark in both frames.

In order to make the distance measure of Equation (2) more robust to such conditions we introduce an alternative distance measure Δ', that takes into account this problem by not counting dark pixels in the frames. We define this alternative distance measure as follows:

$$\Delta' = \frac{\sum_{h=0}^{15}\sum_{s=0}^{3}\sum_{v=1}^{3}\left|HSV_t[h,s,v] - HSV_{t-1}[h,s,v]\right|}{\max\left[\frac{1}{4}, 1 - \min_{t,t-1}\left[\sum_{h,s} HSV[h,s,1]\right]\right]} \tag{3}$$

The numerator counts the bin-to-bin difference between the histograms, but leaves out bins for which the brightness component is low (i.e., only pixels with brightness components in the three highest bins are taken into account). The minimum in the denominator should be taken between the sums of the bins with the lowest brightness of the two consecutive frames. The denominator leaves out the dark parts that are common to both frames. It is bound to a minimum value of 1/4, to avoid extremely large distance values between the histograms of two video frames when both have very large dark areas. The distance measure Δ' of Equation (3) thus emphasizes the difference between the non-dark parts of the images.

Next, for each frame t we compute two values:

1. The first is the **estimated light source** LSE_t (expressed as RGB values) for that frame. The exact nature of the algorithm used to find the light source of the current frame does not matter as long as for each frame we find a color vector (in the linear RGB color space) that reflects some properties of the dominant light source illuminating the scene:
$$LSE_t = (R_{LSE}, G_{LSE}, B_{LSE})_t \tag{4}$$
2. The second value we calculate is the **resulting light source**, LSR_t after temporal filtering:
$$\begin{aligned} LSR_t &= (R_{LSR}, G_{LSR}, B_{LSR})_t \\ &= (1-s) \cdot LSE_t + s \cdot LSR_{t-1} \end{aligned} \tag{5}$$

It is computed as a linear combination of the estimated light source for the current frame and the color that was calculated from the previous frame. The smoothing factor s is defined as

$$s = \begin{cases} 0.98 & \text{if} \quad \Delta' \leq 0.02 \\ 1 - \Delta' & \text{if} \quad 0.02 < \Delta' \leq 1 \\ 0 & \text{if} \quad \Delta' > 1 \end{cases} \tag{6}$$

For dynamic scenes the smoothing factor s is small, giving a high weight to the light source estimated for the current frame. For calm, static scenes the smoothing factor is large, leading to a calm and gradual transition between colors because the previous value has a large weight. The minimum smoothing factor is larger than 0 to make sure that the filtered light color will always converge to the estimated light source of the current frame LSE_t if the video freezes or becomes completely static (i.e., if the distance computed between several consecutive frames is 0).

VALIDATION FRAMEWORK

In this section, we present a framework to quantize the dynamic properties of video sequences in order to characterize the properties and the behavior of the proposed temporal control algorithm. We start by describing our test set; this test set is used both for the quantization in this section as well as for the user study of the temporal filtering algorithms that is described in the next section. We then describe which features we extract from the video sequences to characterize their dynamic properties. We continue by analyzing the effects of temporal filtering on the dynamics of estimated light source.

Test content

The test set consists of six video clips of 30 seconds each. They were selected based on the presence of very different lighting conditions which characterize different genres in film and TV series. The clips from the test set can be described as follows:

- ***Walk the Line*** — the first sequence is a clip from the movie "*Walk the Line*"; this particular scene depicts a concert with different illumination sources: the backstage lighting, with a relatively dark and saturated color and the non-saturated, bright illumination of the singer which dominates the scene. The scene has a very high contrast, is very calm and shots are relatively long.
- ***Hellboy*** — the second sequence is a clip from the movie "*Hellboy II: The Golden Army*"; this particular sequence has a filmed part and a computer generated part. Both are highly saturated and the filmed part has the additional particularity of having a very distinctly colored light source in the left and the right side of the screen.
- ***Friends*** — the third sequence is a clip from the episode "*The One with the Kips*" (season 5, episode 5) of the popular soap opera *"Friends"*; like most soap operas, Friends has a flat appearance: there is little contrast, and it is filmed in high-key, i.e., it has an abundance of unsaturated light, and the scenes are free from shadows. The colors are mostly pastel and although there is not a lot of movement on the scene, the shots are relatively short as it mainly consists of dialogues.
- ***Hulk*** — the fourth sequence is a clip from the movie "*The Incredible Hulk*"; this particular clip takes place in a cave, at night, during a thunderstorm. Although the shots are long and dark and the contrast is high, the lightning strikes and the rain add a very dynamic element to the scene lighting.
- ***Wall-E*** — the fifth sequence is a clip from the animation movie "*Wall-E"*; this particular computer generated clip depicts an indoors scene, illuminated by one of the characters (a robot). During the scene the illumination varies drastically, from very well lit, high-key, to very dark and saturated.
- ***Platoon*** — the sixth and last sequence is a clip from the movie "*Platoon*"; this particular scene depicts a combat situation at night; apart from being a very dark scene, contrast is relatively low and gunshots and explosions dominate the scene, making it very dynamic and intense.

Visual feature extraction

The variety of clips and genres will help us explore the behavior of the temporal control algorithm proposed in this paper. As the clips we use are not part of any public domain test set and therefore are not available for free, it is important to characterize them as well as possible. Not only will this offer the reader a better description of the test set used in our study, but it will also help us explain the results of that study later on in this paper.

In this section, we describe this characterization of the dynamics of the video sequences in terms of temporal changes of their visual properties. To quantify these visual properties, we extract a number of video descriptors from the content. These descriptors offer a numerical representation of visual properties which can be analyzed in terms of their dynamic behavior in time.

Video descriptors

In order to characterize the dynamics of each sequence in our test set, we will use three different descriptors: the shot duration, the HSV histogram and the light source color.

The first descriptor we will use is the shot duration. A shot is defined as a sequence of video frames, captured uninterruptedly by a movie camera. It is delimited by a shot transition (commonly called a "shot cut") at its beginning and at its end. The transition between shots can be abrupt, in which case the new shot will start on a frame immediately after the last frame of the previous shot, or gradual, in which case the actual transition lasts for a number of frames (e.g. cross-fade, fade in, fade out).

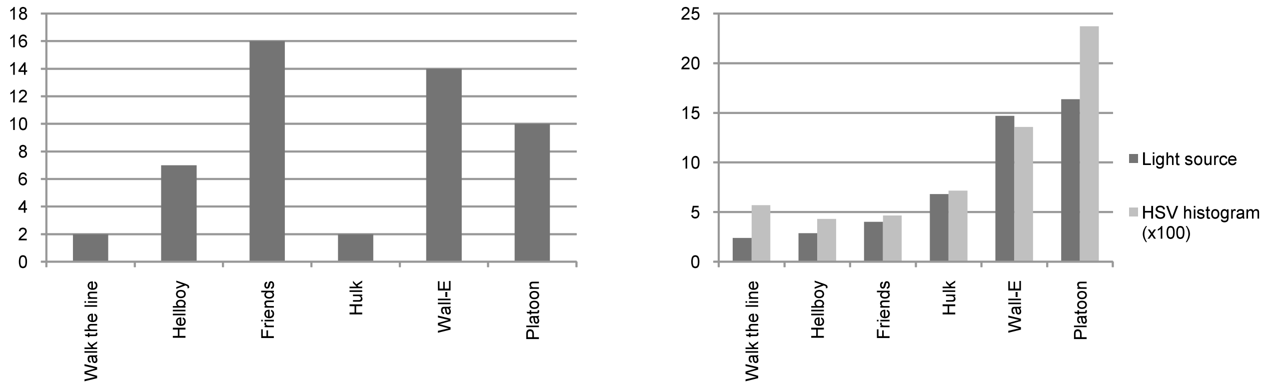

Figure 1 – (left) Number of shots in each of the test sequences and (right) average intra-shot feature differences. Note that the HSV histogram difference values were scaled up so both features can be visually compared.

Different shots often correspond to different points of view within the same scenario; other times, they belong to distinct scenes and thus have completely different visual properties. These shot transitions represent visual discontinuities and should be taken into account when characterizing the video sequences. An important way to characterize the dynamics of film content is by measuring the average shot length. Since most of the shots end in abrupt transitions, shot boundaries are moments when the visual properties (including the lighting of a scene) change drastically from one moment to another. This does not necessarily mean, however, that the sequence is very dynamic. In a soap opera, mainly comprised of dialogues, shots are typically very short and alternate between two or more view points within the same scene. However, the properties of each shot are very similar because the dialogues take place in the same physical location. Furthermore, within each shot, there is little or no change since usually, during dialogues, only the face of the actors is shown in the image. In an action movie, on the other hand, directors usually keep the shots short to indicate action and induce a high tempo. In this case, the visual properties of each shot are very different from each other, offering the viewer very much different visual information within a short period of time.

The second video descriptor we will use is the HSV histogram. This descriptor was introduced in the previous section. It describes the color properties of each frame of the video in terms of the hue, saturation and brightness (value) of all its pixels.

The third and final descriptor we will use is the light source color. It gives an approximation of the color of the light entering a scene. As remarked before, the temporal control algorithm that is the main focus of this paper is independent of the algorithm used to estimate the light source, and a full description of the different methods available is out of scope here. We use a method based on a least-squares fit in the RGB-space representing all pixels in a single video frame.

Characterization of visual properties

The number of shots in each sequence of our test set is illustrated in Figure 1 (left).

To express the temporal behavior of the two remaining visual descriptors, we compute the corresponding average feature differences. The average HSV histogram difference is given by:

$$\overline{\Delta H} = \frac{1}{N-1}\sum_{t=1}^{N-1}\sum\nolimits_{h,s,v}\left|HSV_t[h,s,v] - HSV_{t-1}[h,s,v]\right| \qquad (7)$$

where the histogram $HSV_t[h,s,v]$ was described in the previous section. The outer summation is over all N frames, the first frame being $t=0$, and the inner summation is over all the 16×4×4 bins of the histogram.

The average light source difference is given by:

$$\overline{\Delta L} = \frac{1}{N-1}\sum_{t=1}^{N-1}\Delta L_t \qquad (8)$$

with

$$\Delta L_t = \sqrt{(r_t - r_{t-1})^2 + (g_t - g_{t-1})^2 + (b_t - b_{t-1})^2} \qquad (9)$$

i.e., the Euclidian distance in RGB space between the light source colors in two consecutive frames, and where r_t, g_t and b_t are the RGB values of the light source computed for frame t.

As was mentioned above, shot cuts represent visual discontinuities. To better assess the dynamic properties of the sequences, while at the same time excluding the influence of the shots boundaries from this process, the computation of the average feature difference will be restricted to all frames that are neither the starting frame of a shot nor the frames that make up a gradual transition. Figure 1 (right) illustrates the intra-shot average feature differences for the sequences in the test set, ordered by increasing average light source differences.

As can be clearly seen, the sequence *Friends* has one of the lowest variations in terms of both visual descriptors, even though the clip contains the highest number of shots in the

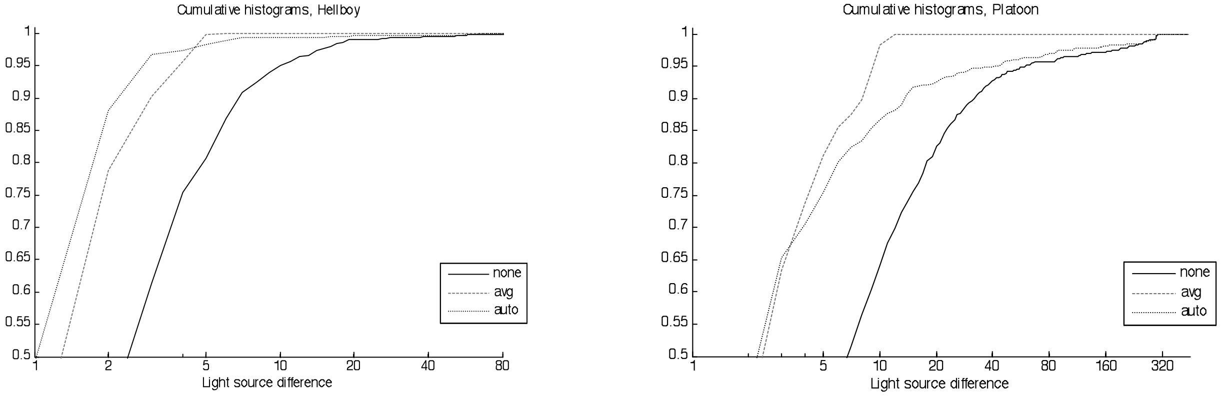

Figure 2 – Cumulative histogram of light source differences, filtered with the three different settings for Hellboy (left) and Platoon (right); note that the horizontal scales are different for the two graphs. The fact that the *avg* setting is in both cases above the unfiltered result, shows that simple averaging always decreases the variations in the light source. The *auto* setting, on the other hand, is first above and later below the *avg* setting: this indicates that small changes are smoothed even more than in the *avg* case, while large changes are kept (see text). Note that the maximum possible light source difference is 442; however, all of the graphs saturate much earlier.

clips in our test set. This is typical of soap operas: short shots are necessary for dialogues but the scene is kept rather static to avoid inducing a notion of action and activity to the viewer. In contrast, *Platoon* is the sequence with the most relative activity, as expressed by the high variation of visual features. This is also expected from an action scene in a war movie: a combination of short shots and high intra-shot visual variation help convey a notion of high activity and intense action.

Characterization of temporal control techniques

In this section we will characterize the properties of three different temporal filtering strategies for the estimated light source estimation. In the next section, these are compared in a user study.

The three strategies (or "settings") that we examine here are the following:

- No smoothing, or ***none***: no filtering is done on the results of light source estimation. Light source is estimated frame by frame without any sort of temporal filtering;
- Low-pass filtering with a windowed average, or ***avg***: a low-pass filter smoothes out abrupt transitions and sudden light source changes, as well as small variations that can occur on certain frames. In particular, the estimated light source of the past 20 frames (i.e., 0.8 seconds in a video with a frame rate of 25 frames per second) is averaged.
- Content-based temporal filtering, or ***auto***: as described in the temporal control algorithm section: small variations that might occur from frame to frame are smoothed out, but abrupt transitions with high amplitude are retained.

In order to visualize the different behavior of each of these temporal filtering mechanisms, we first apply each method to the light source computed for each frame of a sequence. Then, we compute a histogram of light source differences for each setting.

This histogram gives an indication of the type of variations that occur for the filtered light source for each video and helps us compare the different temporal filtering strategies. The light source difference is computed as defined by Equation (8). If r, g and b can have any value in the range $[0,...,255]$ then the maximum light source difference ΔL will be $255 \cdot \sqrt{3} \approx 441.7$. The light source difference will therefore be a value in the range $[0,...,442)$.

The distribution of light source differences ΔL in an entire movie sequence gives important insight into the dynamics of the light source: if all light source differences are small, this means that the light source changes very gradually, whereas a more homogeneous distribution would point towards a case where both small and larger changes are present. To characterize this distribution, we look at the histogram of light source differences, which is computed as follows:

$$D[k] = \frac{1}{N-1} \left| \{ t : k \le \Delta L_t < k+1 \} \right| \qquad (10)$$

where $t = 1,...,N$ for each frame in the sequence except for the first, $t = 0$ and with $k = 0,...,441$. In order to make it easier to visualize, we compute a cumulative histogram based on $D[k]$ as:

$$C[k] = \sum_{i=0}^{k} D[i] \qquad (11)$$

Note that the histogram $D[k]$ is normalized, i.e., the sum of all bins in the histogram will add up to 1. Conversely, the last bin on the cumulative histogram will also be 1, i.e., $C[441] = 1$.

		p		
Sequence	**Setting**	**75%**	**90%**	**99%**
Walk the line	*none*	6	9	54
	avg	2	5	9
	auto	2	3	6
Hellboy	*none*	5	9	52
	avg	3	6	8
	auto	2	3	7
Friends	*none*	5	9	69
	avg	3	5	8
	auto	2	3	62
Hulk	*none*	5	10	264
	avg	2	3	11
	auto	2	3	272
Wall-E	*none*	12	25	102
	avg	5	8	13
	auto	4	7	44
Platoon	*none*	15	35	284
	avg	5	8	11
	auto	5	13	270

Table 1 – Light source difference below which 75%, 90%, or 99% of all light source difference are accounted for, i.e., when compared to the graphs in Figure 2, we look for the light source difference values for which the graphs cross the 75%, 90%, or 99% point, respectively. Note that the maximum possible light source difference is 442, and that almost all of the sequences and settings saturate much earlier than that.

Figure 2 illustrates the cumulative histograms computed for each temporal control setting for two very distinct video clips: *Hellboy* and *Platoon*.

As can be clearly seen for *Hellboy,* – Figure 2 (left) – without any type of filtering (setting *none*), the cumulative histogram saturates much later than for the other two settings. This means that with *avg* and *auto*, most light source variations are simply filtered out.

When comparing this with Figure 2 (right), notice that the horizontal scale is different – light source differences in *Hellboy* are much smaller (for all settings) than for *Platoon*. It can be easily seen that the cumulative histogram for setting *avg* saturates very quickly; this is expected, as this algorithm is nothing more than a low-pass filter which cuts out any large sudden variation.

More interesting is the difference between the settings *none* and *auto*. The latter has a steeper curve for low difference values – this means that small consecutive differences in light source are simply smoothed out. However, after this initial point, the curves of *auto* and *none* are similar for higher difference values. This means that large light source differences are kept. This behavior is characteristic for the the temporal filtering technique proposed in this paper. In scenes with rather static content most variations of estimated light source are smoothed out. In scenes with very dynamic content, on the other hand, variations are sharp and pronounced, reflecting the amount of dynamics of the content on the screen.

In order to characterize the behavior of the temporal filtering techniques for the remaining sequences, we compute the lowest bin in the histograms for which a certain percentage of light source differences are found:

$$T[p] = \min\left[k : \sum_{i=0}^{k} D[i] > p\right] \qquad (12)$$

This measure is computed for the percentages of 75%, 90% and 99%, i.e., $p = 0.75, 0.9, 0.99$. Table 1 lists these values for all sequences, for the three different temporal filtering settings. Compare this to cumulative histograms like those of Figure 2: we look for the light source differences (horizontal scale) for which the curves cross a horizontal line at p=75%, p=90% and p=100%, respectively.

As can be easily seen in Table 1, for sequences with little visual variation (e.g, *Walk the Line*, *Hellboy*), the saturation point for both *avg* and *auto* settings occurs quite early, with 99% of the light source differences occurring already below bin 9 for both settings. This means that 99% of the differences as defined in Equation (8), after each of these temporal control settings were applied, are smaller than a value of 9. On the other hand, for sequences with high visual variation (in particular *Hulk* and *Platoon*), this early saturation stays low for the *avg* setting but is much higher for setting *auto*. This again reflects the characteristic of the setting *auto*, which smoothes out small variations but not large variations in light source.

Based on the analysis done in this section, we expect that the setting *none* will be appropriate for sequences which are very dynamic, because all the variations in detected light source are maintained, but won't be very useful for less dynamics scenes, for which small but potentially disturbing changes in the estimated light source will also be present in the filtered result.

We expect the setting *avg* to be appropriate for sequences which are calm, since most small and large variations are smoothed out. It will probably not work very well for dynamic scenes, particularly those with special effects such as lightning and explosions, as these will be averaged out of the filtered result.

Finally, we expect the setting *auto* to be appropriate for most sequences, both calm and dynamic, because it is able to match the dynamics of the filtered light source to the actual dynamics of the content.

In the next section we will present the results of our user study, performed to test these hypotheses.

USER STUDY

In this section we describe the user study that we have performed in order to evaluate the perceived quality of the temporal filtering method described earlier.

To test the settings, we created a system that plays a movie clip and analyses the light source of the content in real-time. The estimated light source is then filtered in one of the three ways ("settings") described in the previous section. The resulting, filtered light source color is projected into the user's living room using four Philips LivingColors lamps, creating an effect from here on designated as "surround light". In this way, the atmosphere of the movie clip is brought into the user's living room, potentially increasing the user's immersion in the content.

Two basic questions arise:

1. Does this new atmospheric context improve the users' viewing experience?
2. How do the three different settings influence the viewing experience?

Answers to these questions will help us explore the temporal filtering algorithms to further tune and develop them. For this purpose, we need to answer the following research questions:

- Do the surround light settings match the video content?
- Do the surround light settings help increase the level of immersion?
- Do the three different temporal filtering settings help increase the feeling of presence and engagement in different ways?
- Which of the three temporal filtering setting for the surround light system do users prefer?

We expect that the presence of surround light settings will improve the level of presence and engagement for the users, and as explained in the previous section, we expect the *auto* temporal filtering setting to best reflect the dynamics of the video content. Hypotheses are therefore:

1 The level of immersion while watching video with the surround light turned on is higher than without surround light.

2 The level of immersion while watching video using the *auto* temporal filtering setting for the surround light system is higher than when the other two settings (*none* and *avg*) are used.

Based on the research questions and the hypotheses, the surround light settings were evaluated with 25 participants, using a within-subjects design in which participants watched six video clips in four variations: without surround light and with the three different light settings. Additionally, before the six regular clips, an additional movie sequence from the movie "*Shrek*" was used as a training for the participant. A Presence and Engagement questionnaire [10] was used to measure the level of presence and engagement. Additionally, the participants were asked to rank their preference for the three settings.

Participants

For the user test, 25 voluntary participants from Philips Research with ages ranging from 22 to 33 (mean=26.4, sd=3.3), were recruited (11 males and 14 females). The participants were selected not to suffer from color deficiency in red and green hue. Each participant received a 5-euro voucher as a surprise at the end of the experiment.

Material

We developed a surround light system as described before, which can operate using the three different temporal filter settings described in the previous section. The three light settings constitute experimental conditions. In the control condition, no surround light is used.

The six test video clips used were described in the previous section. A seventh 30-second video clip, extracted from the movie "*Shrek*", was used to explain the procedure and to let the participants become familiar with the questionnaires.

Each video clip is presented to each participant four times. The first viewing uses the control condition (i.e., without surround light), and is followed by three experimental conditions (i.e., the three light settings) in a randomized order. The first of the seven video clips shown to the participants (the clip from '*Shrek*') is used as a test video. The test video provides a training opportunity of the experimental setting, and allows the participants to calibrate their rating scales for the following test video clips. The results from the test clip are not used in further analysis of the measurements. The order of remaining six video clips is randomized. The order in which the three light settings and the six video clips are shown to the participants was pre-edited in order to ensure a balanced distribution over the 25 participants. A script program was used to play the video clips and light settings according to the pre-edited order with a single key press by the experiment leader.

In human computer interaction (HCI), immersion [4,13], presence [8,9,13,14,19], engagement [3,9], and flow [5] are often related to the experience of interacting with virtual environments. Various questionnaires [9,10,12,19] were developed to measure immersion or engagement. Most of these questionnaires were developed for interactive virtual environments, whereas our experimental context is passive television watching. This makes some common factors in the aforementioned questionnaires not applicable for our experiment, for example, the 'Control' factor.

Although there is an ongoing scientific debate on the notion of immersion and presence (technology space or subjective experience) [12,19], our goal is to test the participants' subjective experience. The difference between the two notions lies in whether it is measured by objective parameters (e.g., the amount of the virtual space the user can interact with) or by subjective ratings of his/her own experience.

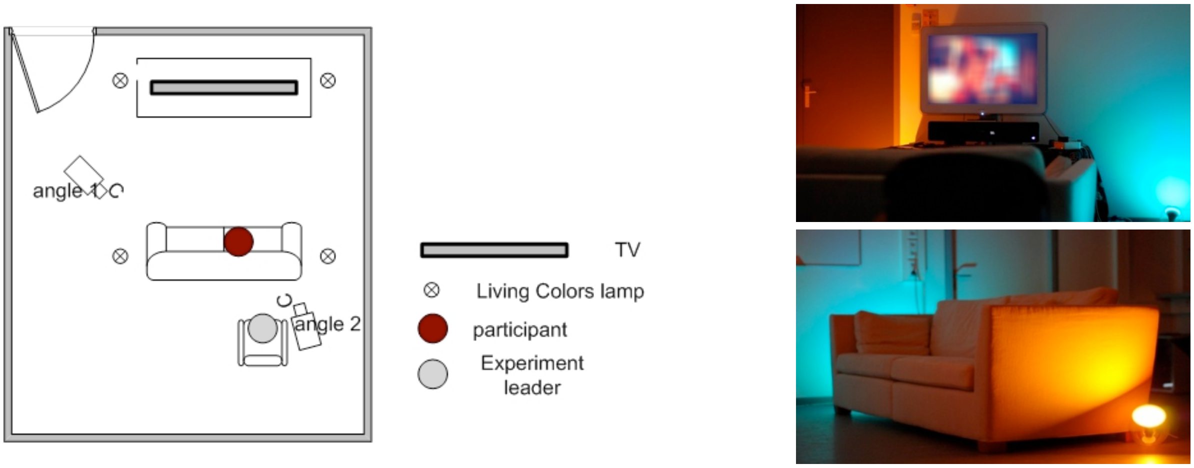

Figure 3 – (left) Map of the lab room used, (right) photo of the setup from angle (top) 2 and (bottom) 1.

For the test, we used a 13-item Presence and Engagement questionnaire[1] [10] which was originally developed for the context of 3D-TV watching, and which measures the subjective experience of the participant. The questionnaire consists of a number of questions which should be answered on a five-point Likert scale, ranging from '*strongly disagree*' to '*strongly agree*'. The question items contribute to two factors: Feeling of Presence (5 items) and Engagement (8 items). However, since the questionnaire was originally developed for 3D-TV, two items (contributing to Feeling of Presence) from the questionnaire are not applicable for our experiment. These two items are '*I had a strong sense that the characters and objects were solid*', and '*I felt I could have reached out and touch things*'. We excluded these from our questionnaires.

Based on the research questions as stated above, we would like to test whether the dynamics of the lights in the living room match the video content. We developed one question item to measure this aspect: '*The surrounding setting matches the video clip*'. This question item was not asked after the control condition, i.e., when no surround light is used.

Procedure

The test started by handing the questionnaire booklet to the participant. The participant was asked to fill in his/her personal information and TV watching experiences. The purpose of this experiment was not explained beforehand in order to avoid biasing participants, thus preventing that they would pay too much attention to the surround light. The experiment leader explained the procedure of the following steps.

The following steps encompassed seven sessions, in which the first session was a training session. Each session consisted of four sub-sessions, where one video was played with one light setting from the four variations. The starting time of each sub-session was manually controlled by the experiment leader with a remote keypad. After each sub-session, the participant had to fill in a questionnaire about the movie–lighting setting combination that he/she had just watched. In addition, he/she was encouraged to write down his/her comments on the same page of the questionnaire. When the participant finished filling in the questionnaire, the experiment leader pressed the keypad to proceed to the next sub-session. At the end of each session, the participant had to rank the light settings based on his/her preference. To make sure the participant could follow the experiment, the experiment leader (only during the first session) asked whether the questions and the procedure were clear. All participants in the experiment understood the questions and the procedure after the first session. The same process was repeated for the remaining sub-sessions.

After the seven sessions, the experiment leader had a short interview with the participant. The conversation was noted down by the experiment leader.

Data analysis

In order to avoid inconsistencies across different raters [7], a within-subject design with two factors was chosen. The two factors are: type of video and type of setting (6×4), where *Walk the Line* is used as the baseline video (as it constitutes the calmest sequence) and the *auto* setting is used as the baseline setting. The questionnaire data on the test video was not used.

On each questionnaire item, we collected 600 (6 video clips × 4 settings) data points from 25 participants. A two-way repeated measures ANOVA was used to analyze data. Main effects were analyzed by multivariate tests.

The interview was conducted in a semi-structured way. Participants were given printed posters of the movies and TV series they had watched on an A4 paper. This helped them remember the video clips they had watched and easily start the conversation. The experiment leader started the conversation by talking about the movies. This helped observe their emotional reaction to the movies and later on the light settings which were not captured in the previous

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[1] This questionnaire has not yet been validated.

sessions. During the conversation, the experiment leader asked their general impression about the settings, whether any settings made them uncomfortable or distracting, and if they had any wishes to improve the settings. The experiment leader tried to ask these questions in a spontaneous way, thus not following a particular order. For example, if a participant started talking about annoying settings, the experiment leader followed by asking 'so did any other settings made you annoyed or made you feel uncomfortable?'

Presence and Engagement questionnaire data

The Presence and Engagement questionnaire we used in this experiment was comprised of eleven items, contributing to two factors: Feeling of Presence and Engagement.

On the Feeling of Presence score (range from 3 to 15), which was aggregated from three question items, all main effects: type of video (F(6,19)=6.35 p=0.001), type of setting (F(3,22)=78.636 p<0.001), and interaction type of video × type of setting (F(18,7)=5.174, p<0.01) were significant at p<0.05. The significant interaction effect indicates that type of setting had different effects on the Feeling of Presence score depending on which type of video was used. Figure 4 shows the mean scores for all the light settings on each video.

Paired comparisons[2] were performed comparing the three settings to their baseline setting (i.e., no light setting). It revealed that the three settings: *none* setting, *avg* setting and *auto* setting resulted significantly (p<0.001) higher ratings on the Feeling of Presence score than the baseline setting. Further, paired comparisons comparing the *none* and *avg* setting to the *auto* setting revealed that the *auto* setting resulted significantly (p<0.005) higher rating than the *none* and *avg* setting.

On the Engagement score (range from 8 to 40), which was aggregated from eight question items, significant main effects were found on: type of video (F(6,19)=7.627, p<0.001) and type of setting (F(3,22)=16.045, p<0.001). The interaction main effect (F(18,7)=1.934, p=0.147) was found not significant.

Paired comparisons comparing the three settings to their baseline settings showed that the *avg* setting and the *auto* setting resulted significantly (p<0.01) higher rating than the baseline setting, whilst the *none* setting did not result significantly higher rating (p=0.601). This can be observed from Figure 5 as well, where the mean score of *none* setting on two video clips (i.e., Walk the Line and Friends) were lower than the baseline setting.

Matching question data

An extra question 'The surrounding setting matches the video clip.' was used with the *none*, *avg* and *auto* setting.

Factor	**F**	**Sig**
type of video	F(6,19) = 6.35	0.001
type of setting	F(3,22) = 78.636	<0.001
type of video × type of setting	F(18,7) = 5.174	0.006

Table 2 - Result of main effect analyses on Feeling of Presence score.

Factor	**F**	**Sig**
type of video	F(6,19)= 7.627	<0.001
type of setting	F(3,22)= 16.045	<0.001
type of video × type of setting	F(18,7)=1.934	0.147

Table 3 - Result of main effect analyses on Engagement score

Factor	**F**	**Sig**
type of video	F(6,19)= 8.475	<0.001
type of setting	F(3,22)= 23.873	<0.001
type of video × type of setting	F(18,7)=5.027	0.003

Table 4 - Result of main effect analyses on the matching score.

On the matching score (range from 1 to 5), all main effects: type of video (F(6,19)=8.475, p<0.001), type of setting (F(3,22)=23.873, p<0.001) and interaction (F(18,7)=5.027, p=0.003), were significant at p<0.05.

Paired comparisons revealed that comparing to the *none* setting and the *avg* setting, the *auto* setting had significantly (p<0.001) higher score. Figure 6 shows the mean scores of matching, from which one can observe that the *avg* setting had very similar matching score comparing to the *auto* setting on the first three videos with lower amount of dynamics (i.e., *Walk the Line*, *Hellboy* and *Friends*), whilst the effect of the *avg* settings became much less comparing to the *auto* setting on the next three videos with higher amount of dynamics (i.e., *Hulk*, *Wall-E* and *Platoon*).

Preference data

As introduced in the previous section, if difference among the experimental light settings was found, participants were asked to rank the three settings[3] *none* setting, *avg* setting and *auto* setting, to their preference on a ranked order scale where 1 is most preferred and 3 is least preferred. After all light settings corresponding to the video were presented, 150 groups (6 video clips × 25 participants) of orders were collected from the 25 participants, of which 141 groups

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[2] Adjustment for multiple comparisons: Bonferroni was used.

[3] The actual setting labels were replaced with the labels 'setting 1', 'setting 2' and 'setting 3', which were randomized over the video clips.

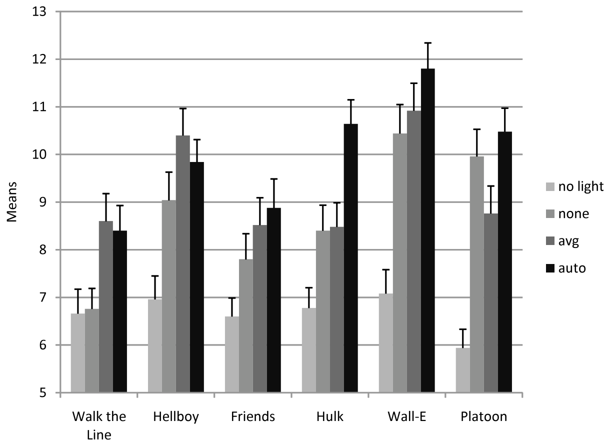


Figure 4 - Mean scores of Feeling of Presence for all the settings on each video clip.

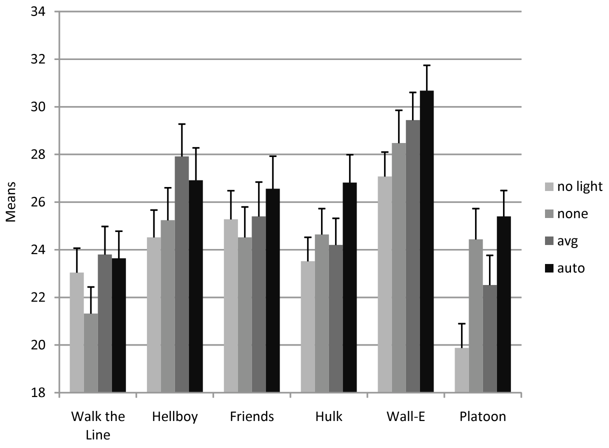


Figure 5 - Mean scores of Engagement for all the settings on each video clip

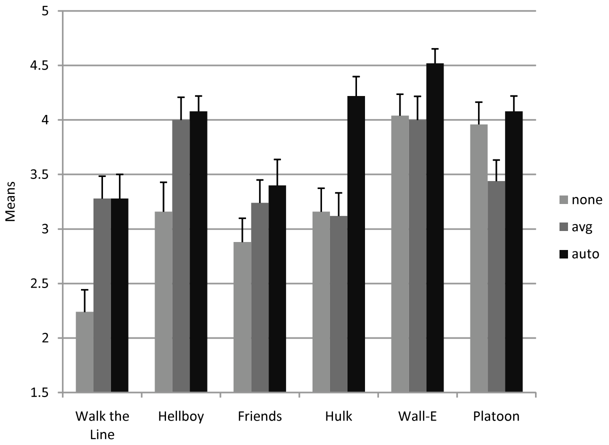


Figure 6 - Mean scores of matching for the three experimental settings on each video clip.

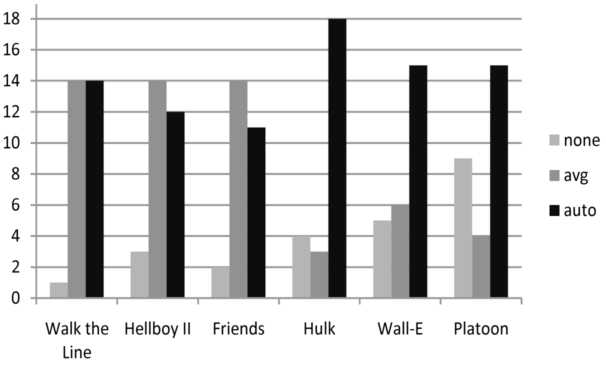
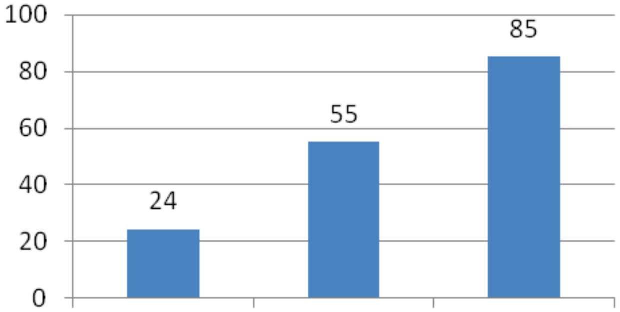


Figure 8 - Number of occurrence in the highest preference for the three experimental settings on each video.

were found different and were indicated with preference order. In general, the *auto* setting got the highest number of highest preference votes from the participants (see Figure 7).



To break down this aggregated result, we categorized it for each video (Figure 8). Figure 8 shows a trend where the *auto* setting is more preferred (when compared with the other two settings) when higher dynamics are present in video clips, whilst preference on the *avg* setting is close to the *auto* setting when lower dynamics are present. This trend is consistent with the results from the matching question item (see Figure 6).

Interview

Most participants liked the idea of surround light settings. They mentioned particularly positive impressions about the settings with cartoon movies, such as *Wall-E*. One participant expressed his feeling as:

Wall-E impressed me the best, because the settings were bright and gave me the feeling of presence in space.

Participants found that the *none* setting is distracting or annoying in most cases, but they accepted it more when it is used with a fighting or action scene, such as *Platoon*. This is confirmed with the ordering of preference shown in Figure 8. A representative comment made by one participant:

Whenever the lights flicker too much, it's very distracting, especially for static moments! However, on Platoon, the flicker at the same time as the bullet was a nice touch!

On calm scenes such as *Walk the Line*, the participants did not express much difference in preference between the *avg* and the *auto* settings. Recalling Table 1 from an earlier section, this is not surprising since the behavior of these two settings is very similar for this particular video clip.

Discussion

The results of the test suggest that the surround light settings helped increasing the feeling of presence. The *avg* and *auto* settings increased the level of engagement, but the effect from the *none* setting was not significant. This may be explained by the comments made by the participants in the final interview, that is, the *none* setting is distracting in most cases. Moreover, the *auto* setting resulted in higher feeling of presence and engagement comparing to the *none* and the *avg* setting. Similarly, tests showed that the *auto* setting also resulted in a better matching effect than the *none* and the *avg* settings.

From qualitative analysis on the preference ordering, the *auto* setting is in general the most preferred one comparing to the *none* and the *avg* setting. However, the *avg* setting seemed to be an equally preferred setting when the dynamics present in the video clips are low.

CONCLUSIONS

We have described a novel method for temporal filtering of light source colors that are extracted from video content. The resulting dynamics of the detected light source fits much better with the content on the screen than previous methods: dynamic, action scenes or scenes with special effects result in dynamic lighting, whereas slow and static scenes result in calm lighting.

We have tested the new algorithm in a user test in which the lighting conditions from video content were projected into the living room. The results of the test show that the users liked the effect of the proposed new algorithm better than the control condition (no lights) and also better than two other tested algorithms for temporal dynamics. In addition, the user test suggests that the novel method provides increased immersion in the video content when compared to the two other algorithms or to the situation without surround light.

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Descriptions, Measurements and Visualizations of Light Distributions in 3D Spaces

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ABSTRACT

The aim of our studies is to understand the physical structure and human perception of natural light fields. The light field depends on the primary illumination, the scattering properties of the environment and the scene geometry. We present our newly developed methods to describe, measure and visualize visually complete descriptions of the light field, the 5-dimensional "plenoptic function". The structures of natural light fields were found to be rather smooth and built up of just a few possible topologies. We show that our visualizations by means of light tubes represent the well-known "flow of light" lighting design concept in a surprisingly intuitive way.

Keywords

Light field, appearance, plenoptic function, visualization, flow of light, scale of light, light-zones.

INTRODUCTION

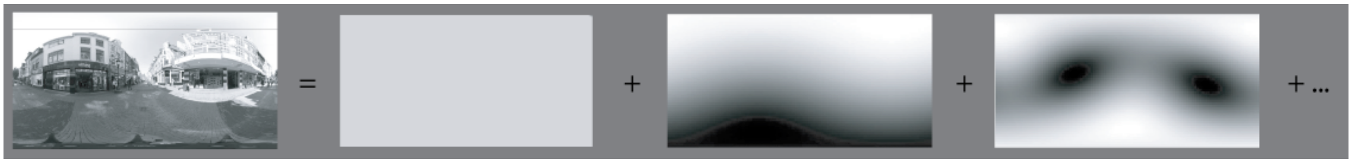
Lighting influences our perceptions of our surroundings, including the "visual light field" [6]. We investigate which aspects of the appearance of scenes underlie these perceptions and how the appearance changes with lighting variations. In this paper we focus on the physical description, measurement and visualization of the light field in three-dimensional (3D) spaces in order to scientifically assess the spatial and form-giving characteristics of light, and we analyze the structure of natural light fields.

On a most basic level one might draw relations between lighting and how well people can see details around them. Such maximization of luminance contrast of visual detail forms the basis of many lighting recommendations and standards. However, lighting may vary in many more ways and influences the appearance of scenes and our perceptions in a very complicated manner [2]. The directional properties of the illumination strongly affect the appearance of an object. For instance, in fully diffuse illumination even a specular object looks rather matte. Diffuse illumination can have directional properties – illumination from an overcast sky is directed vertically downwards. However, the properties of diffuse and highly directional (collimated) illumination are very different. In collimated illumination the shading is dominated by cast and body shadows, whereas in diffuse illumination the shading gradients are much more gradual.

Examples of light properties which artists (light designers, architects, photographers, painters, etcetera) know to be important aspects of scene appearance are the diffuseness, density variations, flow of light, and 3D modeling properties of the light. Such light properties depend in a complicated way on the primary illumination, the scattering properties of the environment and the scene geometry and typically cannot be represented by just a simple number. Moreover, they vary from point to point in 3D scenes. Therefore we first need a visually complete description of the luminous environment, or "the plenoptic function" [1]. If we constrain ourselves (for simplicity) to static scenes and if we ignore color, we can describe the plenoptic function, or the (white) light distribution in 3D space, by the 5D "light field" [4] (the radiance as a function of the 3D position and 2D direction). The light fields of natural scenes are often highly complicated functions. The angular variations can be almost arbitrary, ranging from smooth (such as under an overcast sky) to very spiky (such as on a sunny day on the beach or under forestry). In contradistinction, the surface irradiance is typically fairly smooth, because surface elements of a convex object are illuminated from half spaces.

In this paper we will address our newly developed methods to describe, measure and visualize light fields in 3D spaces. In the discussion we will draw a relation between our visualizations and well-known concepts from lighting design and architecture, namely "the flow of light" [2], "the scale of light"[3], and "light-zones" [8].

Figure 1 A panoramic image (a local light field measurement) and its first three spherical harmonic components (see text for explanation).



FORMAL DESCRIPTIONS OF THE LIGHT FIELD

The light field is a complicated 5D function of position and direction. At any point in space the light field is a function of direction, a spherical function (a 360° × 180° panoramic view), which may well be described by a superposition of components of different angular frequencies. At first sight it might seem important to include all those frequencies in light field studies. However, most objects around us are quite matte and low-pass or "diffuse" the illumination. Thus, only the low frequencies of the light field influence their appearance. This suggests that a decomposition of the light field in components of different frequencies might be useful. For a spherical function such as the light field this comes down to spherical harmonics, usually known as a multipole development in physical context.

Mathematically, it was shown that a second order spherical harmonics description, which is a superposition of just three qualitatively different, low angular frequency components, is sufficient to describe the appearance of perfectly matte convex objects [15]. These three components are physically equivalent to:

- the flux density (a number representing the monopole contribution or average radiance from all directions in the point under consideration),
- the light vector (a number and direction representing the dipole contribution or magnitude and direction of the net maximum transport of light in the point), and
- the squash tensor [12] (two numbers and a direction representing the quadrupole contribution or magnitudes and orientation of a set of orthogonal light and dark two-fold lobes).

The flux density describes a constant illumination from all directions, which is usually known as "ambient illumination" in computer graphics, or Ganzfeld illumination in psychology. Light fields in which this monopole component dominates are rare in nature. An example is an overcast sky over a snow cover ("polar white-out"). The combination of a monopole and a dipole term yields what is known as the "point source at infinity with ambient term" in computer graphics. A natural light field that approximates a dipole dominated field is the overcast sky or hemipsherically diffuse source. Quadrupole dominated light fields occur in the case of ring sources or two point sources at opposite sides of the region of interest – therefore we called it the "squash tensor".

In figure 1 we show a local light field measurement (a panoramic image) and its first three spherical harmonic components; the first component represents the flux density, (it is clearly a constant); the second component represents the light vector (here it is clearly oriented vertically); the third component represents the squash tensor (the two light and two dark lobes are clearly visible).

In figure 2 we show spherical maps of the panoramic image, of the sum of the first three components (mathematically: the second order spherical harmonic approximation), and of matte spheres rendered in those high-resolution and approximated low-pass local light fields. The spheres indeed look the same. Thus, only 9 numbers are sufficient to describe the appearance of a matte convex object.

Figure 2 A panoramic image (a local light field measurement; upper left image) mapped on a sphere, which may be thought of as photographed on a specular sphere. The upper right image shows the superposition of the first three spherical harmonic components, which were shown separately in figure 1. The second row shows renderings of matte spheres in the high-resolution local light field and its low-pass approximation. It is clear that the superposition of flux density, light vector and squash tensor is sufficient to describe the appearance of such a matte convex object.

MEASUREMENTS OF THE LIGHT FIELD

The enormous luminance range that is common in natural scenes forms a second challenge in light field studies. This so-called very high dynamic range (HDR) cannot be covered by photographical methods, even if the dynamic range is extended by techniques such as photographical composition from multiple exposures. This range can however be covered by HDR sensors consisting of a photo-diode and a logarithmic amplifier. The combination of the low-pass approach and HDR sensor finally resulted in the design for our light field measurement system, the "Plenopter", see figure 3. This custom-made apparatus allows for local light field measurements in the order of a second. The Plenopter contains 12 sensors in a regular configuration. A single, local measurement results in 12 numbers, which allow for the estimation of the local low order approximation (9 numbers) which was described in the previous section.

Then, from a set of such local measurements on a suitable matrix of points in a 3D space we can reconstruct the global structure of the light field in that 3D space [10] (by interpolation). This reconstruction thus gives the flux density, light vector and squash tensor at each point within the 3D space. These data can be used to make computer graphics renderings of matte convex objects, e.g. spheres, at arbitrary points in this space (see figure 4 bottom row, for a maybe somewhat more interesting shape). It is known from artistic practice, e.g. in lighting design and architecture [2, 9] that such renderings give a good impression of the visual quality of light in a scene and therefore this method may be very useful in applications.

Figure 3 The plenopter: 12 high dynamic range sensors in a regular dodecahedron configuration. Local measurements result in 12 numbers from which we can estimate the second order spherical harmonic approximation. Sets of local measurements over an array of positions in 3D space allow for reconstructions of the light field in that space by interpolation.

We used our methods to measure 24 different light fields in an empty office room (daylight was screened off) in the Light Lab at Philips Research. We made reconstructions of each of these light fields, which consist of 9 numbers, or the three components depicted in figure 1, at each point of the finite 3D space that we covered with our measurements. Since these basic data of which each of the 24 reconstructed light fields exist are rather abstract and bulky we need intuitive visualizations in order to get some insight into the global structure of the light fields.

VISUALIZATIONS OF LIGHT FIELDS

We visualized the light fields through it's "light tubes" [4], see figure 4, which represent the *net* flow of light (not the rays of light - light tubes can be curved and light rays cannot). The tubes directions are locally tangential to the light vector (the direction of maximum net energy transfer) and their widths are locally inversely related to the magnitude of those vectors (the larger the light transport, the smaller the tube). The tubes usually start at light sources, where they are quite narrow, and end on light absorbing surfaces, where they tend to be quite wide.

In figure 4 we show three light fields with quite typical structures. The upper image shows a case for primary illumination existing of three quite diffuse lamps on the ceiling in a row close to one of the long walls of the empty office room. The tubes diverge out from the sources towards the floor and opposite wall. In the second case the tubes diverge from a diffuse lamp in the middle of the ceiling towards the walls and floor. In the third case the tubes diverge from four quite narrow beams towards the walls and the floor, where they curve upwards due to interreflections from the floor. We rendered white, matte bunnies at three points along one of these curved tubes. The right bunny was rendered closest to the primary illumination in the right front corner of the room. It is clearly visible from its appearance that the light comes from above and slightly towards the right. The shading and shadowing contrasts over the bunny are quite strong, though a small effect of secondary illumination is visible at the bunnies' breast. In the middle case the bunny is clearly illuminated from both primary and secondary illumination. The shading and shadowing contrasts are quite weak. The left bunny is primarily illuminated from below due to interreflections.

In natural scenes the light fields are due to complicated combined effects of primary illumination, scattering and screening by the objects in the scene, and scene geometry. However, the global structures of natural light fields show perhaps surprisingly smooth behavior and can be modeled in a very simple way [10]. Moreover, for 2D light field descriptions we showed which generic topological configurations are possible. These configurations could be described by a small range of singular points [12].

CONCLUSION AND DISCUSSION

Our methods allow low order, HDR measurements of a light field in a finite 3D space. The low order representations exist of the flux density, light vector and squash tensor. We visualized our measurements by means of reconstructions of light tubes, which represent the net transport of flux in the space. These visualizations give intuitive pictures of the light fields, allowing insightful inferences about the light quality in that space. For instance, it could be a scientific tool in the quantitative assessment of "light-zones" [8], or the areas where light from roughly different directions "meet" [9].

In lighting design the concept of the "flow of light" [2] describes the potential of lighting to produce distinct shading patterns. The associated metrics of the flow of light are the vector/scalar ratio of the illuminance, the illuminance vector direction and the flow of light ratio.

Note that our methods deal with the radiance, not the illuminance. Nonetheless, the illuminance vector/scalar ratio and illuminance vector direction correspond to the light vector magnitude and direction up to some normalization factor. Thus, our tubes visualizations directly represent the flow of light.

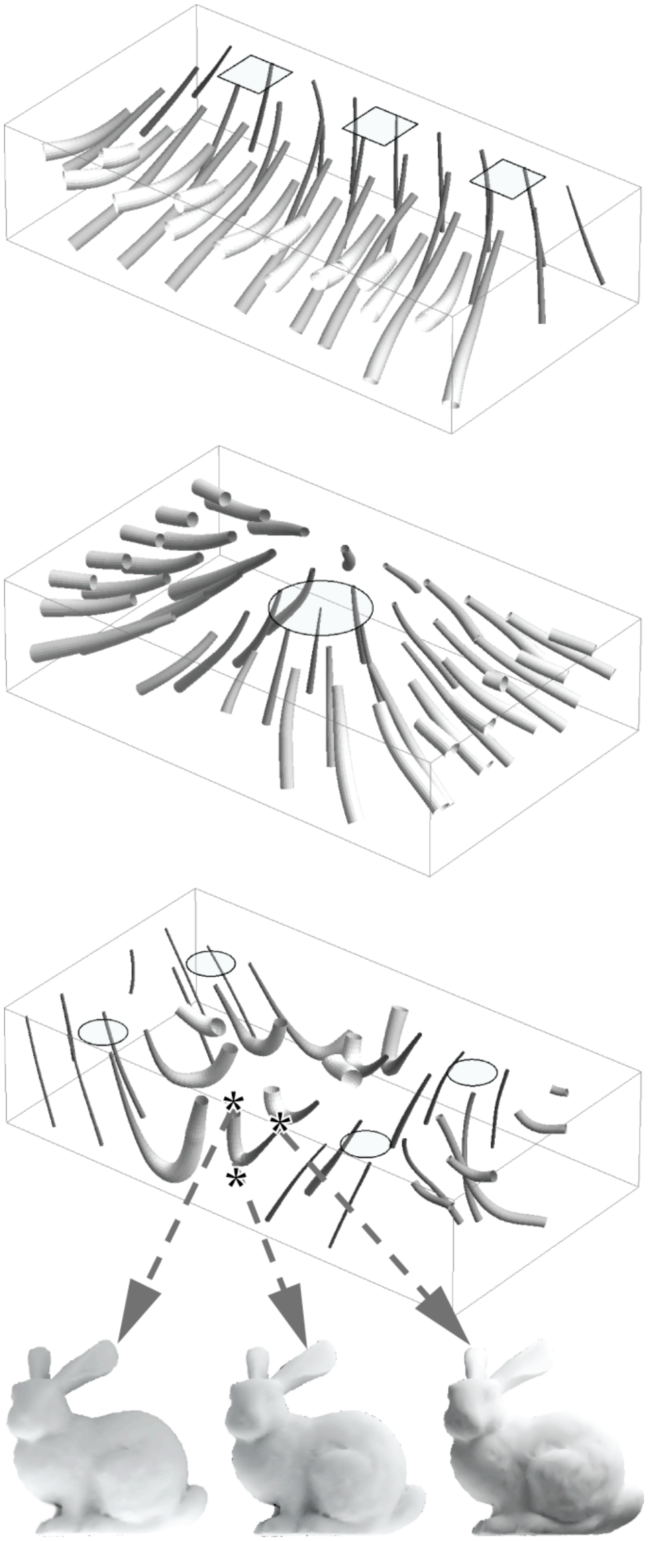


Figure 4 Light fields visualizations by means of light tubes. The local tubes' directions are tangential to the light vectors and the local widths are inversely related to the vectors' magnitudes. The box represents the room and the squares and circles on the ceiling represent the primary light sources, which were quite diffuse in the upper two cases and quite narrow beams in the bottom case.

Cuttle [2] proposed to examine the flow of light using a small matte white sphere to reveal the shading pattern. Madsen and Donn [9] did experiments with a "light-flow-meter" consisting of a grid of matte white spheres that was placed vertically in scenes. They used this method for the visual assessment of the spatial and form-giving character of (day-)light, that is, simultaneous judgments of the flow of light and Frandsen's "scale of light" [3]. The "scale of light" is a measure of the diffuseness of the illumination, ranging from fully collimated to hemispherically diffuse. In psychophysical studies on light field and material perception we found that for smooth matte spheres human observers confuse illumination diffuseness with illumination direction [14] and that they confuse illumination with material properties [13], due to basic image ambiguities. In figure 5 we illustrate the diffuseness-direction ambiguity. The figure shows matte white spheres rendered under illumination which was more or less diffuse (from left to right) coming from the right to almost frontal directions (from top to bottom). Note the similarities of images along the above left to below right diagonals. This diffuseness-direction ambiguity causes interactions of visual judgments of the "scale of light" and the "flow of light". This problem was implicitly noted by Madsen and Donn [9]. The "scale of light" estimates might improve if they would be done for views of matte spheres perpendicular to their average illumination directions or light vectors, since Frandsen's illustrations [3] were made under this condition.

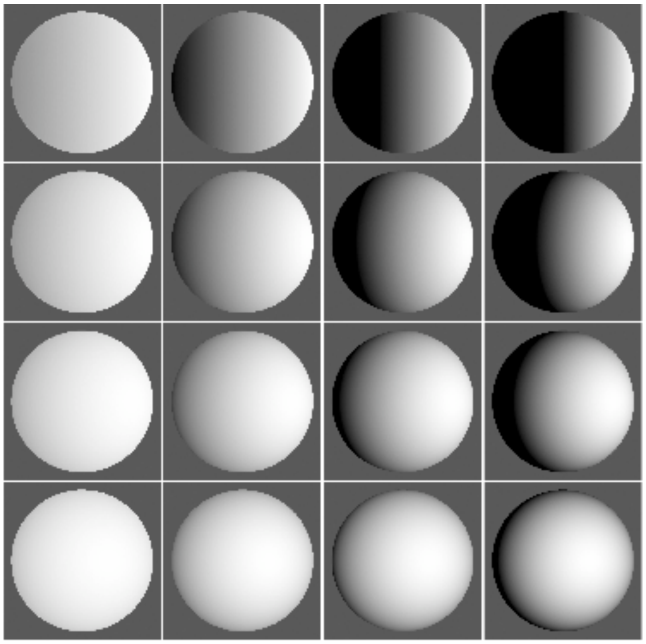


Figure 5 Rendered Lambertian spheres for which the illumination diffuseness and direction were varied systemati- cally: from left to right the diffuseness varies from halfway between fully diffuse and hemispherically diffuse to fully collimated, and from the top to the bottom the direction varies from 90 to 22.5 degrees in steps of 22.5 degrees. Notice that variations along the diagonals from above left to below right result in illuminance patterns which are more similar than along other directions (confusing judgments of the diffuseness and direction).

In figure 6 we demonstrate effects of type of illumination on the appearance of a rough white sphere. The golf-ball shows harsh body shadows and strong texture gradients for collimated illumination (left photograph), medium strong texture gradient for hemispherically diffuse illumination (middle image) and hardly any contrast for totally diffuse, Ganzfeld illumination (right image). The roughness texture provides cues about the illumination, which are additional to the shading and which human observers use to resolve confounds in material and illumination judgments [13]. Therefore, we propose to examine the flow of light with a rough sphere instead of a smooth one. The development of simple intuitive probes for the examination of lighting qualities stays an interesting challenge for future research.

Figure 6 Photographs of a golf-ball in different light fields. The effects on the appearance are huge. The images show, from left to right, harsh effects in collimated illumination, medium in hemispherically diffuse illumination, and very weak in totally diffuse (Ganzfeld) illumination.

Currently we are investigating relations between light field descriptions and visually relevant, known and new measures of lighting.

ACKNOWLEDGMENTS

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Flexible Light Sources for Health and Well-being

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ABSTRACT

The availability of flexible and conformable light sources will enable applications that demand minimal distance between light source and body, such as therapeutic use of light and monitoring of personal health by wearable optical sensors. Organic light emitting diodes are large area, low voltage, thin light sources which can be processed on flexible substrates like foil in Roll-to-Roll process technology and are therefore potentially low cost. All of these characteristics render OLED highly suitable for applications on the body. The Holst Centre is developing Systems in Foil, both OLEDs and sensors. Lighting applications in health and well-being will benefit from both functionalities.

Keywords

OLED, foil, sensors, light source

INTRODUCTION

In recent years it has become clear that there are many positive effects of light on health and well-being of people. Blue light for example can be used for phototherapy of dermatological diseases like psoriasis and neonatal jaundice [1] or even skin rejuvenation [2, 3]. Acne [4] and seasonal affective disorder (SAD) [5] can be successfully treated with light. Pain can be relieved with light treatment [6].

For extra-clinical treatment and home-use wearable or at least conformable light sources are optimal. Not only the comfort of patients will be increased, also a serious cost reduction will be possible with these conformable light sources as the burden on clinical personnel and space will become less for cases which do not need continuous supervision.

With these wearable light sources, phototreatment can not only be used in healthcare, but mainly in well-being applications such as pain relief, anti-wrinkle measures and perfusion enhancement.

Integration of inorganic LEDs in textile is developed at the moment. Organic LEDs are an interesting alternative light source, because of their intrinsic large area and the possibility to be produced in a cost effective Roll-to-Roll processing. Furthermore they operate at a low voltage and will be energy efficient. When in contact to the skin, permeability to ensure regulated humidity at the skin-device interface and sterile contact areas are prerequisites and to be taken into account when developing these systems for health and well-being.

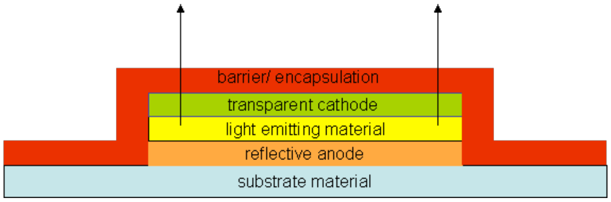
Light can also be of use for well-being and health in optical sensors. The condition of the body in blood perfusion, saturation, skin tone, etc. can be determined when light sources are combined with photodetectors. Both functionalities can be achieved in foil based structures with organic active materials.

These conformable light sources with integrated sensors are yet to be developed for commercialisation. The research at Holst Centre is focusing on enabling technology for these applications. In an open innovation environment, together with industrial and academic partners We develop technology platforms for autonomous wireless transducer solutions and systems-in-foil. The Systems-in-Foil Program Line targets to develop new device architectures, technologies and production processes for foil based electronic devices that will revolutionize the electronics industry. It will enable new ultra-light, ultra-thin, flexible, easy-to-wear electronic products such as lighting and signage devices, reusable and disposable sensor devices, foldable solar and battery panels and displays. The research addresses batch-wise and web-based processing (Roll-to-Roll), encompassing processes like printing, vacuum deposition, lithography, lamination and interconnection, which will enable the manufacturing of these devices in large sizes and quantities at low costs.

We will hereafter highlight the components that can be realised in foil and which are of most interest in light for health and well-being: organic light emitting diodes, organic photo diode, and the assembled sensors.

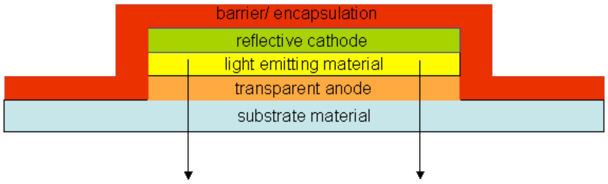
Organic Light-emitting diodes

An organic light-emitting diode (OLED) consists of an active material, sandwiched between two electrodes. At least one of the electrodes must be transparent. By applying a voltage, charge carriers are injected into the light-emitting material. Upon recombination excitons are formed and by subsequent radiative decay photons are emitted from the device. With a transparent cathode a top emissive OLED is formed, whereas a reflective cathode with transparent anode results in a bottom emissive OLED is the result (see figure 1). With two transparent electrodes a transparent OLED can be constructed. By this concept light sources can be realised which are transparent in the off state, i.e. they can be integrated imperceptibly. Transparent windows generating light in the evening is one example of an envisioned application.



a) top emissive OLED

b)



b) bottom emissive OLED

Figure 1 OLED cross-section

In the foil based OLED program of Holst Centre, challenges like design-layout are studied. Flexibility, encapsulation and related lifetime are being optimised.

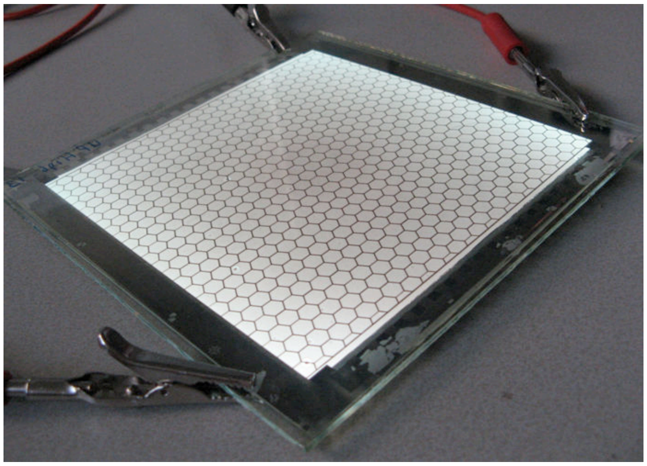


Figure 2 Bottom emissive ITO-less OLED (144 cm²) with inkjet printed metal grid

Recent advances in the Holst Centre include improved light homogeneity and increased reliability. In case a transparent anode is applied, a transparent conductive oxide (TCO) like indium tin oxide (ITO) can be used. ITO is however relatively expensive and shows only limited compatibility with roll to roll processes. Such high speed, low cost processing is considered to be required to meet the low cost per area for these light sources. Moreover in order to fully exploit the large area, the TCO must be conductive enough to ensure a homogeneous current distribution over the complete area. At Holst Centre a combination of printed Ag shunt lines and PEDOT:PSS, (poly (3,4-ethylene dioxy thiophene) : poly (styrene sulphonic acid), was recently presented to be a viable alternative[7].

Because of the reactive materials used in OLED devices encapsulation is key to ensure long lifetimes and reliable systems. If water is allowed to come into contact with the cathode, it is oxidised and the electron injection blocked which becomes visible as dark areas in the OLED. This can be prevented by thin film barrier technology. Holst Centre has developed a barrier with a water vapour transmission rate through the barrier well below 10^{-5} g/m^{2}day under ambient conditions without visible defects in a Ca-mirror test for 67 days. These barriers are capable of bending to radii of 20 mm which allows roll to roll processing [8].

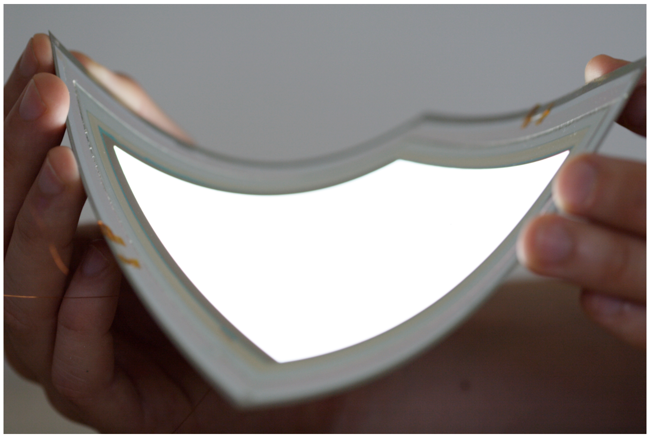


Figure 3 Top emissive OLED (100 cm^2) on metal foil thin film encapsulated

Nowadays energy consumption is a very important topic and therefore the increase of efficiency of OLEDs is given a lot of attention. Reported record value for white light by Konica Minolta is 64 lm/W at 1000 cd/m^2 and a lifetime (50 % luminance decrease) of 10.000 hrs. Kido et al. also reported similar high power efficiency for white OLEDs: 63 lm/W and 64 cd/A at a luminance of 100 cd/m^2 at the MRS meeting in 2006. For blue light emitting devices, record value is 50 lm/W [10], for green OLEDs 130 lm/W [9].

Small molecule OLEDs show currently higher efficiencies and lifetimes than polymer OLEDs. However there is also progress in the latter field: a luminous efficacy of 25 lm/W, 39 cd/A was reported for a white OLED based on a host polymer with phosphorescent dye [11]. A fluorescent, blended polymer system showed 16 lm/W and an external quantum efficiency of 6 % [12]. For roll to roll process technology solution processing has substantial advantages and solution processing of small molecules is therefore gaining interest.

Current challenges for OLEDs on foil lie in increasing efficacy, flexibility, lifetime and reliability.

For on the body applications a new generation of OLEDs are needed to adjust to the shape of the underlying person.

The next generation of conformable OLEDs demand to be truly stretchable and not only bendable. This will cost considerable efforts. Up till now several stretchable electronic circuits have been published including conductive wiring into a stretchable matrix of PDMS or thermoplastic polyurethane [13-15]. The method to render the light generating area stretchable is still to be explored.

Sensors in Foil

The system in foil approach as taken by the Holst Centre will allow to add more functionalities like sensors to the light generating foil. With sensors, feed-back of the effectiveness of the phototherapy can be derived and active control of the phototherapy will become possible. Sensor based functionalities might be focusing on the perfusion of tissue, saturation of the tissue or biological processes associated with healing of f.e. burn wounds. Abnormalities in the healing process, like infection, should at best be detected at a very early stage allowing for the proper action to be taken to minimize negative effects and promote the healing process. These biological processes can be detected by several physical parameters: colour of the skin (e.g. red for infection), a temperature or chemical substances in the wound fluids as indicators. These parameters can be monitored by dedicated sensors of which several examples will be discussed.

The in plane optical sensor (IPOS) platform, developed at the Holst Centre as a platform for many application areas (Figure 4). It can serve as a chemical sensor but can also be used for direct optical measurements of physiological parameters on the skin.

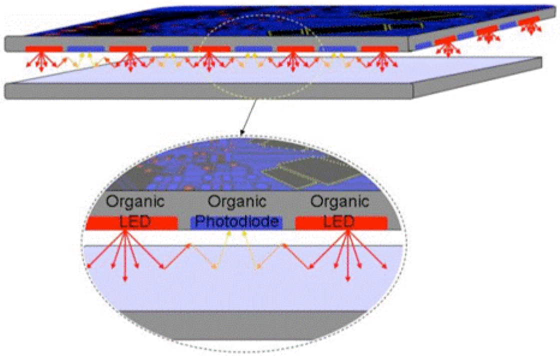


Figure 4 Principle of In plane Optical Sensor (IPOS)

An artist impression of such an application, a smart bandage, is given in Figure 5. The fact that printing can be used as a processing technology allows for the construction of arrays of optical elements, which may be advantageous for large wound areas or a combination of functions.

Figure 5 Artist impression of a smart bandage, integrating organic electronic devices with a wound dressing.

A foil based sensor capable of measuring the perfusion of the microvascular tissue in the wound area by means of photoplethysmography has already been shown [16] (PPG). Traditionally, a PPG is recorded with a pulse-oximeter giving additional information on the blood oxygen saturation (SpO_2). This is achieved by measuring the change in absorption due to the pulse (blood volume) at two wavelengths, typically in the red and near infrared from which the ratio between haemoglobin and oxyhaemoglobin is derived (Figure 6). For perfusion only one wavelength is sufficient, thereby simplifying design and manufacturing of the sensor device.

Apart from being a platform for use in many application areas, the IPOS may also be seen as a platform for the development and testing of manufacturing technologies. These include printing technologies for the active materials, barrier development for encapsulation of the devices, lamination and interconnection technologies for the final device assembly, printing of conductive structures, and lithography on foil.

For our sensor application we aim at an array of organic photo detectors (OPD) and a compatible array of organic light emitting diodes (OLED). The OPDs are based on a blend of poly(3-hexylthiophene) (P3HT, Merck Chemicals Ltd) and [6,6]-phenyl C61butyric acid methyl ester (PCBM, Solenne BV). This blend is used for photovoltaic research but has also been well studied for use in photodetectors [17, 18]. This blend has an optical band gap of 650 nm which is able to detect part of the red light.

The light emitting polymers (LEP) used for this study are a red emitting [19] and yellow emitting [20] material, obtained from Merck OLED Materials GmbH. The emission of the yellow material (λ_{max} 575 nm) has a strong emission shoulder in the red spectral region and has a strong overlap with the diode spectrum.

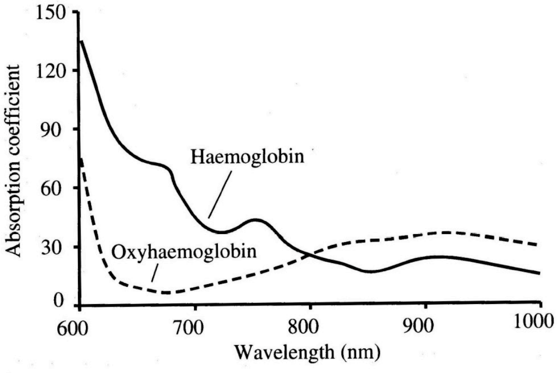


Figure 6 Absorption of haemoglobin and oxy-haemoglobin in the part of the spectrum that is useful for pulse-oximetry

In order to increase the flexibility with regard to the fabrication and design of these devices, we decided to fabricate the detectors and LEDs on separate foils. For example, this allows comparison of various printing and coating technologies and substrates, poly(ethylenenaphthalene) (PEN) and glass. A further implication of this approach is that one is essentially free to choose the order of functional foils in the final device.

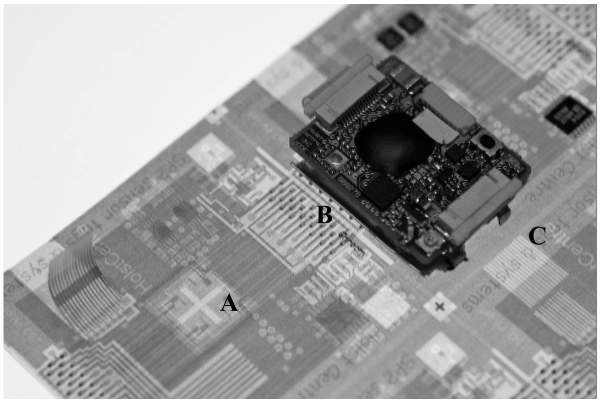


Figure 7 Mock up version of the sensor node showing the optical array (A), interconnection (B) and wireless node (C).

For the device discussed in this study we opted for a three foil assembly containing an OLED foil with an OPD foil laminated on it. The device is finished with a flexible circuit board containing noise filters (band pass 0.5 – 17 Hz), logarithmic amplifier and DC/DC converter for the power supply of the OLEDs. Data collection and OLED driving is controlled with a microprocessor embedded on a multifunctional wireless node [21]. The interconnection between the foils is achieved using a propriety lamination and interconnection technology. Figure 7 shows a mock up version used for testing the interconnection technology and of the attached node as well as a picture of the OLED and OPD foils.

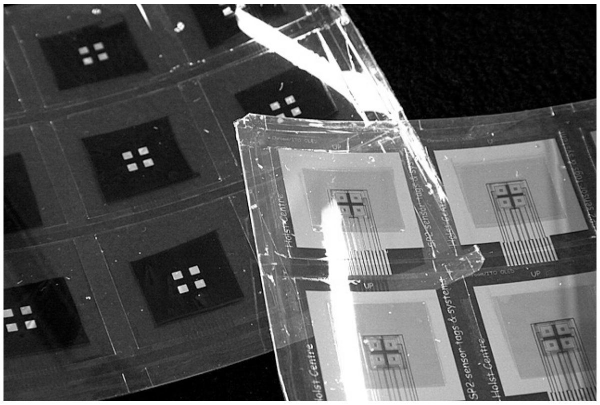


Figure 8 OLED (foreground) and OPD (background) foils.

The functional foils were processed in a batch wise manner. A typical work flow for both the OLED and OPD foils involves: lamination of a substrate to a carrier; deposition of the barrier; deposition and patterning of the anode and shunt lines; deposition of PEDOT:PSS and the active layer by means of spin coating or inkjet printing; evaporation of the cathode; and, finally thin film encapsulation [85]. Both foils can be made either bottom or top emissive (receptive) giving a large design freedom. Although processing on glass is a well know procedure, our devices were designed to be double sided. In such a device light leakage through the substrate can be avoided by using a top emissive OLED on one side of the substrate en a bottom receptive OPD on the other. This light will be emitted close to the skin and only reflected and scattered light will pass through a single substrate. Classical encapsulation with a metal lid is therefore not useful and a transparent thin film encapsulation was used. A further advantage of using a double sided device is that spin-coating can be used without the risk of contamination of the devices. A schematic overview of the architecture of both device designs is given in figure 4. The photodiodes with an area of 1 mm^2 are placed behind the LEDs (8 mm^2) and receive the reflected light via an opening in the middle.

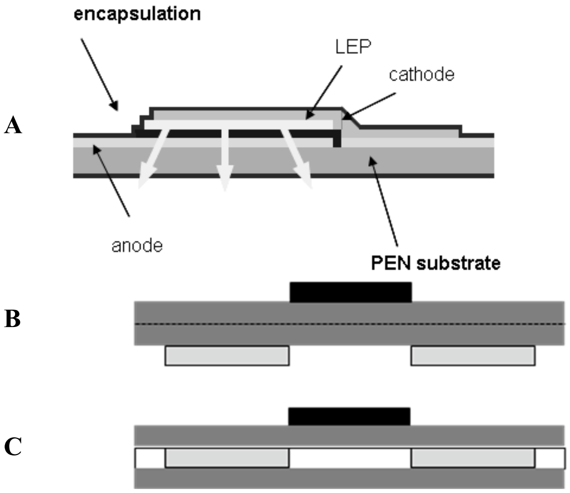


Figure 9 Schematic overview of the buildup (A) and cross section (B,C) of the devices. B shows the architecture in case a top emissive OLED (light gray) is used in combination with a bottom receptive OPD (black). The dotted line in the middle may be seen as the adhesive in case foil is the substrate. C depicts the combination of both bottom emitting and receptive devices. For clarity, the size of the actual devices are strongly exaggerated.

Top-emissive OLEDs

Bottom-emissive OLEDs are considered Lambertian emitters. As indicated before this might reduce the amount of light that is able to penetrate the skin because of "leakage" into the substrate. Clearly, the loss of light is strongly dependent on the thickness of the substrate. For the devices on glass and the first generation on foil (Figure 9, B) we therefore chose to use top emissive OLEDs. Here the light has to pass only through the thin film encapsulation, minimising this loss.

The red emitting material shows a peak emission at 670nm and has a large overlap with the absorption spectrum of the photodiode blend (Figure 10). Also the emission overlaps with the prime wavelength for the PPG measurement, 650 nm. This makes this material particularly useful for the saturation sensor (Figure 6).

The bottom-emissive devices had a maximum efficiency of 1.5 Cd/A. In top emissive devices this was reduced to a maximum efficiency of 0.45 cd/A at 8V and 320 cd/m^2 as measured with a luminance meter. The area of the LED was 8 mm^2, implying a current of 5.6 mA. These results show that the luminescence of top emissive devices is much lower than their bottom emissive counterpart. This is partly due to the reduced transparency of the cathode (60-70%) and partly due to the angle dependent emission by a cavity effect. Figure 10 shows a conoscopic measurement (Eldim, EZ-Contrast L160D) of a top-emission device driven at 9 V. Clearly the light is not emitted in a Lambertian mode but has a maximum between 40° and 50°. Control of this angle dependence, would give an interesting tool for light incoupling.

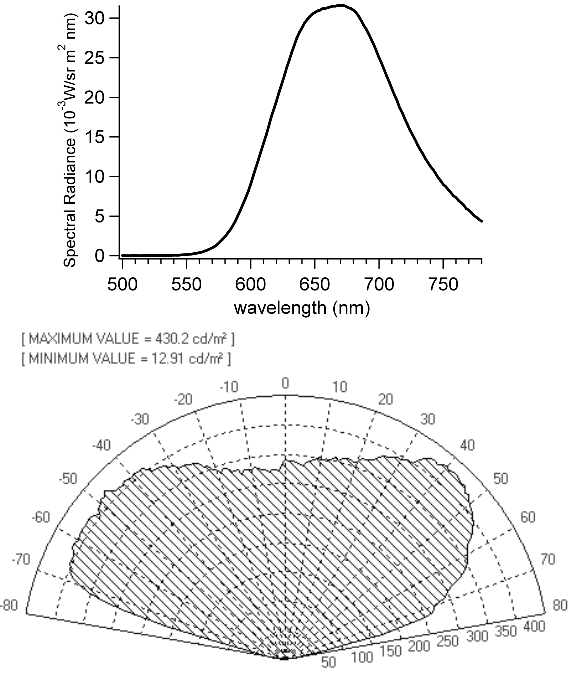


Figure 10 Emission spectrum of the red emitting OLED (top) and Cross section of a conoscopic image in Luminance (Cd/m^2) vs. the viewing angle (bottom).

Organic photodiodes

The photodiodes used in this study were bottom-receptive and had an area of 1 mm^2. The active layer was spin coated from a chlorine free solvent. No separate thermal annealing was required. A TEM picture (Figure 11) of an inkjet printed layer, using the same solvent, showed similar features as reported in literature [23]. This indicates that the morphology is very similar to that of films obtained by chlorinated solvents such as ortho dichloro benzene. This was corroborated with IV-measurements of both spin coated and inkjet printed devices using LiF/Al as cathode. Both showed high short circuit currents (Jsc) of 10 and 8.7 mA/cm^2, respectively (Figure 11) under approximately 100 mW/cm^2 white light illumination. The open circuit voltage (Voc) was 0.58 V with a fill factor (FF) of 0.56 for the spin coated device. The printed device showed a slightly lower Voc of 0.54 V but a dramatically lower FF. We attribute this to the inhomogeneity of the printed layer. Optimisation of the printing process including ink formulation is currently being carried out.

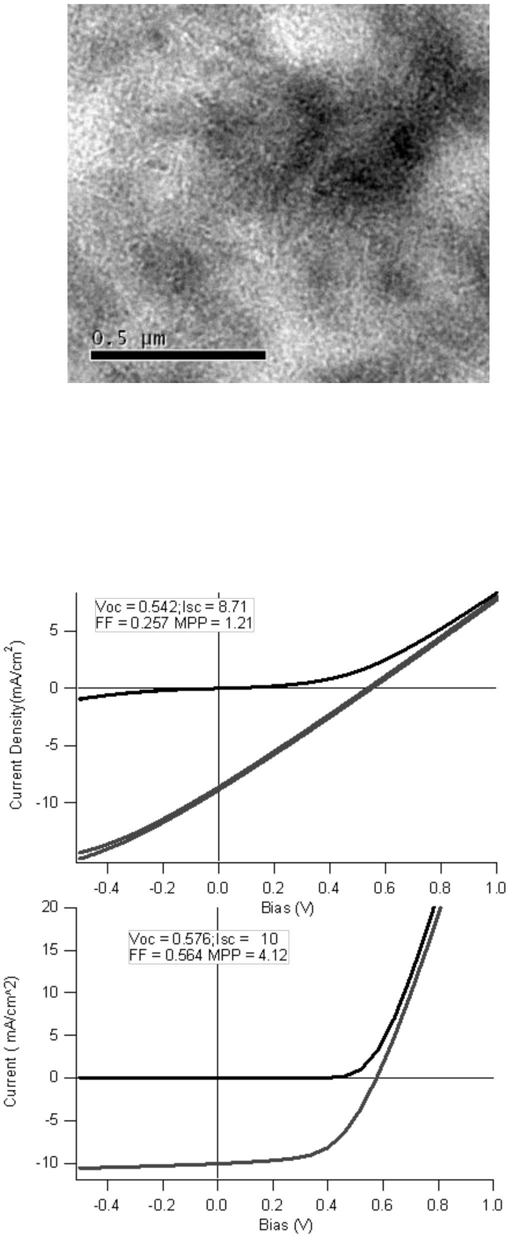


Figure 11 TEM image of an inkjet printed film of P3HT/PCBM blend (top) and IV curves of a spin coated device (bottom) and inkjet printed device (middle).

The noise levels of our devices can be relatively easily estimated from the shunt resistance (R_{sh}) measured in the dark. The measured thermal noise currents are in the order of 20 fA/Hz1/2. This is slightly higher than Si diodes. However, these levels are well below the measured currents, during operation (nA).

Photoplethysmography with OLEDs and OPDs

For the proof of principle we made use of a double side glass based device using two red emitting OLEDs and one photodiode. The OLEDs were driven at 9V. The measured photocurrents were filtered (band pass 0.5-17 Hz) and the AC component was amplified using a logarithmic amplifier (AD8304). The measurement was performed on the right index finger of a test person. A simultaneous measurement with a commercial pulse-oximeter (Nelcor N200) on the middle finger served as control. The resulting photoplethysmograms are shown in Figure 12.

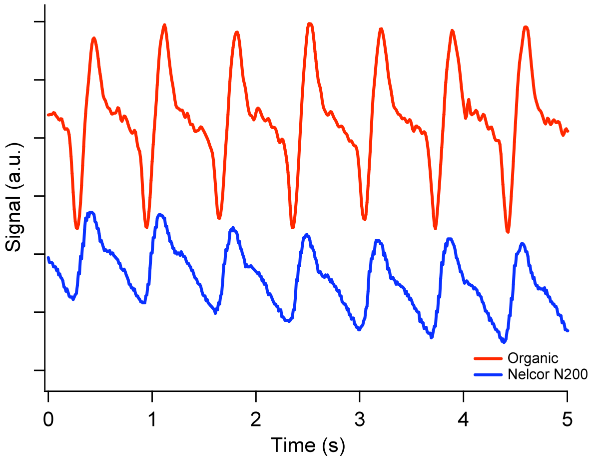


Figure 12 Photoplethysmogram showing the pulse of a test person measured with the organic device (top) and a commercial pulse-oximeter (bottom). The signals have been shifted on the y axis for clarity.

The signal of the organic device and the control match perfectly showing that our sensor can be used for measuring the pulse. The PPG is typical for a measurement on a finger [16]. The commercial device delivers a strongly smoothed signal, whereas the signal of the organic device was only slightly smoothed. The total signal measured by the photodiode was 10 µA, the relevant modulation (AC signal) was approximately 50 nA, estimated from the amplifier characteristics [24].

CONCLUSIONS

Homogeneous flexible light sources can be produced at large areas by OLEDs comprising thin film encapsulation and shunting lines for homogeneous current density. Recent advances at the Holst Centre have shown that areas of more than 100 cm^2 become feasible and compatible with Roll-to-Roll processing, thereby allowing low cost production methods. Holst Centre's strategy furthermore focuses on sensors incorporated in foils. Both functional components are ultimately suited to serve in devices for health and well-being in phototherapeutic applications like dermatological disorders and pain relief. Future developments are expected to increase conformability, area and efficacy of light sources.

Sensors based on organic electronic devices allow for such applications but can also be used for direct measurements of physiological processes on the body. We have shown a functional prototype comprising an in plane optical sensor node containing OLEDs and OPDs on foil that can be integrated with existing electronics using lamination technologies. More specifically the sensor was designed for photoplethysmography, measuring the perfusion in the skin. The sensor produced a signal from measurement on finger extremity which was comparable to a commercial pulse-oximeter, This shows that organic optoelectronic devices can well be used for the direct measurement of physiological parameters such as the perfusion in skin.

We foresee a bright future for light sources and associated sensor systems based on organic electronics in the application fields of health and well-being.

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Effect of Glazing Types on Daylight Quality in Interiors: Conclusions from Three Scale Model Studies

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ABSTRACT

This paper reports the results of three scale model studies about the effect of glazing types on daylight quality in interiors. This paper emphasizes on the constancy in the results of the three studies, which indicate that glazing types have a statistically significant effect on the perception of brightness, naturalness, beauty-pleasantness and precision. Glazing types with higher visual transmittance yield brighter, more natural, beautiful-pleasant and sharp views of the interior. The three studies also indicate that the glazing visual transmittance is negatively correlated with glare comfort: higher transmittance glazing types result in more glaring views of the interior. Finally, the three studies show that the glazing type has no effect on the perception of shadows.

Keywords

Daylight quality, windows, glazing, visual transmittance, glare, tinted glazing, reflective coating, low-e coating.

INTRODUCTION

Fifteen generations ago, most of our ancestors spent the majority of their waking hours outdoors and buildings primarily provided only shelter and security during the hours of darkness [1]. Today, people spend nearly 85-90% of their time indoors [2] and the interior of buildings is the main scenery supporting daily lives.

In interior environments, a contact with the exterior, natural world is of prime importance, and this contact is made possible by the window glazing material. Window glazing is the primary filter of daylight in a building and the main interface between the interior and exterior worlds. A large field study carried out in Denmark [3], indicated that “being able to see outside” was the most important benefit of windows for office workers.

Recently, the need for energy conservation in buildings has spurred innovations in window technologies. The use of coated and tinted glazing is one of the strategies that can improve energy efficiency of buildings [4]. Window coatings and tints alter the quantity and spectral quality of daylight, which may have an effect on user satisfaction, daylight utilization and even photobiological responses in humans. According to Chain et al. [5], glazing types which are thermally efficient are rarely evaluated according to their visual impact: grey or green tints can lead to the impression of being sick. Glazing types which are thermally efficient may also produce a colour distortion of the natural light spectrum which may affect pupillary reflex, alertness, mood and performance in fully daylit buildings. A recent discovery [6, 7] about circadian retinal photoreceptors (photosensitive retinal ganglion cells: ipRGCs) suggests that short-wavelength (blue) light is associated with the good functioning of neuro-endocrinal systems and circadian cycles, with evidence for the involvement of these ipRGCs cells in pupillary reflex, alertness, mood and performance [8].

This paper presents the results of three studies of the effect of glazing types on daylight quality in interiors. The three studies were achieved in scale models under artificial as well as natural skies in Denmark and Canada, using a within-subject experimental design. The objective of the artificial and natural sky studies was to examine the relationship between the optical properties and colour coordinates of different glazing types and various qualitative factors related to daylight quality: brightness, glare, naturalness, beauty and pleasantness, precision, light distribution and shadows. This paper emphasizes on the constancy in the results obtained in the three studies.

LITERATURE REVIEW

There are a large number of researches about artificial light sources in terms of spectral characterization [9] and effects on occupant satisfaction, performance, mood [e.g. 10, 11]. Previous research on electric lighting strongly suggests that both brightness *and* spectral distribution are contributing to the visual experience, to perception and performance in a space. One study [12] indicated a relationship between desktop daylight illuminance and the preferred colour temperature: low daylight levels (500 lux) cause preferred CCT around 3300 °K, while higher daylight levels (1500 lux) result in increased CCT to 4300 °K. This is in agreement with the Curve of Amenity for artificial lighting (Kruithof Diagram [13]), which shows that the higher the overall lighting level, the higher its colour temperature should be. Conversely, high colour temperatures under low luminance tend to make the space look cold and dark, while low colour temperatures under high lighting level tend to make the space look artificial [14]. In relation with this research on electric lighting, older research on glazing types [15, 16] indicated that solar bronze glass (warm shift) had been found to give an enhanced perception of the same transmittance while solextra glass had been found to give a reduced perception of brightness relative to a spectrally neutral glass of the same transmittance.

Overall, research specifically focused on the effect of window glazing type on daylight quality is scarce, dated or confounding:

In a recent doctoral thesis [17], computer simulations with *Lightscape* were used to assess the effect of two tinted glazing (bronze and green) on indoor correlated colour temperature (CCT). The study showed that tinted glazing greatly affected the interior average CCT but the author concluded that this effect would not be important since the occupant would be chromatically adapted to the scene. One research [18], which examined the attitudes towards the use of heat rejecting or low-light-transmission glasses in high-rise office buildings, supports this statement. This research concluded that tinted glass had little or no effect on the visual environment.

On the contrary, another study [19] indicated that people were clearly able to distinguish between a standard three-pane clear glass window and a super insulated four-pane window (green shift) in a full-scale laboratory experiment where two identical rooms furnished alternately as office and bedroom were evaluated by 95 subjects using a between-subject, random order experimental design. The room with the four-pane window felt more enclosed, and the daylight felt less strong and clear. The four-pane window also affected colour perception, making the colours of the room and of the view look drabber.

In a series of experimental model studies [20], where room and window size, room décor, illuminance (total incident light) level and light colour were manipulated, the responses of office staff to the appearances of windows with variable glazing transmission characteristics were analysed. The study showed that the acceptability of an office can be increased by the use of reduced transmittance glazing, and that generally, there is a preference for a colour effect that gives a warm shift, but the author concluded that these preferences can be influenced by room and window sizes and by room décor.

In another experimental study [21] about the minimum acceptable transmittance of glazing where three types of glass (spectrally neutral, brightness enhancing solar bronze and brightness reducing solextra) were tested under a range of conditions by subjects viewing a real sky and scenery through the window of a model office, the authors concluded that the minimum acceptable glazing visual transmittance lied in the range 25-38%. The study also pointed no statistically significant difference between the spectrally neutral glass and the brightness reducing solextra glass regarding the minimum acceptable transmittance.

In summary, this literature review yields the following conclusions:

- Two studies [17, 18] suggest that tinted glazing has no effect on the visual environment due to adaptation of the visual system.
- In contradiction, another study [19] indicates that the glazing type has a significant effect on the perception of the visual environment: a four-pane window with two coatings (green shift) makes the room feel more enclosed and gives an appearance of weaker daylight and drabber colours.
- On the other hand, Cuttle [20] found that the acceptability of an office can be increased by the use of reduced transmittance glazing. Studies by Boyce et al. [21] even concluded that quite low glazing visual transmittance is acceptable.
- Cuttle [20] found a preference for a warm shift, a result which seems to agree with the results of Boyce et al. [15, 16] who found that a brightness enhancing solar bronze glazing is perceived to result in a brighter room environment than the spectrally neutral glazing. This result does not necessarily disagree with Bülow-Hübe's experiment [19] where a window with a green shift, (which is opposite to a warm shift) was studied.

METHOD

This paper presents the results of three separate scale model studies where the effect of window glazing types on daylight quality in interiors was investigated. The first study [22] was carried out at the Danish Building Research Institute in Hørsholm, Denmark (lat. 55,4° N) and the second [23] and third [24] studies were achieved at the École d'Architecture of Université Laval, Quebec City, Canada (lat. 46,5° N).

Scale models

The three studies were achieved using scale models of a regular rectangular room. The scales used were 1: 7,5 in the first study and 1:6 in the second and third studies.

Previous research [25, 26] has shown that scale model studies are a quick and reliable method provided that the scale is not too small and that great care is taken to represent the details and décor of the real environment.

Room geometries and furniture

In all three studies, a regular rectangular room with a single window was simulated. In the first study, no specific décor was represented; the room only contained a scaled table and some objects that research participants could observe (Fig. 1). In the second and third studies, the room was fully furnished as a typical residential living room with sofa, table, book shelf, curtains, etc. (Fig. 2).

In the first (Danish) study, paired comparisons were used. Athough all efforts were made to make the two rooms look exactly the same, some unintentional differences between the Test and Reference rooms did appear, which may have introduced some bias in this first study. The two identical scale models with interior dimensions of 3,5 * 6,0 * 3,0 m^3 (width * depth * height, full-scale) were built and placed next to one another. The scale models thus measured 0,47 * 0,8 * 0,4 m^3 (w * d * h). Each scale model had a unique opening for the window measuring 0,17 * 0,24 m^2 (height * width) placed 0,18 m above the floor (window full-scale dimensions were 1,2 * 1,8 m^2, located 1,35 m above the floor). Opposite the window, a small horizontal hole allowed the research participants to make their observations. The research participants thus looked straight ahead towards the window when making their assessments. The interior of both scale models was painted a diffuse white colour (refl. > 85%) and furnished with a brown, scaled table, a silver key (on the table), a piece of broccoli, a baby tomato, a pine cone, a staple remover and a yellow tennis ball (Fig. 1). There was no electric lighting in the scaled rooms.

In the second and third studies, paired comparisons were abandoned and thus a single scale model (1:6) was built of a typical living room measuring 0,92 m by 0,66 m (width x depth, full scale: 5,5 m x 3,9 m) with a single, centrally placed window measuring 0,41 m by 0,22 m (width x height, full scale: 2,4 m x 1,3 m), with window sill height at 0,14 m (full scale: 0,8 m) from the floor (Fig. 2). The scale selected for the study allowed a detailed and faithful representation of furniture, interior finishes of various colours and textures. The walls were painted a light beige (70% reflectance), the ceiling was white (74% reflectance) and the floor was covered with a veneer similar to a wooden floor (52% reflectance). There was no electric lighting in the scaled room. The research participants observed the room through an opened door on the lateral wall of the model.

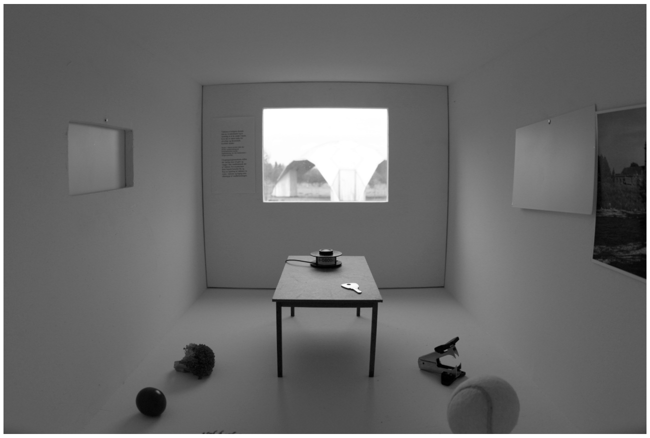


Fig. 1 Photograph showing the interior of the scaled room in the first (Danish) study.

Fig. 2 Photograph showing the interior of the scaled room in the second and third (Canadian) studies.

Orientation, sky conditions and view out

In the first (Danish) study, both scale models (Reference and Test rooms) were placed behind the window of an empty office room at the Danish Building Research Institute (SBI), Hørsholm, Denmark. This window, which had a north orientation, was replaced by a single, iron free window pane (daylight transmittance = 91%). This study was entirely achieved during January and February 2002, between 09.30 and 15.00 hours, under overcast sky conditions, in order to make sure that exterior daylight conditions were as constant as possible. The window allowed a view of a white sculpture placed on a grass lawn and surrounded by trees and shrubs (Fig. 1).

In the second study, the experiments took place during May 2007, between 10.00 and 19.00 hours. The scale model was placed next to the artificial sky of the École d'Architecture of Université Laval, Québec, Canada. The light coming from the artificial sky penetrated through the window opening of the scale model. This artificial sky consists of a mirror box measuring 1,22 m x 1,22 m x 1,22 m, which has the distribution of a typical CIE overcast sky. The illumination is achieved with "daylight" fluorescent tubes placed above a diffuser (acrylic white sheet). In this second experiment, the visible part of the artificial sky was simulated as a typical landscape of a suburb using small plants and shrubs (Fig. 3).

Fig. 3 Photograph showing the view of the interior of the room towards the window in the second study.

Fig. 4 Photograph showing the view of the interior of the room towards the window in the third study.

In the third study, the same scale model (as in the second study) was moved so as to expose the window to the natural climate. The window of the scale model was oriented facing the south-east direction. The experiments took place during October 2007 between 12.00 and 16.00 hours to avoid the presence of any direct sunlight penetration due to the south-east orientation of the window. The position of the observation hole was the same as in the second study (i.e. via a lateral door). The exterior scene viewed through the window of the scale model consisted of one of Quebec City's most beautiful views of a park overlooking St-Lawrence River (Fig. 4).

Glazing samples tested

In the first (Danish) study, paired comparisons were used with one Reference and one Test room. The glazing samples tested (Table 1) were selected because they are widely used in Denmark according to the glazing manufacturer who provided the samples and thermal-optical data. The Reference glazing (Ref_{77}) was selected because it was the most neutral in colour and had a high transmittance.

In the second and third studies, paired comparisons were abandoned and thus a single scale model was used throughout. The window opening of the scale model was alternately covered by different glazing samples presented in random order during the experiments. A set of glazing samples commonly used in residential buildings was chosen from a stock of samples provided by local glazing manufacturers. A total of seven glazing types were selected based on their optical properties (Table 1). Glazing type A_{83} was selected because it was an iron-free combination. The other glazing types were selected because of the availability of measured optical data.

In the third study, only five glazing samples were selected from the second study (Table 1, see *). Glazing B_{82} was selected because it is one of the most common glazing assemblies in older buildings. Apart from glazing G_{38}, all glazing samples looked almost the same in all three studies; the differences between the samples were subtle and the research assistant needed to look at the code written on the side of each sample to be able to identify it.

In the second and third studies, the effect of glazing type on the transmitted light colour was determined using a digital photographic image technique [see 24], which consisted of subtracting colours from two digital images: a reference- and a test-photo. Since colour temperature of daylight varies according to sky type and time of day, four series of photos were taken, each one corresponding to a sky type: (1) clear sky, (2) partly sunny, (3) partly cloudy and (4) overcast. The colour subtractions were then performed using *Photoshop CS2* according to the three channels (red, green and blue) of the RGB model. The RGB data were then converted to CIE-L*a*b coordinates using a colour calculator (see Fig. 5). The more salient points of this analysis are summarized below:

- Glazing A_{83} yields a negligible green shift and small yellow shift;
- Glazing B_{82} is significantly greener and slightly yellower than A_{83};
- Glazing types C_{74} and F_{65} exhibit colour shifts in two directions (similar values for both axes);
- Glazing G_{38} yields the strongest green shift but the weakest yellow shift amongst all glazing types studied. A blue shift appears under clear sky conditions.

Table 1 Glazing samples tested in the three studies with their thermal and optical properties.

	Name	Description	U-value cog	Daylight					Solar
				Tr	CIE*Lab		Rext	Rint	Tr
			($W/m^2 °C$)	(%)	a	b	(%)	(%)	(%)
Study 1 (Denmark)	A_{79}	1 cl. + 1cl. low-e (s)	1.12	79	-2.8	2.3	11	12	63
	B_{76}	1 cl. + 1 cl. low-e (h)	1.45	76	-2.7	3.2	17	16	72
	C_{70}	1cl. low-e (s) + 1 cl. + 1cl. low-e (s)	0.46	70	-4.3	4.1	14	14	46
	D_{66}	1 solar low-e + 1 cl.	1.12	66	-7.0	8.8	20	18	42
	E_{50}	1 solar low-e + 1 cl.	1.04	50	-8.9	3.2	18	15	26
	Ref_{77}	1 ironfree + 1 cl. low-e (h)	1.45	77	-1.8	2.2	17	16	79
Study 2 and 3* (Canada)	A_{83}*	1 iron-free + 1 iron-free	n/a	83	n/a	n/a	7	7	79
	B_{82}*	1 cl. + 1 cl.	n/a	82	n/a	n/a	n/a	n/a	n/a
	C_{74}*	1 cl. + 1 low-e (Ti-PS)	n/a	74	n/a	n/a	11	12	46
	D_{73}	1 cl. + 1 low-e (h)	n/a	73	n/a	n/a	16	15	54
	E_{68}	1 Ti-AC 40 + 1 cl.	n/a	68	n/a	n/a	9	11	34
	F_{65}*	1 Ti-AC 36 + 1 cl.	n/a	65	n/a	n/a	10	10	31
	G_{38}*	1 Ti-AC 23 + 1 cl.	n/a	38	n/a	n/a	13	11	18

n/a= data not available

Research participants

In all three studies, the research participants were recruited by email. In the first study, the participants were mainly from the administrative staff of the Danish Building Research Institute while in the second and third studies, the participants were mainly students from the school of architecture. The participants were not paid to take part in the experiments and they were not aware of the real goal of the research. The participants over 45 years old or with important visual problems, as well as those with knowledge about windows or glazing were excluded from the study. A total of 18 participants (9 males) took part in the first study, 15 (7 males) in the second study and 30 (16 males) in the third study.

Questionnaire

In the first study, a two-page questionnaire (see [22]) which used semantic, seven-grade, bipolar scales was developed to cover most of the following dimensions of light: brightness, distribution, shadows, reflexes, glare, light colour and colours. These factors were identified in the literature as the most important for the description of light quality in interior spaces [27]. The questionnaire was adapted from Bülow-Hübe [19] and focused more specifically on daylight intensity and colour, colours in the interior and in the view out, glare, shadows and textures.

After the first study, a principal component analysis (PCA) was carried on the 27 questions of the questionnaire. Using Jolliffe's criteria [28] which consists of retaining only the factors with associated eigenvalue larger than 0,70, the PCA retained seven (F1-F7) factors explaining 79,5% of the variance in the scores. The number of factors was also confirmed by the scree plot test [29]. The results of the PCA (with a Varimax rotation) and the interpretation of each factor retained is presented in detail in the relevant paper [22].

The questionnaire for the second and third studies was developed from the first questionnaire, taking into consideration the seven factors identified previously: (F1) brightness, (F2) glare comfort, (F3) naturalness, (F4) beauty pleasantness, (F5) precision, (F6) distribution and (F7) shadows. The factor "colour temperature" (from the first study) was abandoned since the research participants did not know what it referred to and we introduced a factor called "distribution", since this parameter is often discussed in lighting design and research. The other qualitative factors were used when designing the questionnaire and throughout the statistical analysis of the results. The questionnaire, which was identical for the second and third study, contained a total of seven questions (14 sub questions) and also used seven-grade bipolar scales (see Table 2).

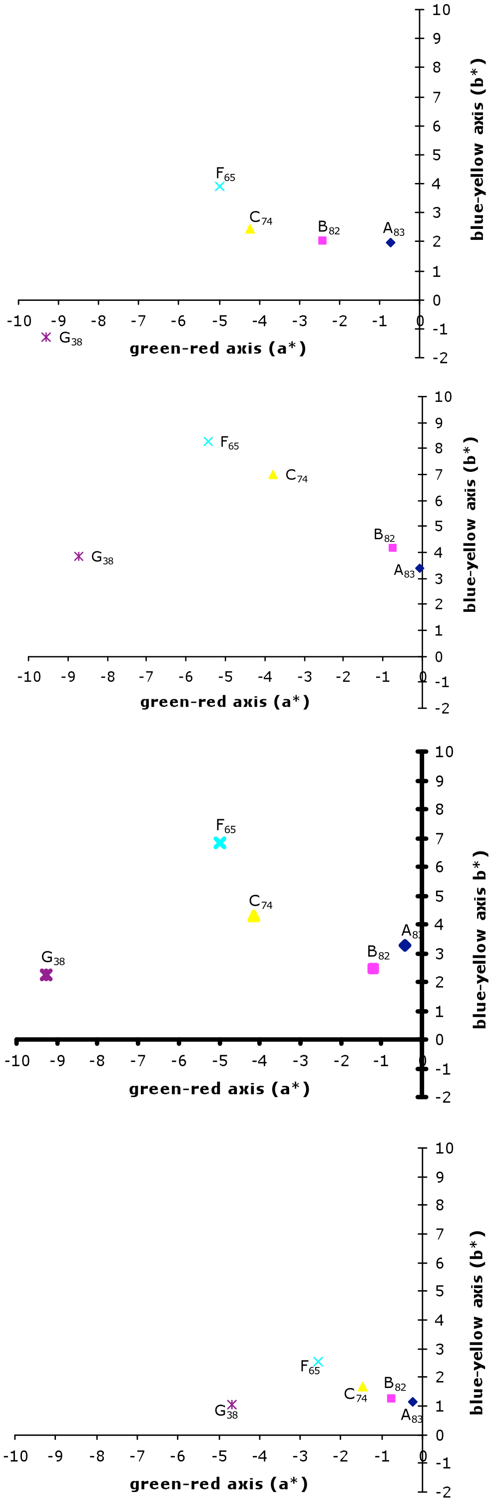


*Fig. 5 Resulting CIE-L*a*b coordinates for (1) clear, (2) partly sunny, (3) partly cloudy and (4) overcast sky.*

Experimental design and research procedure

The three studies used a within-subject experimental design so every research participant evaluated every glazing situation. Each participant had a unique and random order of presentation and no particular order of presentation prevailed. Latin Squares [30] were used to conserve the random order of presentation while narrowing the required number of participants.

In the first study, one of the scale models was used as a Reference Room and fitted with a double-pane window with an iron free and a low-emissivity coated glass (glazing "Ref$_{77}$", see Table 1). The other scale model, called the "Test Room", was alternately fitted with one of the other glazing types (A$_{79}$, B$_{76}$, C$_{70}$, D$_{66}$ or E$_{50}$, see Table 1).

The first study relied on paired comparisons such that during each visit to the lab, the research participant was first asked to look into the Reference Room and fill in the questionnaire concerning the visual conditions in this room. The participant was then asked to look into the Test Room and fill in an identical questionnaire. S/he was allowed to look back into the Reference Room and at the first questionnaire to make sure that the evaluation of the Test room was consistent with the previous one. Once this second questionnaire was completed, the subject was asked to leave the room. The researcher then went into the laboratory, changed the glazing of the Test Room, and told the subject to come back into the laboratory and evaluate the conditions in the Test Room again, filling in a third questionnaire, identical to the two previous ones. The participant was never told that the glazing of the Test Room had been changed and s/he could not see the researcher change the glazing. The exact same procedure was repeated each time the subject had to evaluate a new glazing type.

The evaluation of all glazing types was completed using two sessions per subject, each session lasting about 40-45 minutes and covering only three glazing types (apart from the Ref$_{77}$ glazing). The subjects used three minutes to adapt and the remaining time to fill the questionnaire. Prior to these two sessions (sessions 2 and 3), each subject was also invited to perform one whole session (session 1) to get some training and make sure that there was no misunderstanding in the questionnaire and procedure.

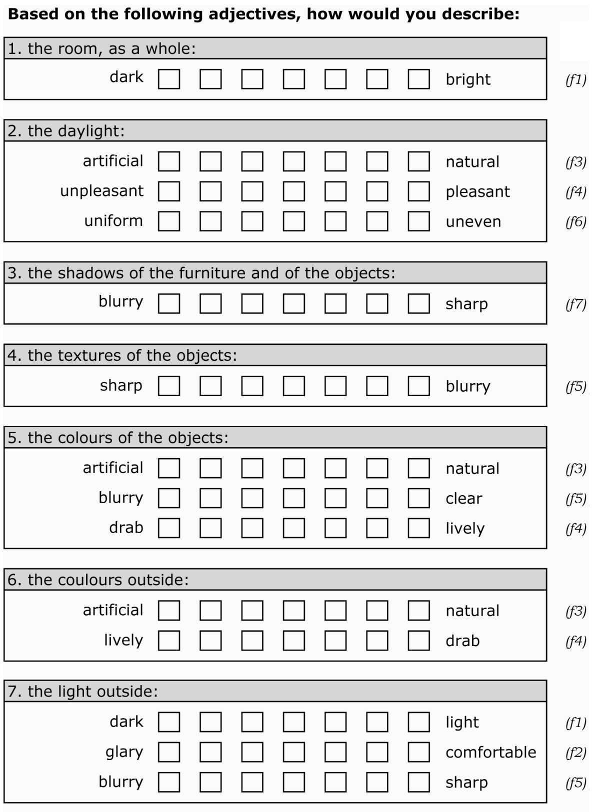
The glazing types were divided into two groups corresponding to each session:

Session 2: glazing types A$_{79}$, C$_{70}$, E$_{50}$

Session 3: glazing types B$_{76}$, D$_{66}$, E$_{50}$

Glazing E$_{50}$ was evaluated during each session, to check that the ratings were consistent from one session to the next. Moreover, each session included glazing types with a high light transmittance (A$_{79}$ and B$_{76}$), an intermediate light transmittance (C$_{70}$ and D$_{66}$) and a low light transmittance (E$_{50}$). A multivariate Wilk's lambda statistic analysis was carried out on the evaluation of glazing Ref$_{77}$ and E$_{50}$, which showed no difference between sessions 2 and 3 for both glazing types (Ref$_{77}$: Wilk's lambda = 0.426, F(9.9) = 1.345, p = 0.333 / Glazing E$_{50}$: Wilk's lambda = 0.441, F(9.9) = 1.270, p = 0.364). For two glazing types, the average value of the factor scores for sessions 2 and 3 was thus used for the rest of the analysis.

Table 2: Questionnaire filled by the research subjects (translated from French) in the second and third studies and associated factor.



Based on the following adjectives, how would you describe:

1. the room, as a whole:			
dark	☐ ☐ ☐ ☐ ☐ ☐ ☐	bright	*(f1)*
2. the daylight:			
artificial	☐ ☐ ☐ ☐ ☐ ☐ ☐	natural	*(f3)*
unpleasant	☐ ☐ ☐ ☐ ☐ ☐ ☐	pleasant	*(f4)*
uniform	☐ ☐ ☐ ☐ ☐ ☐ ☐	uneven	*(f6)*
3. the shadows of the furniture and of the objects:			
blurry	☐ ☐ ☐ ☐ ☐ ☐ ☐	sharp	*(f7)*
4. the textures of the objects:			
sharp	☐ ☐ ☐ ☐ ☐ ☐ ☐	blurry	*(f5)*
5. the colours of the objects:			
artificial	☐ ☐ ☐ ☐ ☐ ☐ ☐	natural	*(f3)*
blurry	☐ ☐ ☐ ☐ ☐ ☐ ☐	clear	*(f5)*
drab	☐ ☐ ☐ ☐ ☐ ☐ ☐	lively	*(f4)*
6. the coulours outside:			
artificial	☐ ☐ ☐ ☐ ☐ ☐ ☐	natural	*(f3)*
lively	☐ ☐ ☐ ☐ ☐ ☐ ☐	drab	*(f4)*
7. the light outside:			
dark	☐ ☐ ☐ ☐ ☐ ☐ ☐	light	*(f1)*
glary	☐ ☐ ☐ ☐ ☐ ☐ ☐	comfortable	*(f2)*
blurry	☐ ☐ ☐ ☐ ☐ ☐ ☐	sharp	*(f5)*

In the second study, the large amount of glazing types studied also required that the experimentation be conducted in two sessions to avoid visual fatigue of the participants. The validation of the results between session 1 and 2 required that glazing type B_{82} was evaluated each time. Subsequently, the scores of the first session were used for the analysis since a univariate repeated measure ANOVA showed that the scores were statistically equivalent between sessions 1 and 2 (F(1,6) = 0,415 and p = 0,867).

In the second study, the artificial sky was lit at least 30 minutes before the beginning of each experiment to stabilize the light output from the fluorescent tubes. At the beginning of each session, the participant entered the laboratory and was instructed to sit in front of the observation point from which s/he looked inside the scale model and filled a questionnaire. Once the first questionnaire was completed, the participant gave it to the researcher and left the laboratory. In the meantime, the researcher changed the glazing type. Once the second glazing was in place, the participant was asked to come back in the laboratory to repeat the exact same procedure. These steps were repeated for each glazing type and each laboratory session.

In the third study, a similar procedure was used as in the second study except that once a first questionnaire was completed, the participant gave it to the researcher and simply closed the door giving access to the observation hole. The time laps for the glazing switch was fairly rapid since the participant could remain seated without being aware of the change. The evaluation of the five glazing types took around 15 to 20 minutes to complete in the third study. The subjects used three minutes to adapt and one to two minutes to fill the questionnaire.

Measurements

In the first study, the following quantities were recorded:

- the interior horizontal illuminance,
- the exterior global illuminance,
- the exterior vertical illuminance (on the north facade),
- the vertical spectral irradiance.

Specific details regarding these measurements are carefully reported in the relevant paper [22].

In the second and third studies, the interior horizontal illuminance was the only physical quantity recorded during the experiments. Details regarding the illuminance measurements are reported in the relevant papers [23, 24].

RESULTS

Danish study (first study)

The statistical analysis was performed using the *SPSS 12.0* software. In the first (Danish) study, a statistical analysis was carried out by identifying seven important factors to which the research questions related (also drawn from the results of a principal component analysis (PCA) and confirmed by scree plot test):

- shadows (F1);
- brightness (F2);
- naturalness and colouring (F3);
- colour temperature (F4);
- beauty and pleasantness (F5);
- comfort (glare) (F6);
- sharpness (F7);

The average of scale scores for each factor was calculated and the factors were classified with respect to their capacity to explain the variance (from F1 to F7).

Subsequently, a randomized complete block design ANOVA [31] was carried out on the average scores for each factor with the different glazing types as the within subject effect. This analysis showed that for all the factors except F1 (shadows), the glazing type had a statistically significant effect on the subjective scores (see [22] for detailed results).

Table 3 Glazing type (Daylight Tr), mean, standard error, and results for the specific orthogonal comparisons (Dunnett) and multiple comparisons (LSD method adjusted with Bonferroni), first (Danish) study.

F1 - Shadows

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction
Ref (77%)	3.181	-0.209	-	■
A (79%)	3.083	-0.209	p=0.997	■
B (76%)	3.083	-0.209	p=0.997	■
C (70%)	2.722	-0.209	p=0.396	■
D (66%)	3.000	-0.209	p=0.961	■
E (50%)	3.056	-0.209	p=0.992	■

F2 - Light level

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction			
Ref (77%)	5.403	-0.189	-	■			
A (79%)	4.556	-0.189	p=0.010		■		
B (76%)	4.194	-0.189	p<0.0001		■		
C (70%)	3.083	-0.189	p<0.0001			■	
D (66%)	2.611	-0.189	p<0.0001			■	■
E (50%)	1.861	-0.189	p<0.0001				■

F3 - Naturalness. colouring

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction		
Ref (77%)	5.377	-0.173	-	■		
A (79%)	4.944	-0.173	p=0.274	■		
B (76%)	4.841	-0.173	p=0.119	■		
C (70%)	3.746	-0.173	p<0.0001		■	
D (66%)	3.611	-0.173	p<0.0001		■	
E (50%)	2.837	-0.173	p<0.0001			■

F4 - Color temperature

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction	
Ref (77%)	3.602	-0.168	-	■	■
A (79%)	3.796	-0.168	p=0.881	■	■
B (76%)	4.315	-0.168	p=0.016	■	
C (70%)	3.889	-0.168	p=0.631	■	■
D (66%)	4.130	-0.168	p=0.112	■	■
E (50%)	3.509	-0.168	p=0.994		■

F5 - Beauty. pleasantness

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction		
Ref (77%)	3.924	-0.164	-	■		
A (79%)	3.833	-0.164	p=0.994	■		
B (76%)	3.667	-0.164	p=0.701	■	■	
C (70%)	3.264	-0.164	p=0.024	■	■	■
D (66%)	3.069	-0.164	p=0.002		■	■
E (50%)	2.632	-0.164	p<0.0001			■

F6 - Comfort. glare

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction	
Ref (77%)	4.792	-0.154	-	■	
A (79%)	4.806	-0.154	p=1.000	■	
B (76%)	5.361	-0.154	p=0.043	■	■
C (70%)	5.639	-0.154	p=0.001		■
D (66%)	5.722	-0.154	p<0.0001		■
E (50%)	5.972	-0.154	p<0.0001		■

F7 - Sharpness

Glazing	Means	(Std. Error)	Dunnett	Protected LSD with Bonferroni correction			
Ref (77%)	5.356	-0.14	-	■			
A (79%)	5.167	-0.14	p=0.805	■			
B (76%)	4.833	-0.14	p=0.042	■	■		
C (70%)	4.511	-0.14	p<0.0001		■	■	
D (66%)	4.233	-0.14	p<0.0001			■	■
E (50%)	3.906	-0.14	p<0.0001				■

The means obtained for each factor and each glazing were also ordered with bipolar scales all presented as negative-positive (1–7) in the analysis (see Table 3). A rating of 7 corresponds to the highest (most positive) score; a rating of 1, to the lowest (most negative) score, and a rating of 4, to a neutral score. This analysis indicated that glazing types of higher transmittance generally obtained higher (more positive) scores than the glazing types with lower transmittance. However, there are two exceptions to this trend. For F1 (shadows), the means were almost constant thus indicating a weak effect of glazing type on the perception of shadows (also showed by the statistical analysis). For F6 (comfort glare), the means (Table 3) are higher for lower transmittance glazing types, indicating that lower transmittance glazing types resulted in less glare.

To improve clarity in the results, a first approach in the statistical analysis consisted of examining five planned specific orthogonal comparisons (single degree of freedom tests) so the average ratings for glazing types A_{79}– E_{50} were contrasted with the results obtained for the reference glazing, which corresponded to the way subjects arrived at their ratings. The results of this analysis are presented in Table 3 ("Dunnett") and discussed in detail in [22]. The main conclusions from this analysis are summarised below:

- The glazing type did not have any statistically significant effect on the ratings for questions related to shadows (F1).
- In terms of brightness (F2), all glazing types resulted in a statistically significant difference compared to the reference glazing.
- In terms of naturalness and colouring (F3) and beauty and pleasantness (F5), glazing types A_{79}– B_{76} did not result in a statistically significant difference compared to the reference glazing, but glazing types C_{70}–D_{66}–E_{50} produced a statistically significant difference with respect to the reference glazing.
- In terms of colour temperature (F4), glazing B_{76} was the only one rated as statistically different compared to the reference glazing.
- In terms of comfort (glare) (F6) and sharpness (F7), all glazing types except A_{79} resulted in statistically significant differences compared to the reference glazing.

Following finding a significant effect of glazing types, a second approach in the statistical analysis was explored which consisted of performing multiple comparisons with the protected LSD method adjusted with Bonferroni correction to control the type I error rate. Detailed discussion of these results are presented in [22]. The LSD tests indicated, among other things, that for all factors studied, except brightness (F2), there was no statistically significant difference between glazing types Ref_{77}, A_{79} and B_{76} (see Table 3, last column to the right).

Second study (artificial sky, Canada)

In the second study, the factors were slightly modified from the first questionnaire in the Danish study after we realised that questions regarding colour temperature were difficult to understand for research subjects who did not really understand the term "colour temperature" (in French "temperature de couleur" is familiar only to lighting researchers). Moreover, it appeared that this factor was already covered by the factor "naturalness". In addition, a factor called "distribution" was added since this parameter is often discussed in the literature about lighting. The factors were ordered as follows according to their capacity to explain the variance:

- brightness (F1);
- glare comfort (F2);
- naturalness (F3);
- beauty pleasantness (F4);
- precision (F5);
- distribution (F6);
- shadows (F7).

A randomized complete block design ANOVA [31] was performed using the *SPSS 12.0* software. This analysis allowed identifying the factors for which there were statistically significant differences between glazing types (p < 0,05). According to this analysis (outlined in Table 4), the glazing type influenced the perception of brightness (F1), beauty pleasantness (F4) and precision (F5) but had no statistically significant effect on glare comfort (F2: p=0,280), naturalness (F3: p=0,920), distribution (F6: p=0,460) and shadows (F7: p=0,056). The results are thus consistent with the previous (Danish) study concerning the perception of brightness (F1), beauty pleasantness (F4), precision (F5) and shadows (F7). Note that the absence of statistically significant effect of glazing type on F2, F3, F6 and F7 may be explained by the low participation rate.

A multiple comparison ANOVA (Tukey's test) was also performed in order to compare each pair of glazing type according to each factor for which a statistical difference was revealed. A detailed discussion of this analysis is presented in the relevant paper [23].

Of interest for the present paper is the study of the relation between the average scores for each factor and the glazing visual transmittance. Positive correlations between the glazing visual transmittance and scores were obtained for all factors except F2 (glare comfort). These results are generally consistent with results of the previous (Danish) study. The correlation with factor F1 (brightness) is very strong (r_{F1}=0,955). This result was expected because transmittance actually corresponds to the quantity of light transmitted. However, it is surprising to obtain that this particular correlation is weaker than the correlations for beauty pleasantness (r_{F4}=0,972) and precision (r_{F5}=0,986). Although the ANOVA did not reveal any statistically significant differences among glazing types for F7 (shadows, p=0,056), the correlation between F7 and the visual transmittance was fairly high (r_{F7}=0,829) indicating that higher transmittances result in a superior perception of shadows. We should however emphasize that the difference between both analyses (ANOVA and correlation between scores and visual transmittance) may be related to the low participation rate. The negative correlation for F2 (glare comfort) (r_{F2}= – 0,185) suggests that a higher visual transmittance yields more glare. Although this is consistent with the previous (Danish) study, the low correlation and absence of statistically significant effect (ANOVA) reduces the overall importance of this finding in this case.

Third study (natural sky, Canada)

In the third study, a randomized complete block design ANOVA [31] was also performed using *SPSS 12.0*. This analysis allowed identifying the factors for which there were statistically significant differences between glazing types (p < 0,05, Table 5). According to this analysis, the glazing type influenced the perception of brightness (F1), naturalness (F3), beauty pleasantness (F4) and precision (F5) but had no statistically significant effect on glare comfort (F2: p=0,580), distribution (F6: p=0,316) and shadows (F7: p=0,050). Except for the factor naturalness, these results are consistent with the results of the second study [23]. The only difference between these new results and the results obtained in the artificial sky study [23] concerns the perception of naturalness (F3). In the artificial sky study, the ANOVA did not indicate that the glazing type had a statistically significant effect on the perception of naturalness. It is possible that this is attributable to the use of an artificial sky, which made the room look rather artificial. Furthermore, the present study also identified the perception of shadows as a qualitative factor not influenced by glazing type, repeating results of the two previous studies [22, 23].

To elaborate on these results, a multiple comparison ANOVA (Tukey's test) was performed in order to compare each pair of glazing type according to each factor for which a statistical difference was revealed. This analysis is presented and discussed in detail in the relevant paper [24].

Subsequently, an analysis of correlation between average scores for each factor and the glazing visual transmittance was also performed. This analysis revealed that the only negative correlation was obtained for glare comfort (F2), which means that a higher visual transmittance yields more glare. This result is consistent with the two previous studies. On the other hand, the positive correlations indicate that a higher transmittance glazing yields more positive ratings for brightness, naturalness, beauty pleasantness, precision, light distribution and shadows. Five correlations (F1, F2, F3, F4 and F5) were found to be very high ($r>|0,95|$). The only low correlation concerns the perception of distribution (r_{F6}= 0,347).

We should however emphasize that the difference between the ANOVA and the correlation study may be related to the low participation rate, especially in the second study. The negative correlation for F2 (r_{F2}=-0,996) suggests that higher visual transmittance glazing type yields more glare.

Although this is consistent with earlier research [22, 23], the absence of statistically significant effect (ANOVA) reduces the overall solidity of this finding.

Table 4 Results of the second study. The ANOVA indicates the statistical significance of a perceptible difference between glazing types for values of p < 0,05. Correlations between the glazing visual transmittance and the seven qualitative factors indicate the direction and strength of the relationship between the variables.

	F1 Brightness	F2 Glare comfort	F3 Naturalness	F4 Beauty pleasantness	F5 Precision	F6 Distribution	F7 Shadows
ANOVA	p < 0,001	p = 0,280	p = 0,920	p < 0,001	p < 0,001	p = 0,460	p = 0,056
Correlation	r = 0,955	r = – 0,185	r = 0,373	r = 0,972	r = 0,986	r = 0,586	r = 0,829

Table 5 Results of the third study. The ANOVA indicates the statistical significance of a perceptible difference between glazing types for values of p<0,05. Correlations between the glazing visual transmittance and the seven qualitative factors indicate the direction and strength of the relationship between the variables.

	F1 Brightness	F2 Glare comfort	F3 Naturalness	F4 Beauty pleasantness	F5 Precision	F6 Distribution	F7 Shadows
ANOVA	p < 0,001	p = 0,580	p < 0,001	p < 0,001	p < 0,001	p = 0,316	p = 0,050
Correlation	r = 0,985	r = – 0,996	r = 0,984	r = 0,976	r = 0,985	r = 0,347	r = 0,596

DISCUSSION AND CONCLUSION

Three studies of the effect of window glazing types on daylight quality were presented in this paper. The first study was carried out at the Danish Building Research Institute in Hørsholm, Denmark. The second and third studies were achieved at the École d'architecture of Université Laval, Québec, Canada. All three studies used scale models and within-subject experimental design. The first study used a paired comparison with two identical 1:7,5 scale models of an unfurnished rectangular room with a single, north oriented window exposed to overcast skies. A total of 18 research participants evaluated daylight conditions in the two rooms, by looking straight ahead towards the window through an observation hole placed at the back of the room. The second study used a single 1:6 scale model of a rectangular room, which was fully furnished as a typical residential living room and provided with different glazing types presented in random order. This room had a single window facing an artificial, overcast sky. The third study used the same scale model as the second study but the model was exposed to the natural sky with a sunlight free, south-east oriented window. A total of 15 and 30 research participants took part in the second and third study respectively. In both studies, the participants evaluated the light conditions in the rooms (after three minutes of adaptation) from an observation hole located in one of the lateral walls of the model. Their view of the interior thus had a diagonal direction with respect to the window.

This paper focuses on the constancy in the results obtained in the three studies, which were achieved using different experimental designs. In all three studies, the results indicated the following:

The glazing visual transmittance was positively correlated with brightness, naturalness, beauty pleasantness, and precision or sharpness. Previously, Cuttle [20] found that the acceptability of an office can be increased by the use of reduced transmittance glazing, which is in contradiction with the findings of our three studies. In general we found that increasing the glazing visual transmittance produced higher scores for beauty pleasantness, naturalness, precision, brightness. However, in our three studies, all glazing types had a dominantly green or green-yellow shift in colour. We did not have any bronze glazing (with a warm shift). Cuttle [20] found that there is a preference for a colour effect that gives a warm shift and Boyce et al [15, 16] indicated that solar bronze glass (warm shift) had been found to give an enhanced perception of the same transmittance. One explanation for these confounding results may be the fact that a warm shift is preferred because it gives an impression of sunshine (sunny day) even on overcast days while dominantly greenish shifts tend to flatten out the colours in the scene, as shown by Bülow-Hübe's experiment [19]. Since the human spectral sensitivity curve ($v(\lambda)$) peaks in the green-yellow region (550 nm) in the photopic state, it may be that more stimulus is needed in the other colour bands (e.g. red) in order to produce a colourful, lively image. Also, Hårleman et al.

[32] pointed out that reddish colours are associated with human skin, facial colour, strong emotional expressions such as affection and defiance and other mental characteristics.

The glazing visual transmittance was negatively correlated with glare comfort. In other words, glazing types with higher visual transmittance created more glaring views of the interior. The difference between the glazing types was statistically significant only in the first study but the participants looked at the window directly, which may have emphasized the difference between the participants' ratings in this case. These results show that glazing with lower transmittance may contribute to reduce glare to some extent. However, the same glazing types also create interiors that are darker, less beautiful, pleasant, natural and precise. This is very interesting because it means that someone may experience an interior as more beautiful, pleasant, natural and precise, although more glaring. In the recent years, lighting research has focused on glare as the single most important parameter of lighting quality in interiors. The results of these three studies emphasize the importance of considering glare in parallel with other parameters.

Finally, the three studies indicated that the glazing type did not have a statistically significant effect on the perception of shadows. In the last studies, the perception of shadows was positively correlated with the glazing visual transmittance but the difference between the glazing types was not statistically significant according to the ANOVA. We did not obtain statistically significant differences between glazing types for a factor called distribution either. This can be explained by the fact that the glazing type do not affect contrasts between different surfaces, it reduces the luminance of both bright and dark surfaces proportionally, with no resulting effect on shadows or distribution.

Our future research in this field will investigate the effect of colour shifts, including warm shifts, for glazing types of constant visual transmittance. We also plan to include energy and photobiology related effects, and to take into consideration the use of electric lighting together with daylighting for various compass orientations and types of skies. The use of longer adaptation times and full-scale experiments are also two important aspects that should be improved in this research on window glazing types.

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Effect of LED-based Study-Lamp on Visual Functions

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ABSTRACT

Changes in visual functions following near vision tasks under lighting provided by an LED-based study lamp were analysed. Visual performance and basal tear production before and after reading and painting tasks were assessed in the light provided by an LED and a CFL based study lamps on thirty volunteers with normal vision. Measurements were made for each light with room lights on and off. Visual comfort was assessed using a questionnaire. Statistically significant but clinically insignificant changes were seen only in basal tear production in three conditions. Unexplainable changes were seen in the near visual acuity for two contrast levels in certain conditions. No other parameters showed any significant change in any condition.

Keywords

LED lamp, visual functions, Munsell chips, Near vision tasks

INTRODUCTION

Reading is a complex visual process involving visual and environmental variables [19, 9]. The predominant factors that influence reading performance are luminance [13], uniformity of illumination, contrast of the task [8]. Color of the source and/or the target does not affect performance [10, 11, 5]. Berman et al studied the effect of lighting color temperature and luminance on near visual acuity in children and found that higher the color temperature the better the acuity and that lower the luminance the lower the acuity at higher color temperatures [2].

Reading speed and critical print size at which the subject has the maximum reading speed are usually measured with MNRead acuity charts [17]. Reading performance can be improved in illumination levels of 100-300 lux. Age-Related Macular Degeneration (ARMD – an ocular condition which affects the central part of the retina called macula that aids in fine vision) patients are known to prefer yellow filters to improve their reading speed [5]. The reading rates for normally sighted subjects are greatest for a range of intermediate character sizes ranging from 0.3 degree to two degree. Reading speed declines for characters smaller than 0.13 degrees and characters larger than 4 degrees [1].

Traditional incandescent lamps use high amount of energy to produce standard amounts of indoor lighting and also sodium light is known to cause visual fatigue [3] after sources use progressively less amounts of energy to produce the same amount of light [15]. Since LEDs are low energy but directional sources, the visual performance under these light sources could be different. Our aim was to estimate the efficacy of LED lamp for continuous and/or demanding near vision tasks. Therefore we compared the effect of LED based reading lamp and CFL on various visual tasks and also estimated the visual comfort.

METHODS

The study adhered to the tenets of Declaration of Helsinki and was approved by the institutional review board (IRB). Signed informed consent was obtained from all subjects. All subjects underwent complete optometric and orthoptic evaluations [4]. These included determination of monocular visual acuity (resolving ability) for distant and near targets, refractive error, action of the eye muscles, alignment of the two eyes (phoria status), ability and speed of shifting gaze from distant to near targets (accommodation amplitude and facility), ability of the two eye to work together for near objects (convergence). In addition, their color vision, stereopsis (ability to perceive depth using the two eyes) and basal tear production were tested. Screening for color vision was done using Ishihara pseudo-isochromatic plates, stereopsis using Wirt circles and basal tear production using Schirmer's test II. Only subjects who met our inclusion criteria were included. The inclusion criteria were:

- Age: 13 – 25 years
- Read and write English at 8 grade level
- Best corrected distance visual acuity – equal to or better than 6/6
- Best corrected near visual acuity – equal to or better than N6
- Near point of accommodation as per Hoffstetter's average formula [6, p70]
- Accommodative facility better than or equal to 10 cycles per minute using ±1.75D flippers
- Near point of convergence $\leq$ 10 cm
- Distance and near Phoria as per Morgan's values [14]
- Basal tear production using Schirmer's Test II $\geq$ 10mm
- Stereopsis using Wirt circles - 40 arc sec
- Normal findings in the anterior and posterior segment evaluations

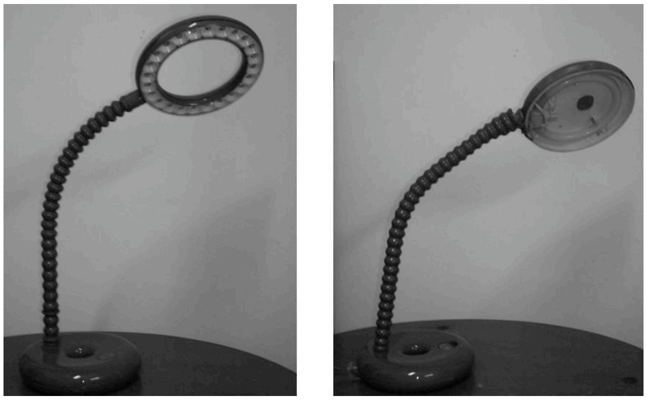
Those who had the following were excluded:

- Severe dry eyes (< 10mm wetting length in Schirmer's test II)

- Overaction/underaction of any extraocular muscle
- Any ocular pathologies/diseases.

Study Lamps:

The LED based lamp consisted of an array of 24 white LED-s spaced equally on the circumference of a circle of diameter 15 cm (Fig 1a). Figure 2 displays the manufacturer supplied power spectrum of the LEDs used in the lamp. The CFL lamp consisted of a single circular CFL source of the same radius (Fig 1b). We were not able to get the power spectrum of the CFL from the manufacturers nor did we have the facility to measure the same. However, spectral power distribution of common fluorescent light sources could be easily found on the internet [20]. Figure 3 shows the primary and secondary task areas as defined in the study. Uniformity index was calculated as the ratio of the illuminance of the light falling at the boundary between the primary and secondary task area and the illuminance at the center of the primary task area.



(a) (b)

Figure 1: (a): The LED based light study lamp; (b): CFL study lamp. For description refer text.

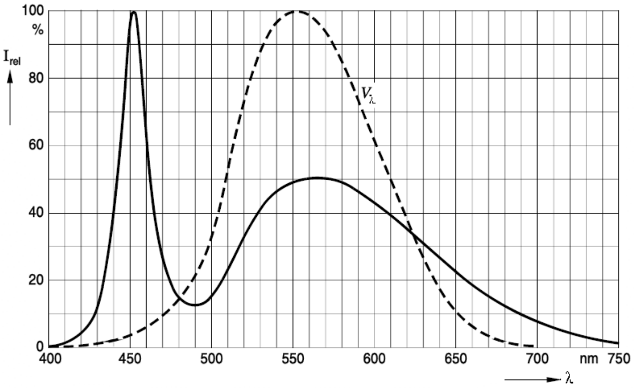


Figure 2: The dark continuous line in the upper figure denotes the relative spectral power distribution of the LED used in the LED based study lamp. The dashed curve denote the human photopic sensitivity function, commonly known as the V(λ) curve. The graph was supplied by the manufacturer of the LEDs.

Study area:

A standard study table and chair was placed in the middle of a windowless room that measured 4.2 m x 4.2 m x 3.1 m. Since all subjects who participated in the study were right handed, the study lamp was placed on the left side of the table so that light from the lamp illuminated the center of the table. The subjects were allowed to adjust the position of the lamp. The subjects were instructed to keep the task materials where the maximum light was falling on the table, i.e., on the primary task area. A video camera focused on the face of the subject was placed without obstructing the light falling on the task area. Two fluorescent lamps fitted on the ceiling directly above the reading table provided illumination of approximately 200 lux on the table.

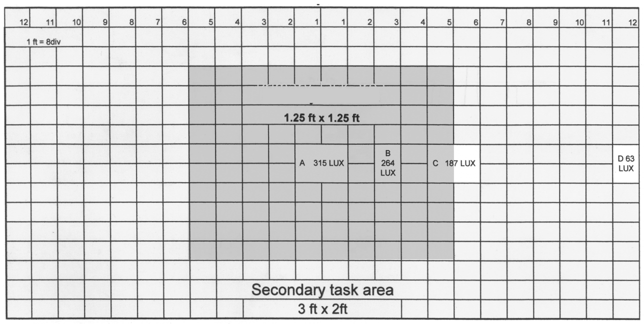


Figure 3: Primary and secondary task areas defined in the study. The shaded portion is the primary task area and the non-shaded portion is the secondary task area. The primary task area measured 1.25 ft x 1.25 ft and the secondary task area measured 3ft (length) x 2 feet (depth). Area outside the secondary task area is known as the tertiary task area and it is not depicted in the figure.

Experiment:

In an attempt to study the interaction of the study light with the environmental lighting, the experiments were done under four different lighting conditions as shown in table 1.

Table 1: Definition of the four conditions used in this study

Condition name*	Room lights	Lamp used
I	On	CFL lamp
II	Off	CFL lamp
III	On	LED lamp
IV	Off	LED lamp

*Conditions II and IV were called "Dark Conditions" since the room lights were off. Similarly, conditions I and III were called "Light Conditions".

During each condition, the same set of experimental procedures was performed. The procedures were done in the following order: (i) ten minutes of adaptation to the lighting condition – the standard and LED lamps were kept on and only the room lights were switched either on or off, (ii) evaluation of basal tear function using Schirmer's strip, (iii) achromatic point estimation using Munsell chips, (iv) Near visual acuity at various contrast levels using a Landolt-C based near vision chart, (v) stereopsis estimation based on Wirt circles, (vi) reading speed measurement using variations of MNREAD chart (which we named SNREAD, to avoid confusion with MNREAD), (vii) reading task for ten minutes, (viii) coloring task for ten minutes, (ix) procedures (ii), (iv) and (v) mentioned above (post-task measurements), and (x) administration of a five-point Likert scale questionnaire. Procedures (vi), (vii) and (viii) (i.e., reading speed measurement with SNREAD charts, reading and paining tasks) were video recorded to extract the reading speed, critical print size and blink rate.

Basal Tear Production:

Basal tear function is a measure of normal production of tears and hence is also a measure of dry eyes. It is usually quantified using Schirmer's test II. This test uses a thin strip of Whatman filter paper #40 called the Schirmer's strip. The Schirmer's strip is 5mm x 35mm in dimension and has graduations along its length at every millimeter. The subject's eye is anesthetized using a single drop of proparacaine 0.5%. The Schirmer's tear strip is inserted into the temporal part of the lower cul-de-sac (the area under the lower eye lid) in both the eyes. The strip remains in the eye for 5 minutes. Due to capillary action, the tear from the eye wets the Schirmer's strip. The wetting length at the end of 5 minutes is noted. If the wetting length is 15 mm or more, the tear production is considered as normal. Wetting lengths less than 10 mm are considered indicative of severe dry eyes. Basal tear production was measured using Schirmer's test II before and after the reading and painting tasks in each condition. The Schirmer's test II is conventionally done only with room lights turned off. But in our experiment it was done under the lighting provided for each condition to study the effect of the light on tear production.

Achromatic Point Estimation:

Achromatic setting was measured using 40 plates of Munsell chips. Achromatic point as defined by Werner et al (1993) is "Typically called the white point, … more accurately called the achromatic point, as it may appear dark gray, light gray or white, depending upon its luminance and surrounding conditions of illumination" [18]. Each plate consisted of 7 chips that varied from one hue to its opponent hue and arranged randomly on the plate. Of the 7 chips, one would be achromatic. The task would be to identify the chip that looks "hueless" or "colourless" or "the chip that is devoid of the hues in the opponent axes of that particular plate". A practice session was given using few randomly chosen plates. The response was recorded in the scoring sheet that accompanies the Munsell chips. Each chip has a score attached to it ranging from -3 to +3 with 0 denoting the achromatic point and values closer to zero denoting chromaticities closer to the achromatic point on that axis. For our experiment, we only noted the number of errors made in the 40 plates irrespective of the direction on error. We did this because we were interested how the different lighting conditions affected this task.

Near Visual Acuity at Various Contrast Levels:

Near vision acuity was measured using a variation of the VALiD kit [16]. To avoid confusion with VALiD kit we called our chart the SVIS chart (Fig 4). The SVIS chart was designed for use at 40 cm. The chart was constructed using the Landolt-C optotypes facing up, down, right and left. The chart contained ten sets of three rows of C-s. Orientations of C-s were randomized using the pseudorandom number generator in Microsoft Excel. Each row contained C-s of various sizes that decreased from 1.0 logMAR to -0.3 logMAR in steps of 0.1 logMAR. Each set of C-s had a fixed contrast value. The contrast decreased from 100% to 4% in steps of 0.15 log units down the chart. The chart was placed in the primary task area such that the light from lamp under consideration fell on the chart. The subject was instructed to speak aloud the orientation of the C from the top-most line. At any contrast level, the acuity will be the smallest size of C that was correctly identified. Each subject was asked to read only one of the three lines at each contrast level. For each contrast level, the visual acuity was thus noted. We use the term visual acuity to mean visual acuity at 100% contrast. For all other contrasts, we mention the contrast value.

Stereopsis:

Stereopsis is the ability to perceive depth using the two eyes together. We measured stereopsis using Wirt circles illuminated by the lighting of the given condition. In this procedure the subject will be asked to wear a polarizing spectacle and asked to view a polarizing sheet. The polarizing sheet contains groups of four circles. In each group one circle will appear to float above the rest at some distance. The subject's task is to point out the floating circle. This distance is given in terms of what is called the retinal disparity measured in arc seconds. Because of the laterality of the two eyes, the image on the retinae of two eyes will be slightly laterally displayed. This is known as retinal disparity [7]. Wirt circles are useful for measuring stereopsis from 800 arc seconds and 40 arc seconds.

Reading Speed Estimation:

Reading speed was calculated using the SNREAD chart. SNREAD is a variation of the MNREAD near vision reading chart that contains eleven lines of continuous text. Each line has 60 characters and the size of the lines decreased down the chart. There are two versions of the chart that are available. We constructed 12 versions of the chart. These charts were called SNREAD chart. The SNREAD charts had the same construction design as the MNREAD chart, but the sentences in these charts were different. The sentences used in these charts were selected from books recommended for 8th grade students. Essentially designed for use at 40 cm, the chart was placed in the primary task area illuminated using the lamp. The same version of the chart was not given to a subject more than once. The subjects were asked to read the chart aloud clearly with minimum mistakes. Video recording of the procedures was started at this point. Reading errors and reading time was calculated from the recording. The lines in the chart vary in size from 4.0M to 0.4M. M notation is a metric measure of the Visual Acuity. Each mm of letter height is set equal to 0.7M. The measurement is done with lower case letters without any ascending or descending limb, such as e, o and c. If the visual acuity is 1M it means that the letter subtends 5 arc minutes at a distance of 1 m.

Reading Task:

The subject was given a reading task for ten minutes. The reading material was kept at their habitual working distance. The subjects were instructed to read at their usual reading speed. The text in the reading material was printed in 8 point Times New Roman font with 1.5 line spacing.

The contents of the reading task varied across experimental conditions. All reading materials had a side box that highlighted the salient point of the material. This highlight was printed in 10 pt Times New Roman.

Colouring Task:

A set of drawings were chosen from a collection of colouring book. One of the investigators coloured a randomly chosen drawing with crayons and the subject was asked to colour another copy of the same drawing with this as the template. The crayon set that was used had totally 36 shades. Hue variations were quite small and not easy to make out. For example, shades in green varied as “Olive green”, “Emerald green”, “Deep green”, “Virdian hue”, “Light green” and “green”. Subjective responses for the shades that were difficult to match were noted. The same crayon set that was used by the investigator to colour the template was given to the subjects for the colouring task too. This was done for ten minutes. If the subject finished the task within ten minutes, a new drawing was given to be completed in the remaining time.

Blink Rate:

Blink rate was calculated from the video recording when the reading and coloring tasks were in progress. The total number of blinks over the period of 20 minutes was determined and from that the number of blinks per minute was calculated.

Questionnaire:

The questionnaire aimed to assess visual discomfort during various tasks. At the end of each experimental condition, a 5-point Likert scale questionnaire was given to the subjects to fill out. This questionnaire had 14 questions six of which dealt with visual comfort (such as glare, eye strain, dry eyes, eye fatigue, eye pain and headache) and the remaining eight were fillers (such as hunger, back ache, anxiety, questions from the text given for reading and painting, etc). From the responses, the visual discomfort score was calculated [3].

Other Procedures:

The order of the conditions was randomized for each subject. Different versions of the same chart were used for different experimental conditions for both reading speed and visual acuity measurements. The contents of the reading task and objects for the coloring task were varied across experimental conditions. Not more than three sessions per day were done for each subject. Minimum of half-hour breaks were given between conditions.

Analysis:

Changes in visual functions in a single condition before and after the reading and painting tasks were analysed. These are variously called “within condition changes” or “pre-post changes” or just “changes”. Differences in these changes across lighting conditions were also analyzed. Unless stated otherwise, all comparisons were done using Wilcoxon signed-rank test. Results were considered significant when $p < 0.05$. All analysis was done using SPSS 15, MATLAB 7.2 and Microsoft Excel.

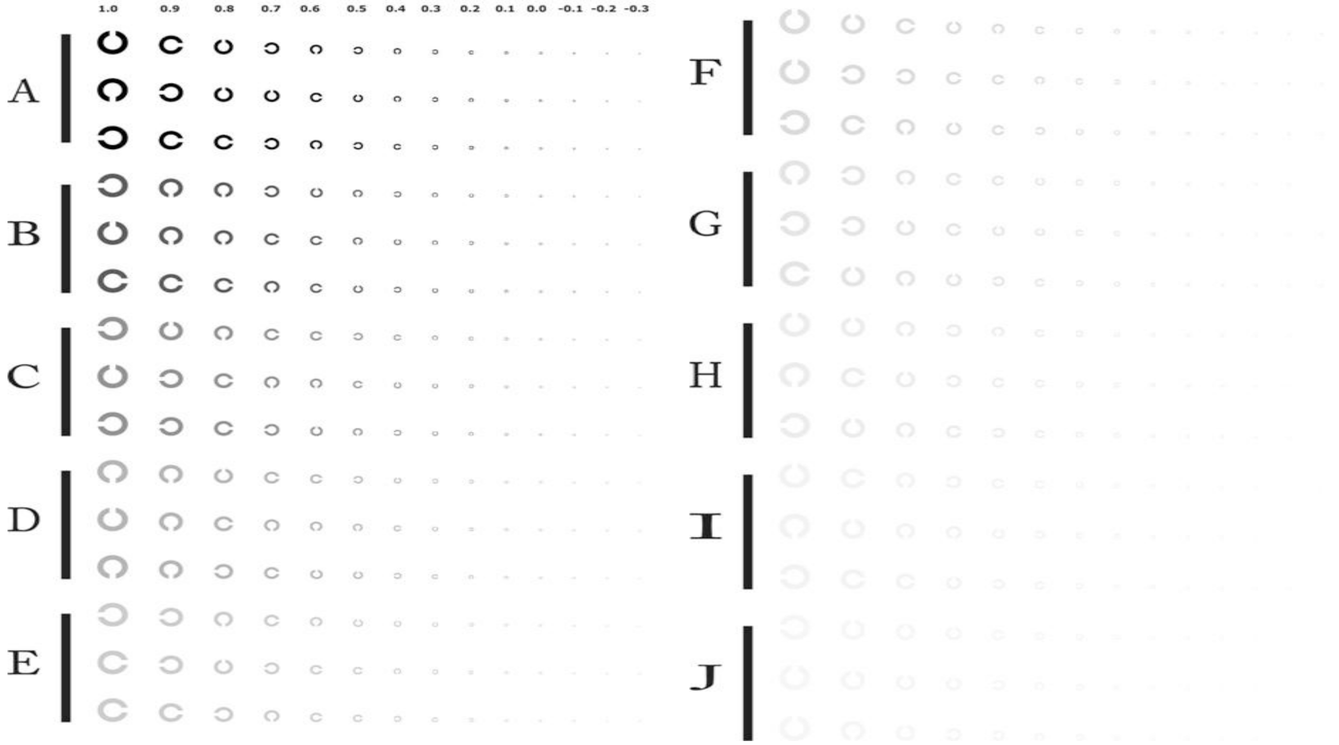


Figure 4: SVIS chart. The contrast varies after every three rows. All the letters in a given triplet have the same contrast. The contrast values were: A-100%; B-71%; C-50%; D-35%; E-25%; F-18%; G-13%; H-9%; I-6%; J-4%. The acuity level varies along the row of every line in every triplet in steps of 0.1 logMAR starting from 1.0 logMAR to -0.3 logMAR. The chart is designed for use at 40 cm reading distance

RESULTS

The illuminance values due to the LED lamp alone in the primary task area for various subjects were around 200 lux and with the CFL lamp the value was around 500 lux. The uniformity index was found to be 0.73 for the LED lamp and 0.50 for the CFL lamp.

Thirty subjects participated in the experiments. The number of subjects, however, for following variables was reduced as given in parenthesis: Visual Discomfort Score (29); Blink Rate (20); Reading Speed (26); Critical Print Size (26). The reduction in numbers was due to either incomplete response or failure of video recording. All subjects were college students, doing their undergraduate or postgraduate studies. The age of the students ranged from 18 to 23.5 years. There were 25 female subjects and 5 male subjects who participated in the study.

Changes Within a Condition:

Basal Tear Production:

The mean changes in tear production in various conditions are shown in fig 5. Clinically, changes in Schirmer's test are said to be significant when the difference between two readings is 5mm or more. In condition I, the change was found to be statistically insignificant (mean change; 0.65 mm; p=0.45). In condition II (mean change = 1.75 mm; p=0.01), III (mean change = 2.13 mm; p=0.01) and IV (mean change = 2.12 mm; p=0.01) though statistically significant changes were found, these changes were clinically insignificant. The maximal mean change was 2.13 mm in the third condition. The median changes in all these four conditions were 0 mm.

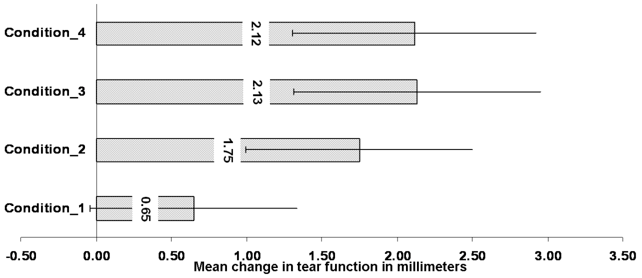


Figure 5: Mean change in basal tear production in the four conditions. The boxes denote the mean values and the lines denote ± 1 std error of means.

Near Visual Acuity at Various Contrast Levels:

The changes in the near visual acuity at various contrast levels for the four conditions are shown in table 2. As can be seen, most changes were statistically insignificant. Only the changes for condition IV (i.e., LED lamp on with the room lights turned off) at contrast values of 13% and 9% were statistically significant. Since there is no a priori reason why only these should be statistically significant changes, we propose that these changes are spurious in nature.

Stereopsis:

All subjects had zero change in stereopsis in all the four conditions and hence we did not do any statistical analysis on this parameter.

Differences Across Conditions:

Comparison of changes in conditions I and III was done to study the behavior of LED lamp as compared to the CFL lamp in a bright environment and between II and IV to study the same in a dark environment. Analysis between conditions I and II was done to understand the effect of the room lighting on the CFL lamp; similarly, comparison of changes in conditions III and IV was done to find the effect of external illumination on the LED lamp.

Table 2: Changes in near visual acuity across four conditions

Contrast (%)	Condition	Mean	Median	p – value
100	I	-0.04	0.00	0.10
	II	0.02	0.00	0.20
	III	0.02	0.00	0.48
	IV	0.03	0.00	0.10
71	I	-0.02	0.00	0.18
	II	0.00	0.00	0.68
	III	0.00	0.00	0.84
	IV	0.00	0.00	1.00
50	I	0.01	0.00	0.43
	II	-0.02	0.00	0.40
	III	0.03	0.00	0.19
	IV	-0.01	0.00	0.55
35	I	0.01	0.00	0.62
	II	0.01	0.00	0.49
	III	-0.01	0.00	0.82
	IV	0.03	0.00	0.13
25	I	0.00	0.00	0.98
	II	0.02	0.00	0.20
	III	-0.01	0.00	0.85
	IV	0.02	0.00	0.51
18	I	0.02	0.00	0.24
	II	0.00	0.00	0.78
	III	0.03	0.00	0.18
	IV	-0.01	0.00	0.78
13	I	0.04	0.00	0.09
	II	0.01	0.00	0.98
	III	0.01	0.00	0.56
	IV	***0.04***	***0.00***	***0.03***
9	I	-0.03	0.05	0.18
	II	0.03	0.00	0.16
	III	0.02	0.00	0.32
	IV	***0.05***	***0.00***	***0.01***
6	I	0.02	0.00	0.51
	II	0.04	0.00	0.07
	III	0.02	0.00	0.30
	IV	0.02	0.00	0.38
4	I	-.06	0.00	0.47

	II	0.02	0.00	0.42
	III	-0.03	0.00	0.22
	IV	0.00	0.00	0.86

Near Visual Acuity at Various Contrast Levels:

The differences in near visual acuity at various contrast levels across conditions are shown in the table 4. As can be seen most differences are statistically insignificant. Significant differences were seen only between conditions I and III at 100 % contrast and between conditions I and II at 9 % contrast. The first difference could be indicative of a real difference in the light provided by the two lamps when the room lights were kept on. However, the difference between conditions I and II at 9% contrasts level has no rationale to be believed. Moreover, the differences were only 0.05 logMAR which is clinically insignificant.

Basal Tear Production:

Differences in changes in tear production across the various conditions were found to be statistically insignificant (table 3). Since the maximal mean change was 2.13 mm in the third condition, these differences across conditions were neither clinically significant. The median difference value was found to be 0 mm for all the four comparisons.

Table 3: Change in basal tear production across conditions.

Conditions compared	Mean Difference (mm)	p-value
I and III	-1.48	0.13
II and IV	-0.37	0.79
I and II	-1.10	0.09
III and IV	0.02	0.57

Stereopsis:

The amount of change in depth perception (stereopsis) in each of the lighting condition is 0 arc seconds. Therefore the amount of change across lighting conditions was of no difference.

Achromatic Point Estimation:

Mean error scores were 3.66 (± 3.85), 3.5 (± 4.14), 5.33 (±5.83), and 5.2 (± 4.77) for conditions I, II, III, and IV respectively. Under the LED lamp, the average error scores were around 5 irrespective of whether the room lights were kept on or off, while it was around 4 for the CFL lamp. Comparison of error values in achromatic point estimation using the Munsell chips across the four conditions are shown in figure 6. None of the differences were found to be statistically significant (p > 0.05 for all the four comparisons). Since there is no standard for clinical usage of achromatic setting we cannot comment about the clinical significance of the differences. However, we surmise that the differences are clinically insignificant since the magnitude of difference is only about 1.5 out of 40 plate which translates to an error rate difference of 3.75%.

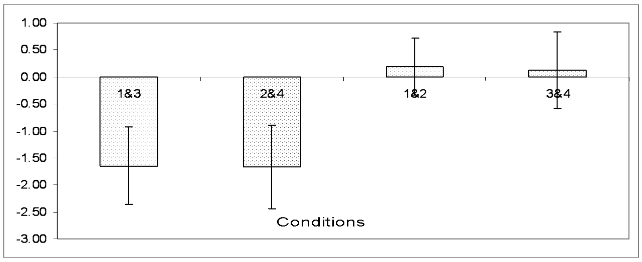


Figure 6: Mean differences in error scores in Munsell colour chips across various conditions.

Table 4: Difference in changes in visual acuity at various contrast levels compared across various conditions

Contrast (%)	**Conditions compared**	**Mean**	**Median**	**p - value**
100	I and III	**-0.05**	**-0.10**	**0.05**
	II and IV	-0.01	0.00	0.39
	I and II	-0.05	-0.05	0.08
	III and IV	-0.01	0.00	0.52
71	I and III	-0.02	0.00	0.39
	II and IV	0.01	0.00	0.70
	I and II	-0.03	0.00	0.22
	III and IV	0.00	0.00	0.71
50	I and III	-0.01	0.00	0.82
	II and IV	-0.01	0.00	0.83
	I and II	0.04	0.00	0.11
	III and IV	0.04	0.00	0.35
35	I and III	0.01	0.00	0.61
	II and IV	-0.02	0.00	0.62
	I and II	-0.01	0.00	0.75
	III and IV	-0.04	0.00	0.18
25	I and III	0.01	0.00	0.88
	II and IV	0.01	0.00	0.92
	I and II	-0.02	0.00	0.48
	III and IV	-0.02	0.00	0.55
18	I and III	-0.01	0.00	0.59
	II and IV	0.00	0.00	0.93
	I and II	0.02	0.00	0.32
	III and IV	0.04	0.00	0.23
13	I and III	0.03	0.00	0.39
	II and IV	-0.03	0.00	0.21
	I and II	0.03	0.00	0.27
	III and IV	-0.03	0.00	0.21
9	I and III	-0.04	0.00	0.09
	II and IV	-0.02	0.00	0.37
	I and II	**-0.05**	**-0.05**	**0.03**
	III and IV	-0.03	0.00	0.26
6	I and III	-0.01	0.00	0.78
	II and IV	0.02	0.00	0.43
	I and II	-0.02	-0.10	0.51
	III and IV	0.00	0.00	0.93
4	I and III	-0.04	0.00	0.74
	II and IV	0.02	0.00	0.64
	I and II	-0.08	0.00	0.35
	III and IV	-0.02	0.00	0.41

Maximum Reading Speed and Critical Print Size:

Maximum reading speed (MRS) measured as number of words correctly read per minute and critical print sizes (CPS – critical print size is one acuity level above the size at which the maximum reading speed was obtained) were estimated using recommended methods. Comparison of these two quantities across the four conditions revealed no statistically significant differences (table 5) except for critical print size when compared between conditions II and IV; even this was only of marginal significance. Both of these conditions are "Dark conditions". We hypothesize that the light provided by the LED lamp was such that better reading performance was obtained with larger print sizes when using CFL lamp. This is justified by the illuminances provided by the two lamps. A plot of reading speed against font size did not come up as an inverted U for all subjects.

Table 5: Maximum Reading speed and critical print size on comparing between various conditions

Conditions compared	MRS difference (wpm)		CPS (logMAR)	
	Mean	p-value	Mean	p-value
I and III	3	0.92	-0.1	0.74
II and IV	-10	0.10	-0.2	0.05
I and II	6	0.33	0.0	0.24
III and IV	-7	0.27	0.1	0.94

Blink rate:

Blink rate was reduced from normal across all condition and had a value of around 5 per minute. None of the comparisons across conditions showed any significant difference.

Visual Discomfort Score:

Visual discomfort score was obtained using Rasch analysis. Different weights were given for each of the visual comfort variable. The response to a given question had values ranging from 0 to 5. For each question, the answer was multiplied by the weight for that question and these were summed to get the total score. Maximum score (14 out of 85) was obtained for condition 3. Most people responded 'no discomfort' for all the tested parameters, namely, fatigue, pain, glare, headache, eyestrain and dryness. Among those who had discomfort, glare was the most common visual discomfort across all conditions. Comparison of visual discomfort score across conditions revealed no significant difference.

LED – CFL Comparison: Pooled Analysis:

Since we did not find substantial differences in the visual performance under the two lamps under the two lighting conditions, we decided to pool date from the two lighting conditions for each of the lamps to see any difference in these two lamps. Statistically significant differences in changes were seen in the visual acuity at 100% contrast using the SVIS chart. Under the CFL lamp, the visual acuity improved by 0.02 logMAR unit and deteriorated by 0.01 logMAR unit under the LED lamp. However, both these values are way too small compared to be of any clinical significance. The only other parameter that showed any statistically significant difference between the two lamps was the achromatic point setting. The mean setting for the CFL lamp was 3.58 and 5.27 for the LED lamp. These translate to an error rate of 8.95% for the CFL lamp and 13.18% for the LED lamp.

DISCUSSION AND CONCLUSION:

Statistically significant change was not seen in most of the visual/ocular parameters tested. Where statistically significant change was seen, the magnitude of change was not clinically significant. Basal tear secretion was statistically significantly reduced in all but the first condition. However, none of these reductions were clinically significant. Blink rate was observed to be subnormal across all conditions. Therefore, the changes that were seen could be not large enough to show statistical significance.

Reading speed could not be taken as a reliable measure since the variation of reading speed with font size did not come up as an inverted U. The critical print size was statistically significantly larger for the LED lamp than for the CFL lamp when the room lights were kept off. The difference was two logMAR sizes which could also be clinically significant. Under the "Light condition", however, the difference was only one logMAR size which was not found to be statistically significant. Our LED lamp provided on average 200 lux at the primary task area while the CFL lamp provided 2.5 times that amount. Therefore, this difference in critical print size could be due to the glare produced by the CFL lamp due to its larger light level. On the other hand, at 100% contrast, in the "Light Condition", (i.e., when the room lights were kept on), the visual acuity change was ½ a line smaller under the CFL lamp than under the LED lamp. This difference in change however is not clinically significant but its statistical significance could be due to the less light level provided by the LED lamp.

Glare was the most commonly complained visual discomfort using both lamps and in both lighting conditions. However, complaint of glare was reported by more number of people when using the CFL Lamp under "Dark Condition" and minimum number of people complained of glare when using LED lamp in the "Light Condition". In both the dark and light conditions, the LED lamp had the least number of complaints with respect to glare. This could be attributed to the low light level provided by the LED lamp.

Pooled data from the dark and light conditions for both the lamps showed expected difference in the change in visual acuity under the two lamps. However, to our surprise, difference in the achromatic setting was also seen. For these visual parameters, the CFL lamp seemed to have fared well. While it is possible that the effect on visual acuity could be explained by the higher illuminance provided by the CFL lamp, we are not in a position to speculate on the reason behind the difference observed in the achromatic setting. Measurement (or the availability) of the colour rendering index of the light sources used in the two lamps could have thrown some light on this issue.

From the results, we find that there is not much of a difference in the effects produced by the LED based study lamp and the CFL lamp on most visual functions, irrespective of whether the room lights were kept on or off. The performance of the subjects in discrimination of various hues, resolution at various levels of contrast, perception of depth across all four lighting conditions was not much affected in any condition.

In conclusion, the two lamps that we used in our experiment did not produce statistically or clinically significant different effects for the most of the visual parameters we studied. The small number of statistically significantly different affect that we observed could possibly be explained by the vast differences in the illuminances provided by the two lamps. Therefore, we speculate that equalising the illuminances could probably have shown some significant differences. In addition, the near vision tasks were done only for 20 minutes. The task and its duration might not have stressed the visual system to bring out the differences in the effect the two lamps had.

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Using Core Sunlighting to Improve Office Illumination

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ABSTRACT

Today's lighting industry is challenged to deliver high quality illumination while using less electrical energy and, to achieve this, it is generally agreed that it is useful to incorporate daylighting techniques. We present a new system that is capable of delivering sunlight deep into the core of multi-floor buildings. This is the first direct sunlighting system that has the potential for sufficiently low net lifecycle costs to enable widespread implementation. While the energy savings are important, the impact of sunlight on the visual environment is perhaps even more important, given possible effects on health and well-being. A demonstration of this core sunlighting system has been installed in an existing building located at the British Columbia Institute of Technology in Burnaby, Canada. The demonstration shows a substantial reduction in the electrical lighting load and enables an evaluation of the spectral quality of the sunlight illumination from the perspective of the occupants.

Keywords

Illumination, daylighting, energy efficiency, light guides

INTRODUCTION

We have developed a sunlighting collection and distribution system to deliver sunlight to the core, or interior regions, of multi-floor office buildings, in order to substantially reduce the need for electric lighting and improve the quality of the illumination [11, 12]. This system has the potential to reduce energy for standard commercial building lighting by at least 25%, replace electric lighting 75% of the time each day that the sun shines within six core daylight hours, reduce peak electrical power demand when it is needed (i.e. midday on clear, sunny days) and provide high quality illumination with excellent colour rendering properties. The recognized value of core daylighting is not new [2, 4, 14, 17], and some recent systems using optical fibers have been under development [8, 16]. However, the cost-effectiveness and performance (in terms of expenditure rate per delivered lumen) of these systems has not been established. As a result, this is the first sunlighting system with potential for widespread adoption.

SYSTEM DESIGN

The sunlighting system combines two structures, one for collecting sunlight and another for distributing it within the building.

Collecting the sunlight

The sunlight collection system shown in Fig. 1 is housed inside an enclosure that extends along the south-facing facade, above the windows and adjacent to the plenum space. The enclosure protects the components from wind, precipitation and dirt, enabling the use of relatively inexpensive and lightweight materials and eliminating the need for regular maintenance.

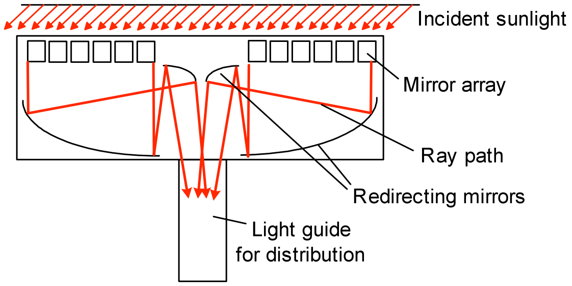

Fig. 1. Design of the sunlight collection module

The key feature of the collection system is an array of thin, approximately square mirrors that move to track the motion of the sun across the sky. The mirrors reflect the sunlight directly toward the building so that it can efficiently be concentrated throughout most the day, in order to enter the interior light guide system and thus illuminate the building interior. They are interconnected so that they can be reoriented in unison using only two simple, inexpensive motors. To achieve this motion, low cost universal joints positioned in the centre of the top and bottom mirrors in each column allow the mirrors to rotate easily about two axes to adjust to the changing altitude and azimuth of the sun, but prevent neighbouring columns from interfering with one another. The mirrors in a single column are attached by wires in each of the four corners, as shown in Fig. 2, and two mirror arrays, each consisting of 35 mirrors, are enclosed within each 3 meter wide collection module.

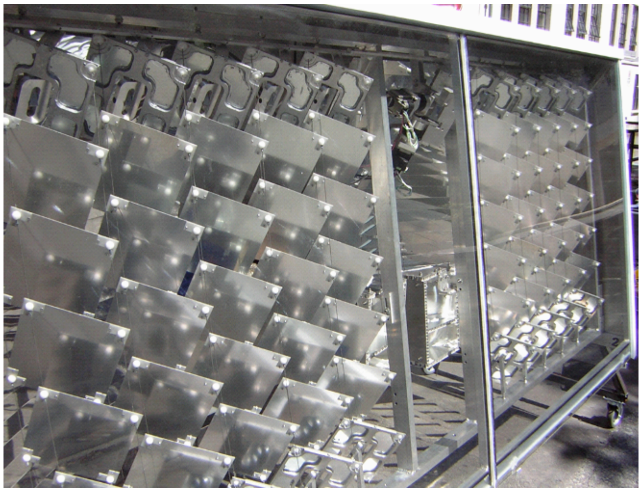

Fig. 2. The collection system includes an array of small computer-controlled tracking mirrors.

As with any moving system, it is important to consider the lifetime of the device. Since moving parts are commonplace in many devices, such as automobiles, elevators and computers, moving components are generally designed to run, maintenance-free and often unprotected from environmental elements, at a rate of many cycles per second for at least hundreds of thousand of cycles. In contrast, the mirror array in this system is protected from the weather and dirt by the exterior canopy, and it need only move at a rate of one cycle per day. As a result, the lifetime reliability requirements are greatly reduced. An accelerated-aging test of a prototype unit has demonstrated performance that far exceeds the typical 30-year requirement for building installations.

The demonstration devices use machined metal components, but they have been designed in such a way that they can be fabricated in plastic using standard injection molding processes. These processes will require a capital investment in tooling, but will result in the inexpensive components that are required for a commercially-viable device.

Following its reflection from the mirror array, the sunlight is concentrated and recollimated by off-axis paraboloidal mirrors and then directed into the building through a small window.

Distributing the sunlight

The concentrated and still partially collimated sunbeam is directed through the small window and into light distribution structures housed within the ceiling cavity. These specially-designed interior light guides are integrated with dimmable electric lamps. Sensors monitor the illumination to supplement the sunlight as required [13]. In the demonstration project, the prototype fixtures were integrated into the existing t-bar drop-ceiling configuration. For simplicity, a rectangular cross-section, as shown in Fig. 3, was chosen in order to be compatible with the existing ceiling configuration, but this approach could be readily adapted to other luminaire designs, including discrete fixtures, direct/indirect luminaires or other suspended fixtures.

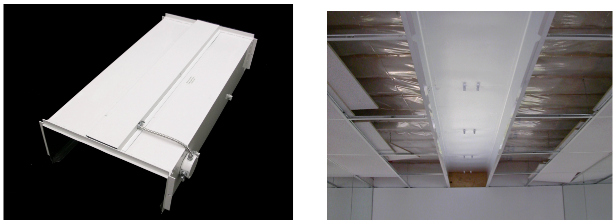

Fig. 3. (a) Single light guide section and (b) modules installed in the ceiling

DEMONSTRATION SYSTEM

The first demonstration of this core sunlighting system has been installed in an existing building located at the British Columbia Institute of Technology in Burnaby, Canada. This building, constructed in the 1980's, is representative of a substantial fraction of the existing commercial building stock, so it showcases the potential of the technology to substantially reduce the electrical lighting in existing buildings as well as new construction, and consequently reduce greenhouse gas emissions. The demonstration shows a substantial reduction in the electrical lighting load and enables an evaluation of the spectral quality of the sunlight illumination from the perspective of the occupants.

For this demonstration, half of the existing building canopy on the third floor was removed in order to install five collection modules, as shown in Fig. 4.

Fig. 4. Collection modules installed at BCIT's

For ease of installation, four of the collector modules, three of which are shown in Fig. 5, redirect sunlight through the existing topmost windows, which previously were not used for view but rather to passively introduce daylight into the room. Only one new window needed to be installed in the building as the aperture for the fifth module, since the existing windows did not extend to the far end of the building. In all installations, the window will meet typical structural and fire safety standards and in practice it can be readily designed into a new building or added as part of a retrofit project. In the case of this project, a double-glazed low iron window with an anti-reflective coating was selected.

Fig. 5. Collectors concentrate the sunlight into light guides for distribution within the building.

The initial design is the same as a recessed luminaire, with a rectangular cross-section. Although this is not the only possible design, these fixtures can be directly mounted in the place of the standard recessed troffer fixture that is common in many office buildings. The fluorescent lamps are installed within the light guide at specific locations to ensure that an even distribution of electric lighting is provided. In this configuration, only the light emitting portion is visible to the occupants in the room; it has been designed to appear like a standard fluorescent fixture, including a diffuser panel that covers the prismatic film.

Fig. 6. The original prismatic troffers were replaced with dual-function light guides.

For simplicity, a rectangular cross-section was chosen for this design since it is compatible with the standard 0.61 m by 1.22 m (2 ft by 4 ft) t-bar drop-ceiling configuration, as shown in Fig. 6. The guide has a depth of 0.25 m, which is about twice that of a standard fixture, but as will be explained in the integration section, there is sufficient space within the ceiling cavity in this building to easily accommodate the thicker profile.

In addition to providing core sunlight, this system, when mounted above the windows on each, provides shade for the windows at high sun elevation, as illustrated by the building profile in Fig. 7. This shading feature reduces the direct solar heating within the building, which commensurately reduces the required air conditioning load, resulting in additional significant energy savings.

Fig. 7. The canopies also provide shade for the windows below, reducing glare and air conditioning cost.

The shading feature also further improves the quality of the interior illumination by substantially reducing the discomfort glare caused by the direct light penetrating sideways into the room through the windows. The result is a workspace with bright, comfortable and pleasant illumination at all times, and requires no electrical lighting whenever direct sunshine is available.

In this demonstration, the canopies were installed in this manner both for ease of installation and to take advantage of the shading feature provided by the exterior canopy. In other installations, depending on the architecture of the building, it may be desirable to integrate the canopies into the building so that they are not visible from the exterior. This architectural flexibility enables the system to be used in many existing buildings as well as new construction, as will be demonstrated in subsequent installations.

The installation of an additional five modules is currently underway to complete the demonstration on the third floor. Although this demonstration installation will only occupy a single floor, the technology has been developed to provide sunlight to all floors of a multistory building, by mounting the modules adjacent to the plenum space on each floor.

EVALUATING THE SYSTEM PERFORMANCE

A preliminary assessment of the resulting electrical energy savings as well as the spectral characteristics and colour rendering properties of the illumination has been completed.

Performance of the electric lighting system

The interior space is largely an open-plan office space with individual workspaces and one interior meeting room that does not have access to the windows. The layout of the light guides ensured that the light is uniformly distributed and the aesthetics suit the size and shape of the rooms.

Originally, 31 1x4 prismatic troffers with 2/34 Watt T8 lamps delivered 44 lumens per watt (lpw) at desk height. In the new installation, 43 hybrid luminaires with 2/T5 28 Watt lamps and dimming ballasts, operating at 60%, yield a net efficacy of 56 lpw when no sun is available. The colour temperature of the lamps was selected to be 4100 K, which is consistent with common illumination trends in North America. These lamps [9] have specified to have a colour rendering index (CRI) value of 85.

Performance of the sunlighting system

The light guides distribute up to 65,000 lumens of sunlight over a distance of 12 m, and illuminance levels provided by the guided sunlight are well above typical standards of 500 lux. Based on the average annual local sunshine probability, it is anticipated that this demonstration system will enable the electric lights to be turned off at least 25% of the time. This 25% displacement by sunlight increases the average net effective efficacy of the lighting system, in terms of the ratio of work plane lumens to average "wall watt" to 74 lumens per watt. (Although fluorescent lamps have been used in this demonstration project, it is worth nothing that higher efficacy sources, such as light emitting diodes, can be used in the same system as soon as they become a cost-effective alternative.)

Fig. 8 shows the measured illuminance distribution provided by the guided sunlight, as measured on a horizontal plane 0.8 m above the floor in one of the rooms in the demonstration space, with the electric lights completed turned off. The results show that the illuminance is greater than the required 500 lx everywhere in the room, except for the extreme rear corners. The illuminance is highest near the windows, since sunlight enters through the window in this region, as well as via the overhead light guide.

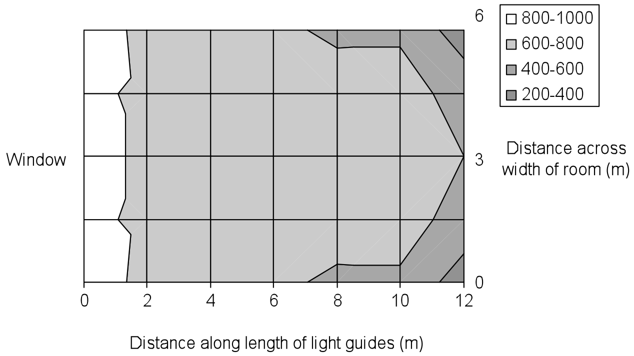

Fig. 8. Illuminance distribution measured in the room

These illuminance measurements were taken under clear sky conditions, with direct sunlight incident on the collection modules. The overall illuminance levels vary somewhat depending on the time of day and year; these measurements are representative of the average illuminance levels achieved in sunny conditions. On overcast days, the diffuse sunlight incident on the collection module does provide a small amount of interior illumination via the light guides, achieving average illuminance levels of 30 lux. This low level of illumination is adequate for occupants to see their surroundings and one another, for example for emergency egress, but it is not adequate for activities such as reading, so supplemental electric light is required on overcast days.

The efficiency of the core sunlighting system is a result of the use of the highly reflective material lining the interior surfaces of the light guide. Without this high reflectance, over the entire visible spectrum, it would not be possible to guide the light deep within the building since it would instead by absorbed as it was transported only a short distance.

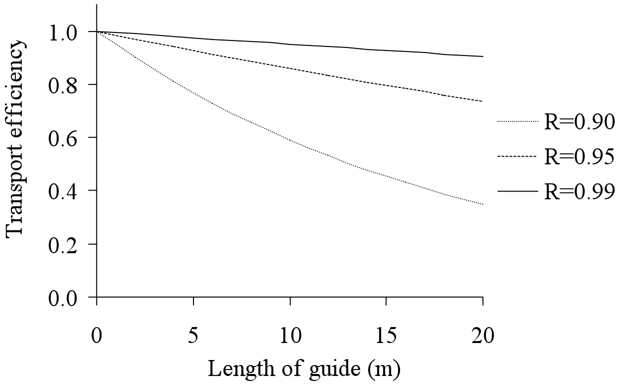

Fig. 9. The transmission efficiency of the light guide depends on the reflectance of the interior surfaces.

In the guides used in the demonstration project, the sunlight interacts with the inner surface of the guide roughly once during each 2m section of the guide. (This distance between reflections is estimated from the roughly 8° collimation half angle of the guided sunlight, and the 0.25 m minimum guide dimension.) Based on this estimate, Fig. 9 illustrates the efficiency with which light is transported down the guide, for different reflectance values.

It is apparent that the reflectance of the surface is the dominant factor in determining the guide efficiency; 90% reflective aluminum sheeting is unacceptable since it causes 60% of the light to be lost after 20 m, compared to only a 10% loss along the same distance for a 99% reflective material. Until recently, there was no cost-effective way to achieve this high reflectance, but the availability of a suitable highly reflective material now makes this a practical solution.

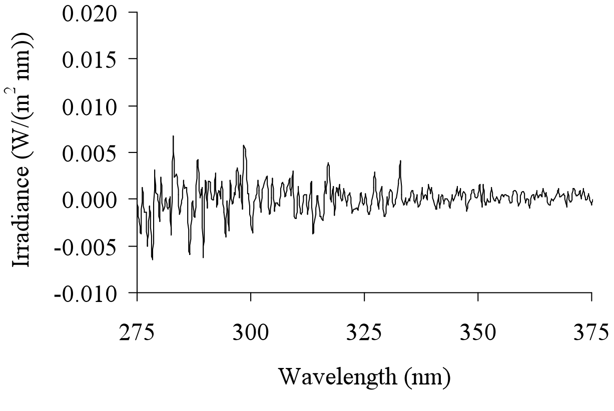

Fig. 10. Irradiance measurements inside the light guide

In addition to the efficiency, the spectral characteristics of the light in the workspace were evaluated in detail. First, a UV spectrometer was used to measure the irradiance within the light guide, next to the light guide aperture from the canopy and through a short pass filter, to establish the degree to which ultraviolet light is transported into the building. As the graph in Fig. 10 shows, the irradiance for wavelengths less than 375 nm shows only statistically insignificant noise, meaning that essentially all of the ultraviolet light is absorbed by the front UV-absorbing front window of the canopy enclosure and does not enter the guide.

The spectral distribution of the light emitted by the guide was then evaluated in the visible band using a spectrophotometer. Fig. 11 shows that the relative intensity of the light as a function of wavelength for the light emitted at the start and the end of the guide (1m and 11m, respectively, from the collector aperture). A comparison of the two sunlight distributions shows that there is a very small amount of absorption of light toward the blue end of the spectrum, but the distribution is largely preserved along the guide. Importantly, the longer reddish wavelengths are efficiently transported along the guide, and these wavelengths are especially important for yielding high quality colour rendering for familiar surfaces, including human complexion. This is a consequence of the continuity and uniformity of the natural black-body emission provided by the sun.

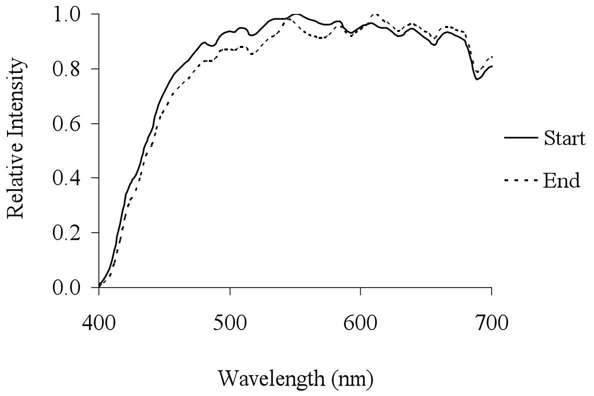

Fig. 11. Spectral distribution of the light emitted from the light guide

Using these spectral distributions and a software program provided by the CIE [3], the value of the colour rendering index (CRI) was determined for each. The CRI for sunlight measured outside the building, at the start of the light guide and at the end of the light guide was calculated to be between 95 and 100, as would be expected for an approximately black-body source. The measurements after light had traveled 12m to the end of the guides showed that the high colour rendering quality was retained..

The correlated colour temperature (CCT) of the unfiltered sunlight was measured to be 5002 K, whereas the CCT was measured to be 4700 K at the start of the guide and 4437 K at the end. While this was a measurable difference, the change in the CCT was not perceptible to occupants in the room. If it were desirable to do so, however, a small amount of filter material within the guide could be used to make the colour temperature more uniform.

These spectral measurements confirmed that the sunlight emitted from the light guide is full-spectrum, natural sunlight along the entire length of the guide and therefore provides a high colour rendering quality throughout the workspace.

Comparison to optical fibers

As mentioned briefly in the introduction, there has been substantial interest in using solid core optical fibers to guide sunlight from a collector module into the building. Optical fibers have the tremendous advantage that they are flexible and therefore can be relatively easily routed through the ceiling cavity to avoid HVAC ducts and other services, in order to provide light where it is needed. However, there are a number of fundamental disadvantages that make optical fibers an impractical method for transporting sunlight deep into buildings.

First, in order to minimize the cost of the fiber, it is desirable to use as small a diameter fiber as possible, to minimize the material cost. However, the smaller the fiber, the more concentrated the sunlight must be, which substantially increases the required precision, complexity, and, ultimately, the cost, of the collector module.

Second, to reduce cost and increase flexibility, a single solid core plastic fiber is generally proposed for this application rather than a bundle of glass fibres, such as those used in the telecommunications industry. Solid core plastic fibers generally include additives that increase their flexible and durability, but at the expense of optical clarity. It is illustrative to compare this transmission efficiency for a hollow light guide to that of a comparable length of optical fiber. The attenuation of light per meter of optical fiber typically ranges from 3% to 10%. These attenuation values result in unacceptably low transport efficiencies for long fiber lengths, as illustrated by the graph in Fig. 12.

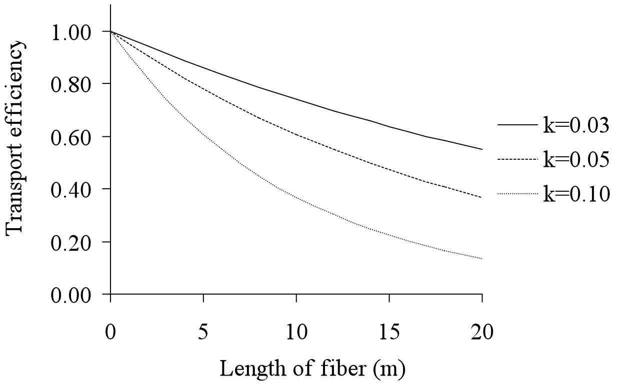

Fig. 12. The transmission efficiency of optical fibers with different attenuation constants.

Even for the most optically clear fibers, the transmission efficiency is considerably less than that of a hollow light guide lined with a highly reflective material. The high concentration factor also poses a fire hazard within the building, if the appropriate (and costly) precautions are not taken to safely transport and distribute the radiation.

Finally, the spectral quality of the transported light in a plastic optical fiber is undesirable, since the absorption is highly wavelength dependent. Fig. 13 shows the spectral transmission of one particular type of fiber [10]. This means that although the light entering the fiber has the natural spectrum of sunlight, by the time it has traveled into the core regions within a building, the light emitted from the end of the fiber no longer has a natural distribution. Rather, it has a noticeable greenish hue and as a result does not provide the high colour rendering that is the appeal of illumination by natural sunlight.

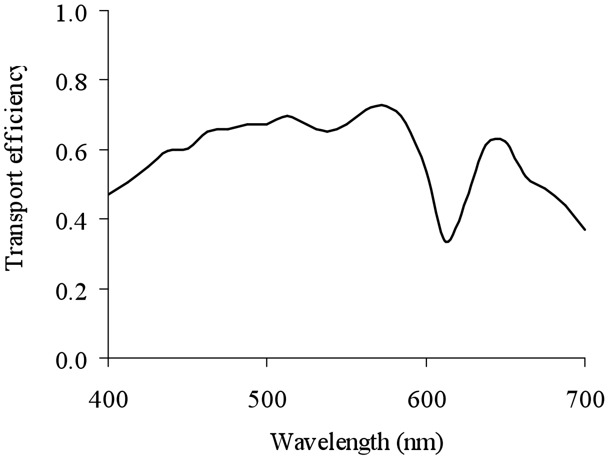

Fig. 13. The transport efficiency of 10 m of optical fiber shows that it preferentially absorbs red light.

While advances in plastics engineering may help to overcome these limitations, at the moment optical fibers do not appear to be a practical method for transporting sunlight deep within a building.

EXPERIENCING SUNLIGHT INDOORS

In addition to its cost-effectiveness advantage, the core sunlighting system demonstrated at BCIT is unique in its ability to deliver concentrated and collimated sunlight, essentially a bright sunbeam, deep within each floor of a building. With the new core sunlighting system operating, the workspace, including the interior meeting room shown in Fig. 14, is entirely illuminated by sunlight whenever direct sunshine is available between roughly three hours before and three hours after noon (true local time).

There are a number of factors associated with the system that can be adjusted based on occupant preference. For example, in the demonstration installation, there is a perceptible shift in colour temperature, depending on whether the dual-function light guide emits sunlight (CCT~4500 K) or fluorescent light (CCT~4100 K). If it is desirable to match the colour temperatures for both sources, this could be achieved by either using so-called "daylight" fluorescent lamps or alternately by filtering the transmitted sunlight at the collector aperture to slightly lower the CCT, albeit with a slight decrease in the overall system efficiency.

Similarly, the current control algorithm allows for a slight and temporary decrease in the illumination level when a cloud passes in front of the sun, before the fluorescent lights are fully powered to compensate for the decreased sunlight. This results in a gentle adjustment of the illumination level at certain times. While these fluctuations in brightness and colour are perceptible, thus far occupants have not found them to be unpleasant or disturbing. On the contrary, many have found that it gives them a desirable feeling of contact with the outdoors and the changing exterior lighting conditions, especially when they do not have access to a window and would otherwise be completely cut off from the outdoors.

Fig. 14. The guide delivers sunlight into a windowless conference room.

The resulting psychological impact of this increased contact with the outdoors combined with the high colour rendering illumination may prove to be significant in terms of the perceived value of core sunlighting in buildings. Some experts feel that the productivity and human factors value of daylighting systems increase their value far beyond the raw energy savings alone [1, 15, 7, 6, 5]. As a result, the unique appeal of sunlight in the visual environment is likely to encourage early adoption of core sunlighting systems before they are able to be cost-effective solely in terms of their energy savings. While such human factors studies are well outside the scope of this paper, the demonstration at BCIT provides an opportunity for more extensive analyses in this area. The results of these human factors studies will be presented in subsequent publications on this work.

CONCLUSION

As a result of the demonstration system, the workspace, including an interior windowless meeting room, is entirely illuminated by sunlight for about six hours during the workday, whenever direct sunshine is available. The demonstration also shows that the system can integrate readily into standard architectural designs for new commercial buildings and retrofit opportunities. This initial demonstration shows the potential for the technology to be cost-effective through energy savings and this economic viability is critical to widespread adoption of any sustainable technology. A detailed study of feedback from the building occupants regarding the quality of the visual environment is currently underway. The evaluation and analysis of both the energy savings and the lighting quality will be ongoing for several years to enable an accurate assessment that is independent of unusual weather patterns.

ACKNOWLEDGMENTS

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Effects of Dynamic Lighting on Office Workers: First-year Results of a Longitudinal Field Study

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ABSTRACT

Dynamic lighting is designed to have positive effects on wellbeing and performance. In a field experiment we tested whether these effects are detectable and stable over time when employed in actual work settings. This 2-year study consists of two tranches, one following a monthly alternating experimental design, the other a yearly alternating one. This paper reports on the first tranche. In a fully counterbalanced design, office workers experienced dynamic or static lighting according to an a-b-a scheme over 3 consecutive periods (N=142, 90, and 83). Questionnaire data suggest no significant differences for need for recovery, vitality, alertness, headache and eyestrain, mental health, sleep quality, or subjective performance, although employees were more satisfied with dynamic lighting. Yet it is too early to discard the hypotheses and claims made about dynamic lighting altogether. Its effects may still emerge in environments with limited daylight, over a longer time period, or when more pronounced or differently shaped lighting patterns are applied.

Keywords

Dynamic Lighting, Wellbeing, Health, Performance

INTRODUCTION

Office work isn't all it's cracked up to be. Although not always physically challenging, having to deal with heaps of paperwork, incessantly incoming emails, and the constant buzz of phones, office humour, and printers rattling does take its toll on one's mental resources. On a more serious note, stress and attention fatigue are all too common in the office, so any environmental or ambient feature that holds the potential to revive office workers or help them recuperate from stress or fatigue throughout the day deserves our attention. In the current study we explore lighting as a potential environmental feature impacting office workers' wellbeing.

Artificial office lighting typically is constant in both intensity and colour temperature, whereas natural light varies throughout the day as a result of weather conditions and the position of the sun. Begemann, Van den Beld and Tenner [1] showed that peoples' preferences for artificial lighting vary with weather conditions and time of the day. Recent research has indicated that new lighting solutions may actually have an impact on biological and psychological processes.

Dynamic lighting is one of these innovative solutions, in which lighting characteristics such as colour temperature and intensity vary during the day according to a preset protocol. This should have a positive effect on users' wellbeing, health and performance. The rationale behind dynamic office lighting is that it supports the natural rhythm of employees' alertness [2]. An exemplary protocol – also applied in the present study – is presented in Figure 1. It is based on the idea that it stimulates workers during the (work) day by exposing them to a high lighting level and colour temperature in the morning and after lunchtime, and creating a relaxing environment with lower and warmer white light during the late morning and afternoon.

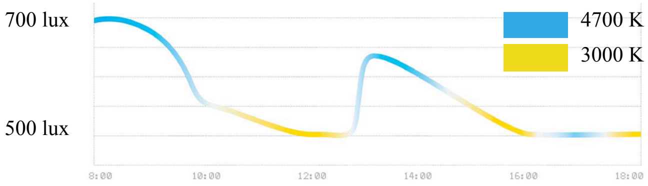

Figure 1. Protocol Philips dynamic lighting, source [2].

Light can influence the regulation of the biological clock, and the secretion of hormones such as melatonin and cortisol. During daytime the secretion of melatonin is low and therefore the influence of light on its suppression minimal [3]. Research has shown that the level of cortisol increases when exposed to high lighting levels in the morning, but not in the afternoon [3,4] or evening [5]. These biological effects are dependent on the colour temperature, lighting level, duration and timing of exposure, as well as on the size and position of the light source [2,6,7,8] and probably have an influence on individuals' wellbeing, health and performance [9].

Light also has a direct effect on people's alertness and sleepiness [2], apart from its indirect effect via the biological clock. Research into the psychological effects of lighting suggests that both a high intensity and a high colour temperature can have positive effects on people's wellbeing, health and performance. For instance Fleischer, Krueger and Schierz [10] showed that exposure to higher colour temperature lighting (5600K) is more stimulating than warm white lighting (3000K). Participants did indicate that they experienced the warm white lighting as more pleasant. Some smaller studies also showed an activating effect of a higher colour temperature (6500-7500K) compared to 3000 K lighting [11,12]. Other studies, however, failed to demonstrate comparable effects (see e.g. [13,14]), so overall the literature is still inconclusive. Employing more extreme lighting conditions, Viola and colleagues [15] found an effect of high colour temperature (17000K) on workers' ability to concentrate, level of fatigue, alertness, daytime sleepiness and subjective performance compared to a lower colour temperature (2900K). Lastly, Mills et al. [16] found comparable effects of colour temperature on wellbeing and performance of employees in a call centre. Yet the range of colour temperatures used in the current study is substantially lower.

Aries [17] reported an inverse correlation between lighting level and employees' level of fatigue and sleep quality. In an earlier experiment by Grünberger and colleagues [18], participants were exposed to either a high lighting level (2500 lux) or a lower lighting level (500 lux) for four hours between 9.00am and 5.00pm. The results showed that the higher lighting level had a positive effect on participants' alertness, their ability to concentrate, the number of errors they made on a performance test, and their mood compared to lower intensity lighting. Other studies also showed positive effects of a high lighting level on people's wellbeing and performance [e.g., 3, 19, 20]. It should be noted that in most of these studies the difference in lighting level between the high and low intensity lighting condition was large (>2000 lux).

Practically all of the rigorous scientific research into the biological and psychological effects of high intensity or high colour temperature office lighting was performed in laboratories, where participants are exposed to – sometimes extreme – lighting conditions for only short periods of time – typically several hours. Studies into the effects of dynamic lighting are scarce both in the field and in the lab and often involve only limited numbers of participants. User evaluation in realised projects shows anecdotal proof for increased wellbeing and performance amongst office employees (e.g., Interpolis and Trigion in the Netherlands, VUB bank in Slovakia). Whether these effects are detectable and whether they are stable over time when actually employed in the work setting has not been thoroughly investigated to date.

The present paper will report on intermediate results of the first large-scale field test into the effects of dynamic lighting for office workers. The longitudinal study follows an experimental design in two tranches, in which four groups of about 100 to 200 employees each are alternately exposed to dynamic and static lighting. In one tranche, which we are reporting on here, lighting conditions change on a monthly basis during winter months, counterbalanced over two groups. In the second tranche the lighting conditions remain stable during winter, dynamic for one group, static for the other. Then during summer both groups switch to the alternate condition. The advantage of this design is that we can both explore the relatively short and long-term effects of dynamic lighting compared to constant lighting. In addition, we can compare the two lighting conditions both between and within groups. In this paper, we describe the results of data gathered during the first winter for the two short-term groups (see Smolders & de Kort [21] for preliminary results of the second tranche).

METHOD

Design

The current study is a field experiment, with Lighting condition (dynamic vs. static) within, and Group (A vs. B) between groups, and three consecutive measurement periods (d-s-d and s-d-s scheme respectively, in January, February and March[1]). In other words, two groups of participants were exposed to dynamic or static lighting, alternating on a monthly basis and counterbalanced between groups. In the dynamic lighting condition, employees experienced a gradually changing lighting scenario with a higher lighting level (700 lux) and colour temperature (4700 K) in the morning and after lunchtime (see Fig1). The static condition had a 500 lux level of 3000K lighting.

The study was performed in a recently renovated high-rise office building, with a large daylight contribution (see Figure 2), in which a flex-working concept is applied. Daylight-dependent control was applied in both conditions. Investigation of the weather in first, second and third measurement period – weekdays of the two weeks before and one week during the survey – showed that during January there were more sun hours than in February and March (approximately 60, 35 and 40 respectively) [22].

Participants

In the first month of the field study, a questionnaire was distributed among 414 office employees from 7 departments, of which 147 were completed and returned (response rate: 35.5%). The data of five participants were removed because they indicated that they were only rarely at their workplace in the high-rise office building, that they were ill during the measurement period, or that they filled out the questionnaire at home. Of the remaining 142 participants (83 in the static and 59 in the dynamic condition), 111 were male and 31 female (mean age 45, SD = 10.23, range: 23 to 65).

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[1] In the original design there were four measurement periods and the lighting condition would change three times. Due to technical problems, the study was delayed and it was not possible to have four measurement periods.

Figure 2. Picture of indoor environment

In the second measurement period, the questionnaire was again distributed and 96 employees (43 in the static and 47 in the dynamic condition) filled out the questionnaire completely (response rate: 23.2%). The data of six participants were removed because they indicated that they were only rarely at their workplace in the office or that they had filled out the questionnaire at home. Of the remaining 90 participants, 67 were male and 23 female with a mean age of 48 (SD = 9.73, range: 25 to 63).

In the third measurement period, 84 employees (42 in the static and 41 in the dynamic condition) completed the questionnaire (response rate: 20.3%). One participant filled out the questionnaire at home and his data was removed from the dataset. Of the remaining 83 participants, 68 were male and 15 female (mean age 48, SD = 9.45, range: 25 to 65).

Measures

The questionnaire consisted of measures for need for recovery (i.e., the need to recuperate from attention fatigue and stress), vitality, alertness, headache and eyestrain, mental health, sleep quality, and subjective performance. Subjective evaluations of lighting conditions were also assessed. In addition, attitudes towards the job and work environment and personal characteristics were included as control variables. Objective measures such as days of sick leave and coffee consumption were collected on department level to corroborate subjective findings.

Need for Recovery

Need for recovery was measured with a behaviour-based scale consisting of 34 items[2] describing behaviours at office employees' discretion to recover from mental strain, psychological distress, motivational deficits, and/or mental fatigue [23], combined with 11 evaluative statements by Van Veldhoven and Broersen [24]. Some items had 5-point response scales ranging from (1) 'never' to (5) 'very often' or from (1) 'never' to (5) 'at least once a day'. Other restorative activities had dichotomous response scales with either (1) 'It happens never or rarely' and (2) 'It happens sometimes or often' as response options, or with (1) 'yes' and (2) 'no' options. The evaluative statements are dichotomous items with (1) 'yes' and (2) 'no' as response options. Separation reliability of the scale was .83 in each consecutive month. The separation reliability matches with a classical definition of reliability; it represents the ratio between the true and estimated variance of people's recovery needs [25]. The reliability score of this scale thus indicates that scale's internal consistency is satisfactory.

Mental health and vitality

Mental health and vitality were assessed with two subscales from the Dutch version of the SF-36 Health Survey (RAND-36) [26]. The mental health subscale consists of 5 items, such as 'Have you been a very nervous person?' and had an internal consistency between α = .75 and α = .81. The vitality subscale consists of 4 items (e.g. 'Did you have a lot of energy?') with Cronbach's alpha between α = .76 and α = .87. The response options of both subscales ranged from (1) never to (5) very often.

Headache and Eyestrain

Headache and eyestrain were measured with 8 items adopted from Viola et al. [15], which describe symptoms, such as 'headache' and 'eye fatigue', with response options ranging from (1) 'absent' to (4) 'severe'. The scale had an internal reliability ranging from α = .84 to α = .89.

Alertness and sleep quality

Alertness was assessed with the Karolinska Sleepiness Scale [27] with 'today' instead of 'at this moment' as time frame. The response options ranged from (1) 'extremely alert' to (9) 'extremely sleepy - fighting sleep'. Sleep quality was measured with the Pittsburgh Sleep Quality Index [28] consisting of 18 items concerning subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, sleeping medication and daytime dysfunction. The scale has an internal consistency between α = .61 and α = .70.

Subjective performance

Subjective performance was measured with the question 'On a scale from 0 to 10, how would you rate your performance on the days you worked during the last 2 weeks?' derived from the World Health Organization Health and Work Performance Questionnaire (WHO-HPQ).

Subjective evaluations

Subjective evaluations of lighting conditions concern pleasantness of the lighting, experienced lighting level, experienced disturbances of the artificial lighting and of daylight, and satisfaction with the lighting. Pleasantness of the lighting was measured with two semantic differential adjective items (pleasant – unpleasant, comfortable - uncomfortable). These items were internally consistent

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[2] The original scale consists of 35 items. The item "I take care of plants in the office" was dropped due to a lack of variance as it was not allowed to have plants in this office.

with Cronbach's alpha ranging from α = .79 to α = .90. Experienced lighting level was measured with three items about lighting level (artificial light and daylight) on the workplace, on the screen and in the office space from Hellinga and de Bruin-Hordijk [29]. The response scale ranged from (1) 'too little light' to (5) 'too much light' and the scale was internally consistent with alphas ranging from α = .72 to α = .84. Experienced disturbance of the artificial lighting was assessed with two items adopted from Hellinga and de Bruin-Hordijk [29]. The 5-point response scale ranged from (1) 'never' to (5) 'very often' and these items had an internal consistency of alpha ranging from α = .75 to α = .91. Experienced disturbance of daylight was measured with similar items. This scale was internally consistent with alpha ranging from α = .69 to α = .77. Satisfaction with the lighting was assessed with the question: 'How satisfied are you with the lighting at your workplace?' with response options ranging from (1) 'very dissatisfied' to (5) 'very satisfied'.

Job and work-related evaluations

Job-related questions concern evaluation of the work atmosphere, job satisfaction, commitment to the company, work diversity, decision authority and job demands. To assess work atmosphere, four evaluative statements were employed, such as 'The work atmosphere is good.' The response scale was a 5-point scale from (1) 'never' to (5) 'very often'. The internal consistency of the four statements ranged from α = .81 to α = .83. Three dichotomous (yes/no) statements were employed to assess job satisfaction ('I am satisfied with my job'), commitment to the company ('I feel committed to the company') and work diversity ('my work is diverse'), respectively. Decision authority and job demands were measured with two subscales of the Job Content Questionnaire [30]. Decision authority was assessed with three statements, such as 'I have freedom to make decisions about my job'. The subscale is internally consistent with alpha ranging from α = .64 to α = .69. Job demands were measured with four statements, such as 'My job requires I work fast'. This subscale had an internal consistency of alpha between α = .68 and α = .76. Both subscales had a 4-point response scale ranging from (1) 'totally disagree' to (4) 'totally agree'.

Work-condition related questions concerned the impression of the office environment, pleasantness of the indoor climate and satisfaction with the indoor climate. Impression of the office environment was assessed with nine adjectives, such as 'pleasant', 'orderly' and 'quiet' from Aries et al. [17]. The unipolar response options ranged from (1) 'not at all to' (5) 'extremely'. The internal consistency of the 9 adjectives ranged from α = .78 to α = .91. Pleasantness of the indoor climate was measured with two semantic differential adjective items (pleasant – unpleasant, comfortable - uncomfortable). This scale was internally consistent with alpha ranging from α = .84 to α = .92. To assess satisfaction with the indoor climate two items concerning satisfaction with the temperature and ventilation at the workplace were employed with response options ranging from (1) 'very dissatisfied' to (5) 'very satisfied'. This scale was internally consistent with alpha between α = .73 and α = .77.

Personal characteristics

Questions regarding personal characteristics concerned gender, age, light sensitivity, and mean number of working hours per week. Light sensitivity was measured with the items 'How much trouble do your eyes give when you are exposed to bright light?' and 'How much do you suffer from headaches when you are exposed to bright light?' on a 5-point scale from (1) 'not at all' to (5) 'extremely'. The reliability of this scale ranged from α = .73 to α = .78.

Procedure

In January, the lighting condition was dynamic for half of the participants (group A) and static for the others (group B). In the third week of this first month, all potential participants received an e-mail with a hyperlink to the questionnaire. A reminder was sent one week later. It took about 15 minutes to fill in the questionnaire. A Living Colors lamp from Philips was raffled every measurement period as an incentive for participants to complete the questionnaire. In February, the lighting condition was switched from dynamic to static and vice versa. In March, the lighting condition was again switched to the same lighting condition as in January. During the second and third measurement periods, the same procedure as in January was used.

RESULTS

To investigate the effect of lighting condition (dynamic vs. static lighting) on employees' well-being, health and performance, Linear Mixed Model analyses were performed on need for recovery, vitality, mental health, alertness, headache and eyestrain, sleep quality and subjective performance (separately), with Lighting condition and Month as fixed factors and participant number as random factor. Light sensitivity, impression of the office and work atmosphere were included as covariates[3].

The results showed that there was no significant effect of Lighting condition on need for recovery, vitality, mental health, alertness, headache and eyestrain, global sleep quality and subjective performance (all F<1, except alertness, F=1.31, NS). In Table 1, the F-statistics for Condition and Month are shown. Table 2 shows the estimated means for all dependent variables in both the static and the dynamic condition.

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[3] We first assessed the Pearson's correlations between potentially confounding variables and dependent variables and added only those covariates that had significant correlations with the dependent measures for wellbeing, health and performance.

Table 1. Results linear Mixed Model analyses: F-statistics for Wellbeing, health and performance measures.

	Need for recovery		Vitality		Mental Health		headache & eyestrain		Alertness		sleep quality		Subjective performance	
	F	df	F	df	F	df	F	df	F	df	F	df	F	df
Lighting condition	.06	(1,167)	.08	(1,190)	.01	(1,179)	.01	(1,193)	1.31	(1,202)	.63	(1,151)	.35	(1,210)
Month	13.27**	(2,153)	.34	(2,169)	2.56†	(2,154)	.45	(2,172)	1.01	(2,180)	2.81†	(2,135)	1.19	(2,190)

* p < .05, ** p < .01 and † p < .10

Table 2. Estimated marginal means of wellbeing, health and performance measures.

	Dynamic		Static	
	M	*SD*	*M*	*SD*
Need for recovery	-0.76	0.05	-0.77	0.05
Vitality	3.59	0.04	3.58	0.04
Mental Health	4.10	0.03	4.10	0.03
Headache and eyestrain	1.53	0.03	1.53	0.03
Alertness	3.74	0.12	3.59	0.11
Sleep quality	4.98	0.18	4.84	0.17
Subjective performance	7.42	0.06	7.46	0.06

The factor Month did show an effect on need for recovery [F(2,153.0) = 13.27; p < .01]. Pair-wise comparisons indicated that workers' recovery needs were lower in January (M = -.95; SD = .77) than in February (M = -.64; SD = .71) and March (M = -.78; SD = .76) with p < .01 for both contrasts. There was no difference in recovery needs between February and March (p = .16). The effects of Month on remaining dependent variables did not reach significance.

We also performed Linear Mixed Model analyses with scales probing the subjective evaluation of the lighting as dependent variable, Lighting condition and Month as fixed factors, participant number as random factor, and light sensitivity, impression of the office environment and work atmosphere as covariates. The results of these analyses showed that Lighting condition had a significant effect on satisfaction with the lighting [F(1,211.5) = 5.16; p < .05]. Office workers were more satisfied with the lighting in the dynamic lighting condition (M = 3.69 and SD = .87) than in the static condition (M = 3.53 and SD = .91). In addition, Lighting condition had a significant effect on the experienced disturbances of artificial lighting [F(1,196.3) = 4.44; p < .05]. Unexpectedly, workers reported fewer disturbances of artificial lighting in the static condition (M = 1.71 and SD = .72) than in the dynamic lighting condition (M = 1.80 and SD = .78). Note that disturbances were measured on a 5-point scale, thus office employees in both conditions, on average never (1) or rarely (2) experienced disturbances of the artificial lighting. There was no significant effect of Lighting condition on experienced disturbances of daylight [F<1, NS]. In addition, the Lighting condition had no significant effect on the evaluation of pleasantness of the lighting [F>1, NS]. The effect of Lighting condition on experienced lighting level approached significance [F(1,247.2) = 3.01; p = .08]: indicating a trend for employees to evaluate the lighting as brighter in the dynamic lighting condition (M = 3.06 and SD = .48) than in the static condition (M = 2.98 and SD = .52). Table 3 reports the F-statistics for Lighting condition and Month concerning the subjective evaluation of the lighting; Table 4 reports the mean scores on all subscales for both experimental conditions.

Month had a significant effect on disturbances of daylight [F(2, 192.0) = 4.98; p < .01]. Pair-wise comparisons indicated that workers experienced more disturbances of daylight in January (M = 2.69; SD = .91) than in February (M = 2.54; SD = .91) and March (M = 2.52; SD = .82) with p < .05 for both contrasts. There was no significant difference between February and March concerning disturbances of daylight (p = .55).

Table 3. Results of Linear Mixed Model analyses: F-statistics of subjective evaluation of the lighting condition.

	Pleasantness lighting		Satisfaction lighting		Lighting level		Disturbances daylight		Disturbances lighting	
	F	df	F	df	F	df	F	df	F	df
Lighting condition	1.87	(1,242)	5.16*	(1,211)	3.01†	(1,247)	.93	(1,215)	4.44*	(1,196)
Month	1.09	(2,220)	.21	(2,192)	2.28	(2,223)	4.98**	(2,192)	1.31	(2,178)

* p < .05, ** p < .01 and † p < .10

Table 4. Estimated marginal means of subjective evaluations of lighting conditions.

	Dynamic		Static	
	M	*SD*	*M*	*SD*
Pleasantness lighting	3.66	0.06	3.55	0.06
Satisfaction lighting	3.73	0.07	3.57	0.06
Lighting level	3.06	0.04	2.97	0.04
Disturbance daylight	2.64	0.07	2.56	0.07
Disturbance lighting	1.82	0.06	1.69	0.06

DISCUSSION

We are investigating the effect of dynamic lighting compared to static lighting on workers' wellbeing, health and subjective performance in a longitudinal field study. In this paper, the results of the linear mixed model analyses on the data of the short-term groups are reported (first tranche). The results showed no significant difference in workers' need for recovery, vitality, sleep quality, mental health, headache and eyestrain, or subjective performance between the dynamic and static lighting condition, controlled for relevant personal, job and work-related characteristics.

Interestingly, in spite of us not finding the beneficial effects that were hypothesized, workers in the dynamic lighting condition did report being more satisfied with the lighting condition, although at the same time they reported more disturbances from the lighting than did workers in the static lighting condition.

Need for recovery showed a significant effect of month of measurement, with employees reporting a lower need in January than in February and March. A lower need for recovery indicates a lesser degree of attention fatigue and stress. This is in line with weather reports, indicating more hours of sun on the workdays during the measurement period in January than in February and March, but may also be related to the fact that most employees had taken time off in December on account of the holidays. The higher number of disturbances of daylight in January may also be explained by the fact that there were more hours of sun in the first measurement period than in the other two.

The question we now need to address is what conclusions could or should be drawn from these data. For this we must consider not only the data, but also the methodology. We had hoped to conduct the study in four consecutive months, running four full-month measuring periods. Yet instead we saw ourselves compelled to cut one period and shorten the remaining periods from four to three weeks. This unfortunately is the reality of doing field studies. However we did manage to uphold a sound experimental design. Also, considering the fact that in the questionnaires participants were always asked to reflect on the last two weeks, the procedure still worked well in the three-times-three-week period compromise that resulted.

Furthermore, we employed a range of measurements, none of which showed significant beneficial effects of dynamic lighting. All scales repeatedly showed good reliability and had been successfully used in earlier studies and although response rates were only modest, participant samples were still large enough to enable testing of these effects. Yet in spite of the robust design, methodology and procedure, we were not able to establish beneficial effects of dynamic lighting when compared to static lighting.

On the other hand, a few considerations caution us to not discard the potential of dynamic lighting just yet. First, a possible reason for the lack of expected findings is the substantial daylight contribution in the renovated building of our study, especially in combination with the daylight responsive lighting control. Dynamic lighting is said to be most effective in situations with low daylight contribution [31], so the building in this study – even if the study was performed during the darker months of the year - may not have been the best candidate for studying the effects of artificial lighting. Moreover, the dynamic pattern of the lighting itself my have attenuated the findings. As was already reflected in the introduction, there as yet exists only little research on dynamic lighting. The pattern employed in the current study employs fairly subtle changes, both in intensity and colour temperature, especially in comparison to changes outdoors, or manipulations applied in laboratory-based studies (e.g. [3,15,16,18,19,20]). These design choices have been based on state-of-the-art insights into human alertness curves, yet we are still far from fully understanding light's effects on humans' psychological and physiological states. The exact height of colour temperature and intensity of the lighting, the exact timing and shape of the curve and the range of wavelengths employed are all still under investigation.

We conclude that in the first tranche of this longitudinal research we have not been able to establish beneficial effects of dynamic lighting on individuals' need for recovery, vitality, sleep quality, mental health, headache and eyestrain, or subjective performance, although office workers did report higher satisfaction with dynamic than static lighting. Yet it is too early to discard the hypotheses and claims made about dynamic lighting altogether. Its effects may well emerge in more long-term applications, environments with limited daylight contribution, or when more pronounced, or differently shaped curves are applied in terms of intensity and/or colour temperature.

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Persuasive Lighting:
The Influence of Feedback through Lighting on Energy Conservation Behavior

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ABSTRACT

Earlier research has investigated persuasive technology: Technology designed to influence human behavior or attitudes. The current research investigates lighting as persuasive technology. In an experimental study, participants could conserve energy while carrying out tasks and received feedback about their energy consumption in each task. We tested the effect of feedback through a lamp that gradually changed color dependent on energy consumption and compared these effects to more widely used factual feedback. Results indicated that feedback through lighting has stronger persuasive effects than factual feedback. Furthermore, factual feedback seemed more difficult to process than lighting feedback, because cognitive load interfered with processing factual feedback, but not with processing lighting feedback. Implications for theory and design of persuasive lighting, and (ambient) persuasive technology are discussed.

Keywords

Lighting feedback, factual feedback, interactive feedback, energy consumption behavior, ambient persuasive technology

INTRODUCTION

The threats of growing CO2-emissions and climate change effects and the exhaustion of natural resources have urged nations worldwide to seek for substantial reductions in energy consumption. Next to important technological solutions like more efficient systems and devices and the development of renewable energy sources, consumer behavior plays a crucial role in bringing down the level of energy consumption.

Influencing consumer behavior to promote energy conservation has become an important target of national and international policy efforts. Thereby, the question which instruments should be applied to promote energy conservation behavior has become highly relevant.

Recent reviews [e.g., 2, 15] have evaluated the effects of interventions to promote energy efficient behavior. In general, mass media public campaigns seem to lack precision in targeting and message concreteness to achieve behavioral change. By contrast, raising people's awareness of energy consumption by providing tailored feedback about their energy consumption (for example in kWh) can promote the achievement of behavioral change [see, e.g., 2, 15]. The results are mixed though. Weak linkages between specific actions and energy outcomes caused by low feedback frequencies (e.g. once per month) and insufficient specificity of the feedback (e.g. household in general vs. specific person or specific devices) are underlying these mixed findings.

Recently, technological solutions have created new opportunities to improve feedback efficacy by embedding feedback in user-system interactions. That is, energy use is in essence always the outcome of an interaction between a user and some energy-consuming device. Intervening in these specific interactions might improve the quality of feedback substantially. Some evidence supports this claim. McCalley and Midden [14] demonstrated in several studies that interactive forms of feedback could be effective in enhancing energy-efficient use of devices like washing machines. By adding an energy meter to the user interface of a washing machine they achieved 18% of energy conservation both in lab and field studies. Basically, their approach entailed giving factual feedback in terms of kWh consumed as a function of programming choices made by the user, like water temperature, spinning speed or the duration of the washing cycle.

However, in many day-to-day situations people might not be motivated or lack the cognitive capacity to consciously process relatively complex information [see e.g. 5]. Factual feedback (e.g., the numbers representing kWh consumption) might be that kind of relatively complex information. In the current research, we will investigate the persuasive effects of a form of feedback that is easier to process. We argue that (interactive) feedback using lighting is simpler to process than (interactive) factual feedback because it can directly express evaluative meaning whereas factual feedback still needs to be processed and evaluated by the user. For example, red lighting might be defined as meaning "high energy consumption", which does not need to be evaluated further, whereas factual feedback that 120 kWh was used does. Also, feedback through (diffused) lighting can be perceived easily without focusing, in contrast to factual feedback. For example, (part of) the environment of the user can be used for lighting feedback, whereas the user needs to focus on factual feedback (e.g., in the form of numbers).

In addition, we argue that lighting has specific qualities that make it particularly suitable for providing user feedback. For example, lighting can be very cheap, is easy to install, lighting can be very energy friendly, lighting can be seen by other people present in a room as well (inducing social pressure as a persuasive mechanism), and lighting might have an emotional appeal or even direct emotional effects. Also, the low conspicuity of light and color changes sets lighting apart from other feedback mechanisms. Furthermore, lighting can be calm (in the sense of 'calm computing'). Other feedback mechanisms often lack these characteristics. For example, feedback mechanisms like factual feedback or feedback that uses sound, smell, or tactile feedback cannot easily be calm in that sense. Therefore, we argue that lighting can be particularly suited as a persuasive agent.

Earlier research indicates that energy consumption feedback that does not consists of specific facts, but rather of lighting changes can influence consumer behavior [see 7, 23, 3, 9, 20, 18, see also 17]. For example, in the eighties of the previous century Becker and Seligman [6] investigated the effectiveness of a light that went on "in a highly visible part of the home" whenever the air conditioner was on, but the outside temperature was 20°C or lower. In homes that contained the signaling device, an average of 15% savings in energy consumption was found. More recently, a device called an energy orb was used that changed color dependent on the time-of-use tariff in operation. This type of information helped users save some energy [12] and the usefulness of the device was positively evaluated by users [20, 12].

The current research will investigate the effects of feedback through lighting on energy consumption and compare them to the effects of factual feedback. The feedback (lighting feedback and factual feedback) that we will investigate in this research will be of a highly interactive nature. Earlier research of lighting feedback has already employed feedback that contained elements of interactivity (e.g., in Becker & Seligman's research [6]). For example, Becker and Seligman's participants received feedback about their action, although not in direct response to those actions. In the current research, participants will receive feedback about consequences of an action in direct response to that action. More specifically, the current research will give users lighting feedback about their current energy consumption in a specific task, and this lighting feedback will change directly when they use more or less energy. Furthermore, the current research will investigate the assumption that lighting feedback is easier to process than factual feedback.

The Current Research

In the present study, we examine whether interactive feedback through lighting can stimulate energy conservation behavior. That is, we will use lighting color as feedback to indicate the absolute level of energy consumption (more green = lower energy consumption, vs. more red = higher energy consumption). We set up an experiment in which participants had the opportunity to conserve energy in a series of tasks and received feedback about their energy consumption during these tasks. We tested the effect of lighting feedback and compared these effects to more widely used factual feedback. More specifically, we compared the effects of lighting feedback using lighting color to indicate energy consumption, to the effects of factual feedback using a number to indicate energy consumption in Watts. When giving lighting feedback, low consumption was indicated by completely green lighting and high consumption by completely red lighting. So, people can quite easily understand whether a specific lighting (e.g. light-green) indicates high or low consumption. However, when factual feedback would consist of only one number (representing energy consumption in Watts), it would be a lot more difficult to know whether that number indicates high or low consumption. Therefore, when giving factual feedback, next to the number indicating the current energy consumption level, two additional numbers were presented indicating low and high consumption. Thereby the amount of information present in lighting feedback and factual feedback is comparable.

As argued above, we expect that feedback through lighting has stronger persuasive effects (leading to lower energy consumption) than factual feedback. In addition, we expected that lighting feedback would be easier to process. To test this, we manipulated cognitive load: Half of the participants performed an additional task. We expected that for participants processing *factual* feedback, performing this additional task would interfere with the persuasive effects of that feedback, leading to more energy consumption than without the additional task. At the same time, we expect that for participants processing *lighting* feedback, performing this additional task would not interfere with the persuasive effects of that feedback, leading to the same energy consumption as without the additional task. Also, we expected that for participants processing factual feedback, performing this additional task would lead to slower processing of that feedback, while for participants processing lighting feedback, performing this additional task would not lead to slower processing of that feedback.

METHOD

Participants and Design

Fifty-seven participants (39 men and 18 women) were randomly assigned to one of the four cells of a 2 (feedback type: lighting feedback versus factual feedback) x 2 (cognitive load: load vs. no load) experimental design. All participants were student at Eindhoven University of Technology, were recruited on campus to participate in a study on ‘How to program a heating thermostat’, and received € 5 for a participation of 30 minutes.

Procedure and Materials

Upon arrival, participants were seated in front of a computer. For all participants, a simulated programmable thermostat panel was presented on the computer screen (see Figure 1). This heating thermostat was modeled to look like a commercially available heating thermostat. It contained a virtual LCD display (with a background that was always green) on which all relevant information and clickable buttons were presented. For participants in the lighting feedback condition, a computer-controlled power-led lamp was positioned behind the participants' desk that reflected its lighting on the wall behind the desk (see Figure 2). For participants in the factual feedback condition, next to this thermostat panel we presented a number indicating the participant’s energy consumption in Watts, and also two numbers indicating low and high consumption levels in Watts.

Figure 1 -- The simulated programmable thermostat panel

More specifically, for each of the ten scenarios (described below) we calculated a low consumption score in Watts (based on a setting of 17°C in relevant rooms) and a high consumption score in Watts (based on a setting of 26°C in all rooms). In the lighting feedback condition, these numbers were used to determine the lighting color. That is, when a participant’s energy consumption caused by his or her setting of the thermostat were at the low consumption level or lower, the lamp was given a completely saturated green color, and when energy consumption was at the high level or higher, the lamp was given a completely saturated red color. When a participant’s thermostat settings lead to an energy consumption in between the low level and the high level, the light the lamp emitted was set to a color between green (indicating low consumption) and white (indicating consumption of a medium level, halfway between low and high) or a color between white and red (indicating high consumption).

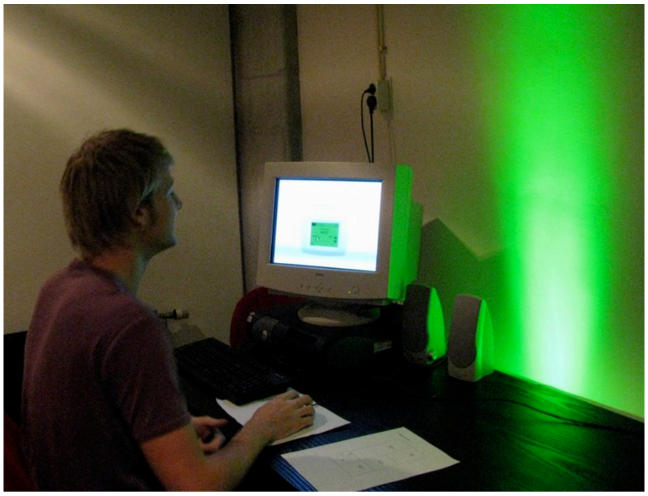

Figure 2 – Feedback through lighting on the wall behind the monitor

After general introductions, participants were asked to program the programmable thermostat in ten different tasks. Also, all participants were given two specific goals to strive for while programming the thermostat. First, they were instructed to strive for optimal comfort levels within each specific task. More specifically, they were asked to “program the programmable thermostat such that your house would be comfortable to live in.”[1] Second, participants were instructed to use as little energy as possible. That is, they were told that heating your house costs energy (fuel) and diminishing the level of the temperature settings for specific rooms would lead to lower energy consumptions. We included the first goal to motivate participants to use energy (to heat the house to comfortable levels). Had we only included the second goal, all participants might have chosen to use as little energy as possible by simply not turning the heating on at all, and any feedback about energy consumption would have been irrelevant.

Next, the thermostat and the energy consumption feedback (factual or ambient) it provided were explained. In each task, participants were instructed to program the thermostat for a different scenario. For this, we used 10 different, short scenario descriptions (e.g., “It is evening and you are having a party at home tonight”, “It is night and you are going to bed. It is -10°C outside”, “On a Sunday afternoon you are at home and outside temperature is 18°C”). In each

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[1] As in real-life programming of programmable heating thermostats, participants did not experience physical effects of changes (e.g., changes in heat) during the programming tasks. So, participants had to judge the comfort level corresponding to their settings of the thermostat based on earlier experiences and their current settings.

task, one of the ten scenarios was displayed above the programmable thermostat panel. Scenarios were drawn randomly from the set of ten and each scenario was used only once. Participants received feedback after each change of settings, until they pressed the "ready" button. For each task, we registered the energy consumption corresponding to the final setting, and the total amount of time a participant used for that task.

Participants in the cognitive load conditions performed an additional task while setting the thermostat. This task was comparable to cognitive load tasks used in earlier research (e.g., [22]). Participants heard numbers (one to thirty) read out aloud on headphones. As a manipulation check, we registered the number of correct responses (pressing the space bar after an odd number). Finally, participants were debriefed and thanked for their participation.

RESULTS

Averaged energy consumption scores (over the 10 tasks) were submitted to a 2 (feedback type: lighting feedback versus factual feedback) x 2 (cognitive load: load vs. no load) ANOVA. As expected, participants who had received feedback through lighting used a lower amount of energy on average on the tasks (*M* = 544 Watt, *SD* = 208) than participants who received factual feedback (*M* = 692 Watt, *SD* = 202), *F*(1,53) = 7.16, *p* = .01 (see Figure 3). This analysis did not indicate the expected interaction of Feedback Type X Cognitive Load, *F* < 1. Also, this analysis did not show a main effect of cognitive load, *F* < 1.

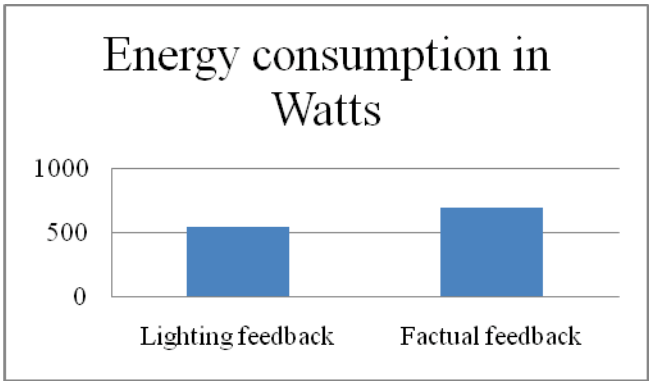

Figure 3 – Energy consumption by type of feedback

However, the manipulation check of the cognitive load task indicated that approximately half of the participants in the cognitive load conditions had not performed the load task in line with instructions (had pressed the space bar for less than 10% of odd numbers). Therefore, to assess whether the effect of feedback type on energy consumption was qualified by cognitive load (indicated by an interaction of feedback type x cognitive load), we submitted the average energy consumption scores of the remaining participants (14 in the load conditions, of whom 7 received lighting feedback and 7 received factual feedback, and 29 in the no load conditions, of whom 15 received lighting feedback and 14 received factual feedback) to an identical 2 (feedback type: lighting feedback versus factual feedback) x 2 (cognitive load: load vs. no load) ANOVA. This analysis showed results completely comparable to the previous one: a main effect of feedback type, *F*(1, 39) = 4.63, *p* < .05, but no interaction of feedback type and cognitive load nor a main effect of cognitive load, both *F*'s < 1.

Finally, to assess whether lighting feedback would be easier to process, we analyzed the time it took these remaining participants to program the thermostat. This dependent variable was calculated by averaging the times they needed on each of the 10 tasks. This analysis showed the expected interaction of Feedback Type X Cognitive Load, *F*(1,39) = 7.20, *p* = .011 (see Figure 4). Further analyses indicated that participants who received factual feedback needed more time to program the thermostat under cognitive load (*M* = 55.0 seconds, *SD* = 15.1) than without cognitive load (*M* = 38.7 seconds, *SD* = 7.0), *F*(1, 40) = 6.02, p = .019, whereas this difference was not found for participants who received lighting feedback, *F*<1. In general, programming the thermostat using lighting feedback was faster (*M* = 39.3 seconds, *SD* = 8.0) than when using factual feedback (*M* = 44.1 seconds, *SD* = 12.7), *F*(1,41) = 9.24, *p* < .01.

Finally, we also explored the effect of cognitive load on energy consumption scores, but found no significant results of cognitive load, all *F*'s<1.

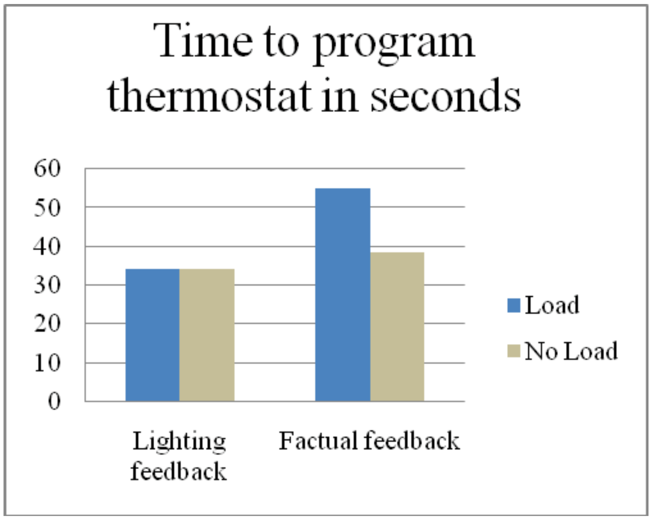

Figure 4 – Time to program thermostat by type of feedback and cognitive load

DISCUSSION

Results indicated that participants who received feedback through lighting used less energy in thermostat programming tasks than participants who received factual feedback. Thereby, the current research suggests that lighting feedback can have stronger persuasive effects than factual feedback (approximately 27%). Also, the current results suggest that for participants processing factual feedback, doing an additional task led to slower processing of that feedback. For participants processing lighting feedback, results suggest that adding cognitive load did not lead to slower processing. This finding fits our suggestion that lighting feedback is more easy to process and use in goal-striving processes than factual feedback.

In contrast to expectations, the current results did not show evidence for effects of cognitive load on energy consumption, or of different effects of cognitive load on energy consumption for participants who received lighting feedback compared to those who received factual feedback. An important reason for this might be that the setup of the current study may not have been ideal for finding such an effect because of the lack of time constraints when setting the thermostat. That is, because there were no time constraints, participants who received factual feedback and who performed an additional task, may have been able to use more time to set the thermostat (and did so, as indicated by the analysis of response times). It seems quite straightforward that these participants used this additional time to process the factual feedback. Thereby these participants may have processed the factual feedback well, even though they also had to spend processing capacity on the additional task. Future research might continue the investigation of whether cognitive load can increase energy consumption for factual feedback. Importantly, the current results indicate that setting time constraints might be important to find those effects.

Another possibility is that cognitive load could exert an effect on energy consumption even without time constraints, especially in a goal-setting paradigm, since it leaves less cognitive capacity for considering the various goals (i.e., ‘comfort’ and ‘energy saving’). Cognitive load might make people forget secondary goals (‘energy saving’ would often be considered secondary), or process additional cues (e.g., light feedback) in a more peripheral rather than central way. Interestingly, both paths would have implications for the most optimal design of feedback cues, and future research could investigate both pathways.

Future research might also investigate using other forms of cognitive load. That is, because the current cognitive load task contained numerical elements (as participants had to identify odd numbers in a spoken list of numbers), it could have interfered especially with processing the factual feedback because that also consisted of numbers (indicating energy consumption). Therefore, cognitive load may not have been equal in both cognitive load conditions. That said, we argue that the numbers in the current load task were only of secondary importance, as the main task participants had to do was to identify specific element in an array of elements (and these could just as easily have been arrays of letters, in which participants would have to identify consonants). In line with this argument, theories that account for effects of information processing demands generally do not identify different effects of processing demands caused by different types of information (for an overview, see [16]). So, these theories would not predict fundamentally different mental load effects of a cognitive load task that consisted of a more numerical load task versus another type of load task. Likewise, cognitive load theory [21] indicates that limitations of human cognitive processing become especially pronounced when dealing with complex tasks [4]. Based on cognitive load theory, we argue that adding an additional task (our load task, which indeed contained numbers) could have revealed limitations of cognitive processing also in the lighting feedback condition, *independent of the specific nature of that additional task*. In other words, because our load task added to the complexity of the overall task participants in the lighting feedback conditions had to perform, it therefore could have revealed limitations of cognitive processing. And indeed results did not indicated these limitations (in terms of slower processing) in lighting feedback conditions, but only revealed these limitations (slower processing) in factual feedback conditions. Still, future research replicating the current findings with different cognitive load tasks would certainly strengthen the evidence for our argument that lighting feedback is easier to process and use in goal-striving processes than factual feedback.

Furthermore, future research could also investigate which other differences between lighting feedback and factual feedback may underlie the stronger persuasive effects of lighting feedback in addition to the higher ease of processing of lighting feedback that the current research suggests. For instance, lighting feedback might be more conspicuous, have specific physiological consequences, or may have stronger emotional or moral effects.

Overall, the current research indicates that diffuse lighting can be used successfully as persuasive technology. These technologies can be incorporated into everyday life in many forms to change different types of behavior or attitudes. For example, the data about energy consumption provided by smart meters might be used to deliver interactive lighting feedback in the living room. The current research suggests that such an application could successfully influence energy consumption behavior, even when users do not spend cognitive attention to this lighting feedback. The current research indicates that lighting can have a particular aptitude as a medium for persuasive communications. Next to being very cheap, or easy to install (and other fitting characteristics, as discussed in the Introduction), the current research suggests that persuasive lighting can have stronger persuasive effects than other forms of persuasion (i.e., factual persuasion), especially under (day-to-day) circumstances of high cognitive load.

In addition, we argue that lighting has specific qualities that make it particularly suitable for providing user feedback. For example, lighting can be very cheap, is easy to install, lighting can be very energy friendly, lighting can be seen by other people present in a room as well (inducing social pressure as a persuasive mechanism), and lighting might have an emotional appeal or even direct emotional effects.

Also, the low conspicuity of light and color changes sets lighting apart from other feedback mechanisms. Furthermore, lighting can be calm (in the sense of 'calm computing'). Other feedback mechanisms often lack these characteristics. For example, feedback mechanisms like factual feedback or feedback that uses sound, smell, or tactile feedback cannot easily be calm in that sense. Therefore, we argue that lighting can be particularly suited as a persuasive agent.

In general, persuasive technologies are generic technologies which are "intentionally designed to change a person's attitude or behavior or both" [7, see also, 12]. Based on current results, we argue that lighting in various modalities can serve as Ambient Persuasive Technology [see also 6, 8, 10, 11, 19]. We propose that Ambient Persuasive Technologies are generic technologies that are intentionally designed to change a person's attitude or behavior or both, that can be integrated unobtrusively into the environment and exert an influence on people without the need for their focal attention. The current research suggests that ambient persuasive technology can have important advantages over more focal persuasive technologies without losing its persuasive potential.

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A Transformational Approach to Interactive Lighting System Design

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ABSTRACT

Light affects our behaviors and experiences. Research into this field mainly focuses on the effects of lighting conditions on people. The current paper focuses on human *interaction* with lighting systems, and the way this interaction transforms people's behaviors and experiences. Technological developments, such as Solid State Lighting and increasingly powerful and economic sensing and control electronics, open up a myriad of possibilities for incorporating interactivity and intelligence in lighting systems design. How can we design an interactive lighting system that influences people's behaviors and experiences in a positive way? This paper explores this area from an industrial design research point of view. It introduces a transformational approach to interactive lighting design, combining frameworks of Technological Mediation, Human Values and Kansei design. In a research-through-design process, a set of interactive lighting systems are designed based on this transformational approach and empirically evaluated. Results indicate that it is indeed possible to invite specific behaviors and experiences through interactive lighting system design.

Keywords

Interactive lighting systems, transformational design, human values.

INTRODUCTION

A growing body of research studies how light influences human behaviors and experiences. Such research mainly focuses on the effect of specific artificial lighting conditions on people, e.g., [8], [12] and [14]. But artificial lighting becomes ever more dynamic. Technological developments, such as Solid State Lighting, and increasingly small, cheap and powerful sensing and control electronics, open up new possibilities for incorporating interactivity and intelligence in lighting systems design [4]. Increasingly intelligent lighting systems are envisioned to integrate into the everyday environment, playing a role in everyday life that goes well beyond task lighting [1][9]. In view of these developments, the current paper focuses on human *interaction* with lighting systems and the way this interaction affects behaviors and experiences, rather than on the influence of given lighting conditions on people. Our focus on interaction entails that we treat situations in which lighting systems and humans respond to each other's actions in a meaningful way. These lighting systems are typically equipped with electronics that enable them to sense human actions, process the data, and respond accordingly with lighting actuators. How can we design interactive lighting systems that influence people's behaviors and experiences in a positive way? The current paper explores this question from an industrial design research point of view.

Technological mediation, ethics and light

The theory of Technological Mediation [13] is used in the current research to conceptualize the influence of interactive light on our behaviors and experiences. The theory states that every technology in use transforms our experiences and behaviors. This transformation has a dual structure. Each technology on the one hand amplifies specific experiences, and on the other hand reduces others. Compare for example how an mp3 player amplifies the experience of music and reduces the experience of the environment, by immersing the listener in music and blocking other sounds. The theory also states that technology in use always invites specific behaviors while inhibiting others. The mp3 player, when used in a busy train, invites a person to concentrate on his work, while at the same time it inhibits social interaction with people in the vicinity. These mechanisms can also be applied to interaction with lighting systems. When we do this, the question arises for designers of interactive lighting systems what experiences their system should amplify or reduce, and what behaviors they should invite or inhibit. This question has an ethical dimension: People with different ethical beliefs might prefer to engage in different behaviors and might prefer to have different experiences in a given context.

A research-through-design process

This paper presents design research that explores how to design interactive lighting systems that aim to invite specific behaviors in interaction. We call this approach to lighting system design *transformational*. In a research-through-design process [3][5], actual lighting systems are designed using a combination of design techniques and auxiliary theoretical frameworks. The aim of these lighting systems is to invite specific behaviors in human-system interaction. These designs are evaluated in an empirical study. Central in the current process is design work from a 40-hour bachelor course called Personality in Interaction [10], conducted at the department of Industrial Design at Eindhoven University of Technology [6]. In this course, students designed interactive lighting systems with the aim to invite behaviors that fitted the personality of a specific fellow student.

A framework for ethical beliefs

Before elaborating on the course, we treat an auxiliary theory that was used to operationalize people's ethical beliefs, namely the theory of Human Values [11]. This theory offers a way to understand what kind of behaviors and experiences a specific person would desire to engage in. Human values are defined as follows: 'Values (1) are concepts or beliefs, (2) pertain to desirable end states or behaviors, (3) transcend specific situations, (4) guide selection or evaluation of behavior and events, and (5) are ordered by relative importance' [11]. Examples of values are Creativity, Helpfulness and Social Power. Empirical research in 20 countries identified a set of 57 values considered near-universal. This research allowed Schwartz to meaningfully locate the 57 values on a plane with four quadrants, labeled Self-Enhancement, Conservation, Self-Transcendence and Openness-to-Change. Figure 1 shows a selection of 13 of the 57 values plotted on this plane. In this value scheme, the distance between values represents their mutual compatibility. Figure 1 shows, for example, that the closely located values Helpful and Loyal are more compatible than Helpful and Social Power. The behaviors these values motivate are compatible (or not) in a similar manner. Schwartz developed a survey to measure individual people's value priorities. The instrument is called the Schwartz Value Survey [11] and consists of the 57 value items that can be scored on a 9-point scale.

A large body of research exists that relates people's value priorities to certain behaviors, attitudes and personalities. Several research projects demonstrate the relevance of Human Value theory to design research. For example, Allen and Ng [2] show how values could be related to choice for products as varied as different sunglasses and different cars. The fact that values guide selection and evaluation of behaviors connects ethical beliefs of people and specific kinds of behaviors. The definitions of values can serve as a characterization of desired behaviors a lighting system should invite. For example, for people that value creativity, we could aim to design an interactive lighting system that invites creative behaviors.

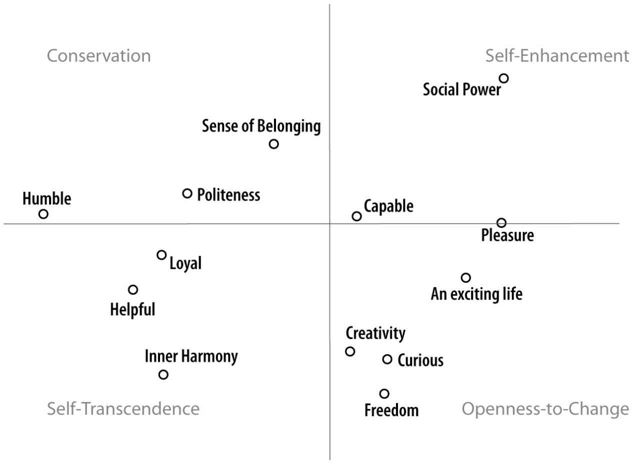


Figure 1: 13 out of 57 value items arranged according to the research of Schwartz and placed in the four quadrants (adapted from [11]). The distance between values indicates motivational compatibility.

DESIGNING INTERACTIVE LAMPS: THE PERSONALITY IN INTERACTION COURSE

Research into the influence of interactive lighting systems on human behavior and experience requires evaluation of actual lighting systems. These lighting systems were designed and built in the Personality in Interaction course. The students' design assignment was to create an interactive lamp or lighting system that invited behaviors and experiences that corresponded to the most important values of a fellow student. So if a fellow student prioritized Creativity highly, the assignment was to create an interactive lighting system that invited creative behaviors from the person interacting with it. Note that the assignment was *not* to create a lamp that acted creatively itself: It was about inviting creative behaviors from the person interacting with the lamp. The lamps did not need to be functional in the sense of providing task lighting.

Course set-up

The course's design process followed a Kansei design approach [7] that was adapted for this specific course. It included the following steps:

1. Students (voluntarily) completed the Schwartz Value Survey [11] to learn about their own personality. Pairs of students with contrasting personalities were created with the test results.
2. Relevant theories (Human Value theory, Kansei) were introduced in a lecture and students read accompanying papers.
3. The students created a one-minute 'dynamic personality collage' on video of their assigned fellow student. This collage had to display behaviors of the fellow student that expressed his or her values.
4. The personality collages were analyzed to find interaction qualities for design.

5. The next step was to design and prototype an interactive living room lamp or lighting system that invited behaviors that related to the fellow student's top priority values.
6. The course ended with a final presentation, in which the students interacted with the prototypes designed for them, and the design and design process were evaluated.

Resulting lighting designs

This section treats three designs resulting from the course, to illustrate the nature of the design work. See Figure 2 to 4 for images of the lighting system interactions and accompanying explanations. Film clips of these lamps and the other nine lamps used in the current research are available at http://www.philipross.nl/thesis.

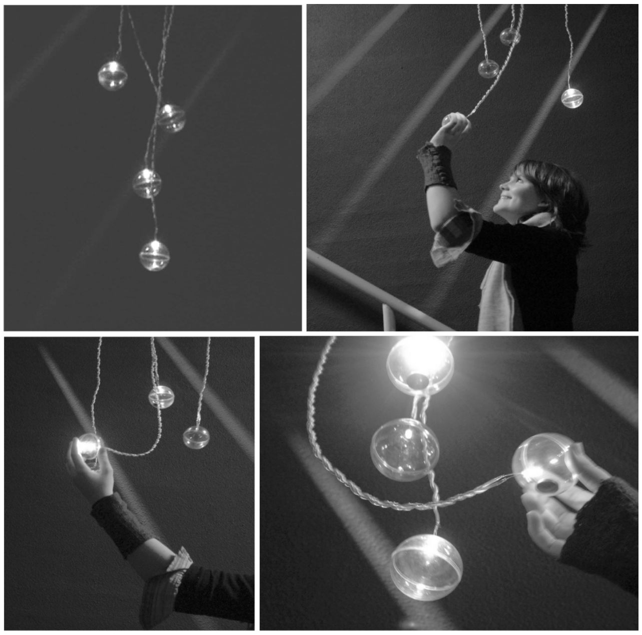
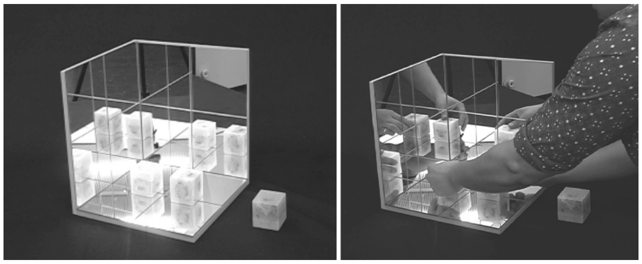


Figure 2: This staircase lighting system targets Creativity related behaviors. It consists of several light balls hanging from the ceiling above the staircase. When the balls are moved, they light up and create a dynamic light and shadow play in the staircase. The balls stick to each other with magnets when they touch, allowing a person to rearrange the layout of light balls as desired. The system's easy interaction, combined with the beautiful, dynamic light and shadow effects that each action creates, invites a person to be creative while walking the stairs.



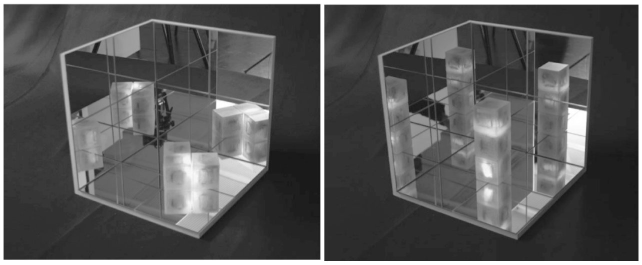


Figure 3: This decorative lamp is designed to invite curious behavior. The lamp's main interaction elements are three semi-transparent light cubes, placed in a cubic space delimited by three mirrors. The cubes are equipped with colored LED's but do not give away their lighting effects until they are combined with each other. Different ways of stacking or aligning the cubes result in different dynamic colored lighting effects. The lamp triggers curiosity in interaction through its intentional absence of feedforward for actions, combined with the reward of beautiful effects after each interaction.

Figure 4: The Throw Ball light object targets the value Pleasure. This design is conceived for a person that likes to have fun in social setting. The final design is a ball the size of a soccer ball with holes in it that transmit light. The ball tries to stimulate people to throw it by blinking when it is held longer than 0.5 seconds. When it is thrown, it lights up fully. When held longer than 2 seconds, the light dies out which could mean the game is over.

THE EVALUATION EXPERIMENT

An evaluation experiment was conducted to see how people naïve to the design intentions would experience the interactive lighting systems. In this experiment, participants viewed film clips of interactions with twelve different lamps (including one trial) and rated them in terms of values. Twenty people participated, thirteen male and seven female. All participants were architecture students, coming from both the bachelor and the master program.

Architecture students were chosen since they have no education in interaction design, but are still sensitive to design in general.

Procedure

The experiment procedure was as follows:

1. The participant received an introduction in which the experiment was explained.
2. A participant watched a film clip showing interaction with a given lamp.
3. The participant filled out a value rating form. Details about this form are treated further on in this paper.
4. Step two and three were repeated for all eleven film clips, preceded by a trial clip.

There were 8 separate sessions with 1 to 5 participants simultaneously. The clips were show in three different orders. Order 1 and 3 were randomized, order 2 was counterbalanced with order 1. The participants received €5,-.

Stimuli

The designs from the Personality in Interaction course were only partly functional prototypes. It was impossible to test them live with participants in an experiment, so film clips of these interactions were shown to the participants. In these film clips, the prototypes seemed to be truly interactive.

A set of eleven lamps (plus one for the trial clip) served as the stimuli. Two of these lamps were not explicitly designed for a value. The students that designed these lamps deviated from the course assignment, and used other personality traits as input. These lamps were still included in the study to explore how they would be rated in terms of values. Ideally, each of the four quadrants of the Schwartz Value Structure was targeted by at least one lamp. This could however not be realized. There were only a few course students with highest priority values in the 'Conservation' quadrant or the 'Self-Transcendence' quadrant. So these values were rarely targeted in the course. The result was that there were no usable designs targeting the Conservation and Self-Transcendence quadrants. Explanations and pictures of all eleven lamp interactions and the trial lamp interaction are available in [9].

One of the clips was selected as the trial clip. The clip duration ranged from 15 seconds to 39 seconds. Screenshots of these clips are shown in Figure 2 to 4. The clips were numbered and shown on a 37'' Flat Screen TV.

Rating form

To measure the way people characterized the interactions in terms of values, a rating form was devised including a list of Human Value rating scales. The form was originally created in Dutch, but treated here in English translation. The participant was asked to imagine they would interact with the lamp themselves. Then they placed a tick mark on the value scale to indicate to what extent a particular value description matched the interaction in the film clip. The value scales looked like this:

Imagine you are interacting with the lamp yourself. Use a tick mark to indicate to what degree the interaction evokes the following terms in you:

Creativity (uniqueness, imagination)

Does not describe it at all	o	o	o	o	o	o	o	Describes it perfectly

The value descriptions used in the scales were copied from the value descriptions in the Schwartz Value Survey [11]. A selection of 13 of the 57 values was made to include on the form, to keep the rating task feasible for the participants. These selected values were spread out over all four quadrants of the value plane. Furthermore, the list contained all the values that were targeted by the selection of lamps. The value rating list contained the following items:

- Inner harmony (at peace with myself)
- Curious (interested in everything, exploring)
- Humble (modest, self effacing)
- Freedom (freedom of action and thought)
- Social power (control over others, dominance)
- Capable (competent, effective, efficient)
- Pleasure (gratification of desires)
- Loyal (faithful to my friends, group)
- Politeness (courtesy, good manners)
- An exciting life (stimulating experiences)
- Sense of belonging (feeling that others care about me)
- Creativity (uniqueness, imagination)
- Helpful (working for the welfare of others)

The distribution of the corresponding values over the 2D structure is depicted in Figure 1.The forms were filled in on a laptop running SPSS Data Entry Station.

Hypotheses

If the design of the lamps has any effect measurable with the value scales, the ratings on the value scales should differ between lamps targeting different values. Formally put:

Hypothesis 1

H0: The mean ratings on the value scales are equal between lamps

H1: The mean ratings on the value scales are not equal between lamps

This effect should have a certain pattern for the lamps that targeted a specific value. One would expect that a target value would always have a significantly higher score on the scales than all other values. This leads to the second hypothesis.

Hypothesis 2

H0: The mean rating of the target values are not higher than those of all other values

H1: The mean rating of the target values are higher than those of all other values

Human value theory predicts a structure in the relation of the score of the target value scale to the scores of the other value scales. As treated earlier in this paper, the mutual distance of value items on Schwartz' value structure is a measure of 'motivational compatibility'. If two values are located close to each other on the value structure, they are compatible. The larger the distance between them, the less compatible they are. For example, the values Helpful and Loyal (closely co-located) are more compatible than Helpful and Social Power (large distance in between). See the locations of these values in Figure 1. This degree of compatibility between values is expected to have a systematic effect on the scores on the value scales. For example, if a lamp in the current experiment succeeds in eliciting the value Helpful, the value scale Helpful would receive the highest mean scores. The value scale Loyal (the most compatible value in this experiment) would receive the second highest score, and the value scale Social Power (the least compatible value) would receive the lowest score. So it is possible to determine a theoretical rank order of the means of all value scale scores, based on the targeted value score. The occurrence of this rank order in the data would be an indication that the ratings are in line with value theory and that the interaction is really relevant in terms of values. The 'fit' of the measured rank order of value scale scores with the theoretical rank order of scores is determined here by a correlation analysis of both rank orders. Put in terms of a hypothesis:

Hypothesis 3

H0: The correlation between the measured and theoretical rank orders of the value scores is not significant

H1: The correlation between the measured and theoretical rank orders of the value scores is significant

Results

Figure 5 shows the ratings of the three lamps treated in the current paper. Most of the evaluated lamps targeted values in the Openness to Change quadrant. This shows in the ratings. The highest scores are generally located in the Openness to Change quadrant. This section continues with a treatment of the three hypotheses in light of the experiment results.

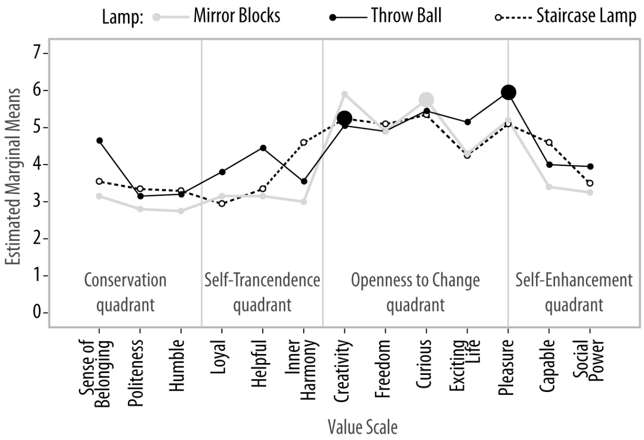


Figure 5: The mean ratings of the three lamp designs explained in this paper. The values are placed in order according to the value structure quadrants along the x-axis. The vertical lines indicate the borders of the quadrants. Each lamp's target values are highlighted with a large, filled dot.

Results for Hypothesis 1:

H1: The mean ratings on the value scales are not equal between lamps

Figure 5 show differences between the scores on the value scales. An 11 (Lamp) x 13 (Scale) repeated measures Analysis of Variance (ANOVA) was performed on scores for the value scales for all 11 lamps. The results are reported in Table 1. Significant main effects were obtained for Lamp, *F*(10, 2717) = 7.7, $p < .001$, and for Scale, *F*(12, 2717) = 47.7, $p < .001$. In addition, the interaction effect was significant, *F*(120, 2717) = 2.2, $p < .001$. Simple main effects analyses (Dunnett T3) were performed to examine the nature of the significant interaction. It was found that the means of 9 of 11 lamps were significantly different from one or more of the other lamps' means. The conclusion is that H(0) is rejected. (Note: Homogeneity of variance could not be assumed. Non-parametric test, the Friedman Two-way Analysis of Variance by Ranks and Kruskal-Wallis tests were performed on the value scale scores. The same significant effects were obtained from these tests.)

Table 1: Results of the ANOVA. Independent Variables are Lamp and Scale, the Dependent Variable is Score.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Lamp	202.8	10	20.3	7.7	0.001
Scale	1515.9	12	126.3	47.7	0.001
Lamp * Scale	704.4	120	5.9	2.2	0.001
Error	7199.5	2717	2.7		
Total	52975.0	2860			

R Squared = 0.252 (Adjusted R Squared = 0.213)

Table 2: Ranks of each lamp's target value scores compared to the other values.

Lamp name	Staircase lighting system	Mirror Blocks	Flower Lamp	Throw Ball	High Five	Segmented Ball	Stacker Lamp	Spring Lamp	Puzzle Lamp	Color Box	Tree of Light
Target value rank	2	2	2	1	n.a.	n.a.	1	2	1	3	5

Results for Hypothesis 2:

H0: The mean rating of the target values are not higher than those of all other values

Nine of eleven lamps tested in this experiment actually targeted a value. The other two designs targeted other aspects of personality, since the designers deviated from the course design brief. Three of the nine lamps targeting values actually received the highest ratings on their target value, i.e., Light Ball for Pleasure, Stacker lamp for Freedom and Puzzle Lamp for Curiosity (See [9] for a description all the experiment's lamps). In four lamps, the target value was rated second highest, one was rated third and one was rated fifth. See Table 2 for an overview. In almost all cases, H(0) cannot be rejected.

However, the target value is in most cases ranked second or third. Value theory says that the values are part of a motivational continuum. When values are located close to each other in the structure, they are similar in motivation. This means that behaviors motivated by a value very near a target value are still highly compatible with the behaviors motivated by the target value. An analysis considering the order of the ranks of all values gives a more nuanced view on how successful the lamps are, as explained for hypothesis 3.

Results for Hypothesis 3:

H1: The correlation between the measured and theoretical rank orders of the value scores is significant

To test whether the rank orders of the values as they are rated are equal to the theoretical rank orders, based on their mutual compatibility, a correlation analysis is conducted. In this analysis, the scored rank orders are compared with the theoretical rank orders. The theoretical rank orders are calculated by determining the distance between the target value and all other measured values on the structure. See Figure 6 for a graphical representation of this process. Table 3 shows the table of correlation coefficients.

The table shows that the value scores of 6 of 9 lamps that target a value correlate significantly with the theoretical rank orders. This indicates that the interactions they elicit show the same 'motivational structure' as the values they try to elicit. So although the target values are not in all cases rated highest, the values that motivate similar behaviors score higher than the values that conflict with the target value. And the structure of gradually increasing and decreasing compatibility is present as well. The approximate sinusoid lines in Figure 5 visually depict this. The results of this analysis indicate that these lamps elicit interactions that are actually relevant in terms of values.

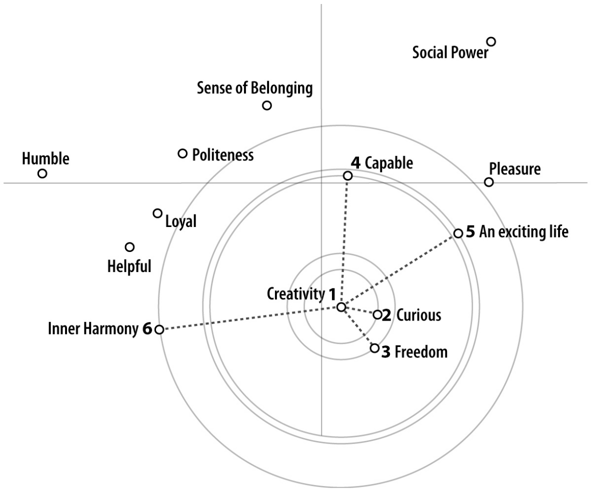


Figure 6: Determining the first six rank orders for Creativity. The circles indicate the different distances from the values to Creativity. The circles have the Creativity value as their centre, and have a radius that corresponds to the distance to another value.

Table 3: Correlations of scored value rank orders with theoretical rank orders (all N=13). Continued on the next page.

Correlations – Kendall's tau

Staircase lighting system (Creativity)	**Correlation Coefficient**	**0.538**
	Sig. (2-tailed)	**0.01**
Mirror Blocks (Curious)	**Correlation Coefficient**	**0.564**
	Sig. (2-tailed)	**0.007**
Flower lamp (Creativity)	**Correlation Coefficient**	**0.641**
	Sig. (2-tailed)	**0.002**
Throw Ball (Pleasure)	**Correlation Coefficient**	**0.538**
	Sig. (2-tailed)	**0.01**

Table 3: continued.

Stacker Lamp (Freedom)	**Correlation Coefficient**	**0.641**
	Sig. (2-tailed)	**0.002**
Spring Lamp (Pleasure)	Pearson Correlation	0.445
	Sig. (2-tailed)	0.128
Puzzle Lamp (Curious)	**Correlation Coefficient**	**0.513**
	Sig. (2-tailed)	**0.015**
Colour Box (Hedonism)	Correlation Coefficient	0.308
	Sig. (2-tailed)	0.143
Tree of Light (Self-Direction)	Correlation Coefficient	0.359
	Sig. (2-tailed)	0.088

Discussion of the experiment

The experiment results are encouraging. However, there are reservations that need to be made. The lamps were tested using video-clips of interaction. Experiencing an interaction captured on video may be different than experiencing interaction live. It is unknown how this difference manifests itself in the measurements. Because of the low number of participants and their specific background, caution is required in generalizing the results to a larger population. All lamps in this test focused on values in the Openness-to-Change quadrant and the Self-Enhancement quadrant. It is therefore still unknown if values in the other quadrants could be targeted. Although the rating form makes use of the exact formulations of the Schwartz Value Survey, it is not a validated measuring instrument.

GENERAL CONCLUSION AND DISCUSSION

The outcomes of this study indicate that it is possible to design interactive lighting systems that invite behaviors that relate to a specific range of values. ‘Range of values’ is mentioned since the lamps in the experiment invite a range of compatible values, rather than only one isolated value. Quantitative analysis of the value scale scores indicated that the behaviors and experiences invited by the lamps in 6 of 9 cases corresponded significantly to the values these lamps targeted. The authors interpret the outcomes of the study as a stimulus to continue this line of research. A follow up research question is to see if people evaluate lamps that invite behaviors that correspond to their own high priority values more positively than lamps that invite conflicting behaviors.

The theoretical frameworks of Technological Mediation and Human Values serve as useful input for design, helping designers define what they would like to achieve with their interactive lighting system. The creative and novel character of the resulting lamps indicate that taking a targeted value related behavior as an input for the design process is a fruitful approach to come to innovation in interactive lighting design.

On a general level, the results show the relevance and potential of design research specifically directed at *interaction* with lighting systems, taking the way they transform our behaviors and experiences into account. The current value-based transformational design approach can help designers create lighting systems that influence our behaviors and experiences in a positive way.

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Effects of Colour and Light on Customer Experience and Time Perception at a virtual Railway Station

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ABSTRACT

Various studies have shown that colour and light influence our emotions and behaviour. In this paper the results will be presented of research into the combined effects of 5 different colours and 2 different intensities of light for Leiden station.

Two experiments in a virtual Leiden station show that although colour and light are perceived subconsciously, the combination of the two does in fact have significant effects.

Most of the passengers appeared to overestimate waiting time on the platform, which concurs with results from earlier fieldwork. Moreover, time would appear to pass more quickly with low intensity lighting as opposed to high intensity lighting.

The second experiment showed that passengers prefer warm colours in combination with dimmed lighting and estimate the waiting time as being shorter than when cooler colours and a more intense lighting are used. Practical implications will be discussed.

Keywords

Colours and lighting, railway station, virtual simulation, customers' evaluation

INTRODUCTION

In many public spaces, such as railway stations, shopping malls and healthcare institutions, colours strongly determine how we feel and act as service customers. As is also the case with temperature, smell, sound and décor, changing these environmental factors can influence both perceptual and emotional reactions as well as the actual behaviour [28].

For the Dutch Railways Corporation colour and lighting are important instruments to manage the overall impression of the service environment. They are expected to affect customer experiences (via perceived pleasantness, feelings of safety and even (waiting) time perception) and thus customer satisfaction. The key question in this paper is:

How can Dutch Railways specifically deploy colour and light on platforms in stations so as to positively influence emotions? The objective is to win more happy customers by improving the 'servicecape' [13] and its potential to 'signal' service quality. and customer care. Of course, in considering the environmental design of public services such as railway stations, many factors may play an important role, and a variety of quality dimensions may be affected by clever design. In this study we specifically focused on the intangible factor 'time', because the train's departure is scheduled and passengers have to get on the train in time. So time is one of the predominant processes that passengers are dealing with during their stay at the platform. Time also has a crucial impact in quality surveys in public transport.

This paper presents the results of 2 studies into the combined effects of colours and intensities of light on emotions and time perception in a virtual simulation of Leiden station.

SERVICE ENVIRONMENT

According to Parasuraman, Zeithaml and Berry [37], three aspects play a role in the service environment: intangibility, the simultaneous course of the production and consumption, and the heterogeneity of the service. Through the intangibility of the service, people cannot feel, taste, see or smell it. They can only experience the service. Owing to a lack of tangible proof, customers perceive other aspects of the environment to evaluate the service and determine its quality [2], [13], [14]. A service environment comprises all the objective factors that can be controlled for by the organization with the aim of prompting employees and consumers to a specific behaviour. Baker [5] divides the physical environment into three components: design elements that are visually and tangibly present, ambient elements that are intangible and often processed subconsciously, and social elements, other people present in the service environment, such as customers and personnel. Colour and lighting belong to the category of ambient and intangible elements of the environment.

STIMULUS, ORGANISM, RESPONSE

This research employs the model of Mehrabian and Russell [32] to investigate whether colour and light influence the degree of pleasure, arousal and dominance that determine behaviour. The relationship between environmental variables and approach or avoidance behaviour in a service setting can be modeled (after Mehrabian and Russell, [32]) as a stimulus-organism-response (SOR) chain:

- *Stimulus (environment)*: all ambient aspects such as colour, light, smell, sound etc.
- *Organism (emotions)*: emotional reactions on the basis of pleasure, arousal and dominance (PAD model).
- *Response (behaviour)*: the degree to which consumers show approach or avoidance behaviour.

Many studies have focussed on the influence of pleasure on behaviour (e.g. [9]). Also the relationship between arousal and behaviour has been empirically demonstrated. However, little attention has been paid in literature to the degree of dominance [9]. Imperative for a station environment is a sense of control, and thus dominance; likewise for emotional aspects such as feelings of uncertainty and pressure, how easy it is to orient oneself and how one experiences the wait. These aspects will thus be included in this research.

LITERATURE OVERVIEW OF COLOUR AND LIGHT

Colours with a short wavelength are specified as cool colours (blue and green), whereas those with a long wavelength are warm (red and yellow). Light comprises the light intensity and the spreading of the colour tone. Bright or dimmed light is determined by the light intensity. Little research has been conducted on the combination of colour and light ([16]; [43]). The majority of (published) studies of the effects of colour in retail environments was conducted in laboratory settings. To our knowledge, no research has yet been published on the usage of light and colour in a railway station.

Colour

In public environments there is often a need for the right colour that incorporates the element of ‘pleasantness’. Although the optimal design may strongly differ across service contexts and situations (and even across individual customers), it appears that specific colours, generally perceived as pleasant, may result in very specific emotions.

Cool colours, such as blue and green, have a relaxing effect, whereas colours with a long wavelength, such as orange and red, are stimulating [1], [26], [43], [47]. Warm colours are perceived as being protective [46]. Clear and saturated colours are generally experienced as more pleasant [24], but are also more strongly associated with fear than cool colours [26]. Dark colours are perceived to be more dominant and more strongly provoke hostility and aggression. So, with the environment and state of mind determining the effects of colour, red in the cinema foyer will exude a warm, festive aura whereas the same colour in a hospital can have a negative influence on the state of mind of the already anxious visitor.

Research on the use of colour in retail environments has shown that it influences buying behaviour [9], purchasing speed [9], time spent in the shop [9], pleasure [9], [18], arousal ([18], image of shop and merchandise [8] [18] and the potential to draw customers into the shop [8]. Blue and green are perceived to be the most pleasant in a retail environment [20], [26] and are also evaluated higher than shops with a warm (orange) interior [8], [18]. The results for pleasure strongly resemble the scores for arousal. From research by Kwallek et al. (1988; in [42]), it appeared that people who performed a business task in red surroundings later scored higher for stress and anxiety. Colours with a short wavelength cause a person to be more externally oriented and to show forceful and extrovert behaviour.

From the study by Belizzi et al. [8], it appeared that respondents, irrespective of their colour preference, felt more drawn physically to warm colours yet perceived surroundings in warm colours as less pleasant [8]. Warm colours are apparently successful when it comes to drawing people in (entrances, shop windows), but less so when it comes to making them feel at ease. In situations where people experience mental pressure, it is better to keep the colours cool; with their calming effect people are prepared to remain longer in such surroundings. Brengman [15; 16] showed respondents photos of a shop in which the colours were manipulated. She concludes that people will spend more time and money in a shop if they find the colours agreeable [15]. Blue and yellowish red are perceived as pleasant, as are light colours. Such atmospheres invoke approach behaviour and the desire to explore. According to Brengman [15], red and yellowish green, just like bright and dark colours are perceived as less pleasant; these colours lead to tension and stress and cause a distasteful feeling. Such negative stress leads to avoidance behaviour [15].

Light

Psychologists state that light has a tremendous influence on human behaviour. Baker and Cameron [5] and Küller et al. [29] indicate that there is a basic level of how people experience light as the most pleasant. A preference for light intensity depends on the situation, the task and one’s surroundings [7], [10], [43].

Light has a strong effect on the degree of arousal [7], [19], [22], [27], [34]. Light also influences a shop’s image and the stimulus to look at and scrutinize the merchandise [6], [16].

Colour *and* light

Valdez and Mehrabian [43] have shown that it is not only colour hue that determines the evoked emotions but also the saturation and brightness (i.e. intensity) thereof. It appears, for example, that although there is hardly any difference in the way men and women react to colour, women are more sensitive to the colours' brightness. In a study of non-chromatic colours (black-white-grey), it appeared that the brightness strongly determines their degree of stimulation and dominance [43]. Mehrabian suggests that "brightly lit rooms are more arousing than dimly lit ones" and that light, besides colour, has a strong influence on arousal [32]. From a scenario study [4], in which a blue and an orange shop were compared, it appeared that the blue shop was preferred the most and that it generated a greater willingness to shop or buy there. A brightly-lit orange shop was perceived as having the greatest adverse effect. However, when soft lighting was introduced to this orange shop, it became almost as positively rated as the blue one. With a blue shop the effects are even more positive in a brightly-lit variation. The combination of light and colour seem to qualify the perceived effects quite convincingly. A restriction, however, is that this was a scenario study and its results should preferably also be tested in a realistic setting [4]. Generally speaking, the studies of the effects of colour have predominantly focussed on the wavelength of the colour and hardly at all on the brightness and the saturation of the colour ([15], [43]). Light and colour combined were seldomly investigated.

COLOUR BRIGHTNESS, LIGHT AND TIME PERCEPTION

Smets [41] demonstrated how people estimate the length of an interval as being shorter after having seen a red as opposed to a blue colour. Under red light, time would appear to pass more slowly and objects seem bigger and heavier, whereas under blue light time seems to pass more quickly and objects look smaller and lighter. Casinos use this information and opt for red as a basic colour which excites the customers without their realizing that they are spending a lot of time there [40]. Research into the waiting time of downloading internet pages in various colours, with different levels of saturation and brightness, revealed that respondents felt more relaxed by particularly the bright colours and that time seemed to pass more quickly. Conversely, tension and stress when downloading seems to slow down the subjective experience of time. Analogous to other studies of the usage of colour, it would appear that blue screens have a more calming effect than red or yellow ones [23].

In the context of traditional –off-line- shopping, Markin et al. [31] suggest that dimmed light calms customers, causing them to move more slowly through the shop, which means that they then take their time to pay attention to and scrutinize the merchandise. This suggests that the shopkeeper can use the intensity of light to keep customers in the shop for a longer or shorter period of time. As pleasant and stimulating colours combined with bright lighting appears to lengthen the perceived waiting time [5], it would be better to opt for softer lighting to prevent overestimation of the actual wait.

STUDY 1: VIRTUAL LABORATORY

Method

A 2 (colour hue: red vs. blue) x 2 (light: high vs. low intensity) between-subjects design was used. At the VR Laboratory at the University of Twente, 130 participants were asked to navigate through a virtual simulation of Leiden station.

Procedure

The experiment ran for four executive days, during which the different conditions were arbitrarily distributed among the respondents. Participants who indicated they wished to take part in the experiment were first subjected to a test for colour blindness, after which they were invited -in a separate room- to practise with the navigation system that was used in the experiment. Subsequently the respondents entered the VR lab where the final instructions were given. After the simulation the respondent was requested to fill out a questionnaire. Following completion, (s)he was thanked for his/her time.

Participants

In total, 142 respondents, all Master/PhD students at the University of Twente, took part in the experiment. Of these, 130 (65 men and 65 women; average age 22; range 18-29 years) questionnaires were included in the final analyses. Twelve respondents dropped out because of colour blindness, or because they experienced a mild nausea in the virtual environment.

Stimulus material

The virtual simulation was projected on a 10 meter screen. Figure 1 depicts one of the participants at the Virtual Reality Laboratory at the University of Twente and Figure 2 depicts two stills of the simulation. After reading an instruction on the start page, participants could navigate through an animation of Leiden station with a mouse and scroll arrows on a keyboard. They were instructed to: "...get the first train to Amsterdam. Find out at which platform and at what time your train leaves. Wait on the platform until your train arrives. You already got your ticket. Please, try to imagine the situation, and try to behave as you would in a real life situation". Then, the 'avatar' could enter the station and freely navigate through the station from a first person perspective. From this perspective they were able to 'walk' through the station, climb the stairs and enter the platform. Real life background noises were played during the session to enhance imaginative power.

Figure 1. One of the participants at the Virtual Reality Laboratory

Figure 2. Two stills of the simulated platform

The colours were manipulated on the platform: blue (colour code 000.128.255) and red (colour code 255.075.075). Level of satuaration was held constant for both conditions. Light was simulated by using a omni 1.0 spot 1.5 for the platform roof and omni 1.0 spot 0.4 for the platform to simulate low intensity of light. A high intensity of light was simulated by using a omni 0.5. spot 1.0 for the roof and omni 0.6 spot 0.2 for the platform.

Measures

A questionnaire was used to measure the overall evaluation of the railway station.

Emotions were measured on the basis of the Pleasure Arousal Dominance (PAD) scale [31] with 19 semantic differential items. Pleasure was measured with 6 items (unhappy-happy, annoyed-pleased, unsatisfied-satisfied, melancholic-contended, despairing-hopeful, unpleasant-pleasant; coefficient alpha = .88). Arousal was measured with 7 items (stimulated-relaxed, exited-calm, frenzied-sluggish, jittery-dull, wide awake-sleepy, aroused-unaroused; fit-tired; coefficient alpha = .71). Dominance was measured with 6 items (controlled-controlling, influenced-influential, cared for-in control, awed-important, submissive-dominant, guided-autonomous; coefficient alpha = .78).

Evaluation of the platform was measured on the basis of a combination of 3 scales [12], [39] which resulted in a 12-item scale. Participants could indicate to what extent they felt the platform was attractive, comfortable or messy (*1 = totally disagree, 7 – totally agree*; coefficient alpha = .86).

Attitude to the waiting time was measured with 4 items based on a study by Pruyn and Smidts [38] on waiting time. Examples of items are ‘I was annoyed because of the time I had to wait’ and ‘I felt bored during the waiting time’ (*1 = totally disagree, 7 – totally agree*; coefficient alpha = .76)

Time perception - Measures included subjective estimations of time spent in the station and on the platform (‘‘How long do you estimate the time (in minutes)” and the experience of time (‘How long did you think this time took’: *1 = very long, 7 = very short*)).

Cognitive preference was measured by asking the participant which colour they thought was best appropriate for a station (grey, green, yellow, red or blue).

Perceived colour was measured by asking participants what the main colour was they saw on the platform. Also included were a number of demographic variables such as age, gender and gaming experience.

RESULTS

On the basis of a multivariate analysis of variance, we then inspected the main and interaction effects of colour and type of light on the different dimensions of the overall evaluation of the station.

Table 1 shows the results per colour and type of light for all aspects of the judgement.

Table 1

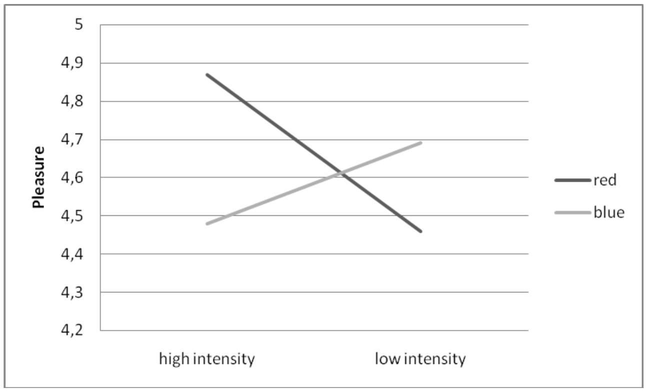
Analysis of variance (interaction) effects colour and light[1]

	Main effect Colour		Main effect Light		Interaction effect Colour x Light	
	F	*P*	*F*	*P*	*F*	*P*
Pleasure	<1		<1		3.55	.06
Arousal	<1		1.08	ns	<1	
Dominance	1.96	ns	<1		<1	
Attitude to the platform	<1		<1		2.72	.10
Attitude to the waiting time	<1		<1		4.95	.03

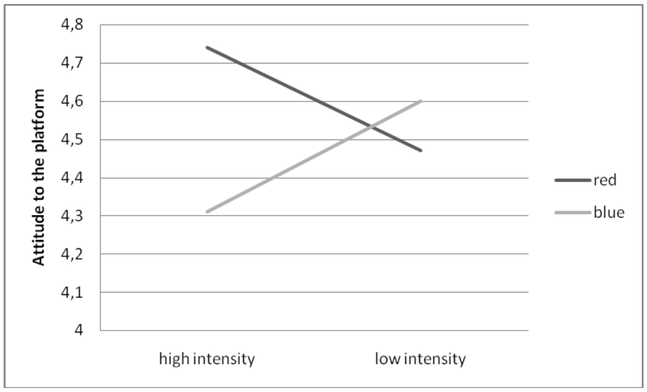
Note: ns = not significant

Although no main effects came to the fore with regard to either colour ($F < 1$) or light ($F < 1$), the analysis does show a marginally significant interaction effect ($F(5,99)=1,93$, p=.09) for colour x light. Because this interaction effect is leaning toward significance, we decided to conduct univariate analyses to further explore a possible tendency.

3A.



3B.



3C.

Figure 3. Interaction effects between colour and light for pleasure (A), attitude to the platform (B), attitude to the waiting time (C)

The presence of the two aspects together appear to determine the scores for pleasure, the attitude with regard to the appearance of the platform and attitude to the waiting time. Figure 3 shows the interaction effects that were found. The results reveal a tendency. Figure 3 (panels a, b and c) shows similar patterns of results for pleasure and the two attitude measurements. With pleasure, the attitude to the environment and the attitude to the time spent on the platform, the blue platform tends to score highest with the dimmed lighting whereas the opposite effect is the case for the red platform. In other words, with a low intensity of light one prefers blue as opposed to red surroundings. As the intensity of light increases, a shift occurs and the red environment is found to be more pleasant. The score for the three aspects of station perception is highest with the red platform with the high intensity of light; even higher than the blue platform with the lower intensity.

Additional analyses were performed to gain insight into participants' preference. When asked which colour they thought was best appropriate for a station (grey, green, yellow, red or blue), participants indicated a cognitive preference for the colour blue (36.2%) followed by a the colour grey (21.5%). Various one-way ANOVA tests show that this preference has no influence on the overall evaluation of the station. That is to say that when one

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[1] Because it is possible that game experience influenced participants' responses, we conducted ANCOVA's with game experience as covariate. The reported results remained (marginally) significant when controlled for game experience.

prefers (e.g.) blue on a platform, one does not necessarily appear to appreciate that platform better than someone who has a preference for another colour. It also appeared that only one third of the participants could actually indicate which colour was dominant on the platform, suggesting that the effects of colour occur subconsciously. This result is in line with studies on automatic consumer behaviour which suggests that consumers are often unaware of environmental factors influencing their behaviour (e.g., [21]).

Time perception

Time perception was included as a specific focus of interest in this study. Generally speaking, respondents estimate their time spent on the platform as significantly longer (M=4:54, SD=1:57) than the actual time of stay (M=3:18, SD=0:49; t(129)=-11.03, p<.00). Four univariate analyses of variance with the objective and subjective time, the overestimated length of time and how the time was experienced were carried out as dependent variables. No main effect for light comes to the fore from these analyses, nor does an interaction effect occur for colour x light. A main effect for colour did appear, however, for how the time was experienced (F(1,104)=4,63, p=.03). Results show that the time on the blue platform (M=4,66, SD=1.46) was perceived as being significantly longer than the time on the red platform (M=3.98, SD=1.79)). These results show that on a blue platform time is experienced to pass relatively slower than on a red one.

In the study 1 we were able to explore the effects of two colours in combination of intensity of light in a virtual laboratory. To further explore the effects of various colours in combination with intensities of light we need to expand the design of study 1. In a virtual laboratory, the actual performance of a study is time consuming. Therefore the number of participants is limited. Study 2 investigated the interactive effects of 5 different colours and two intensities of light in an online environment which allowed us to include a larger number of participants.

STUDY 2: ONLINE STUDY

Method

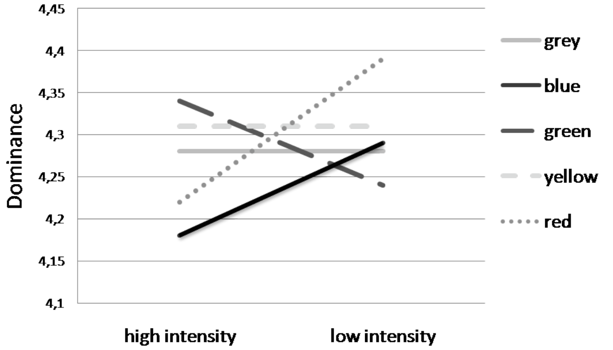
A 5 (colour: grey vs blue vs red vs green vs yellow) x 2 (light: high vs low intensity) between-subjects design was used. The virtual reality environment and the questionnaire from study 1 were converted to an online version. In total 2,360 respondents (56,9% men, 43.1% women) were asked to navigate through the online simulation.

Results

In order to ascertain interaction effects between colour and light, a multivariate analysis was carried out on the various aspects of station perception with colour and intensity of light as independent variables. The analysis yields an interaction effect for colour x light (F(20,9236) = 2.35, p = .001). The interaction effect was found in the degree of dominance (F(4,2310)=2,62, p=.03), and the attitude to the platform (F(4,2310)=2.74, p=.03)[2]. The significant interaction effects 'dominance' and 'attitude to platform' are specified in Figure 4 (panels A and B).

For the degree of 'dominance' the results show that colours with an extreme wavelength (blue and red) achieve the highest score with a lower intensity of light. With a platform with a medium wavelength (green), however, the highest score is reached with a higher intensity of light. With the baseline, or rather the grey platform, the intensity of light makes no difference. The results for the attitude to the platform show that the intensity of light with the blue and green platforms makes little difference. However, the red platform is deemed better with a higher intensity of light. This effect is the opposite of the yellow platform, i.e. on a platform with a yellow colour the platform is appreciated more when the light is less bright. Also noticeable here with the baseline measurement is that the intensity of light has little influence and causes no major differences. The marginal effects for the attitude to the waiting time show another picture: a platform with a short to medium wavelength (blue and green) is valued more positively than a platform with a higher intensity of light. On a platform with colours that have a longer wavelength (yellow and red) the attitude is better with less brightness.

4A.



4B.

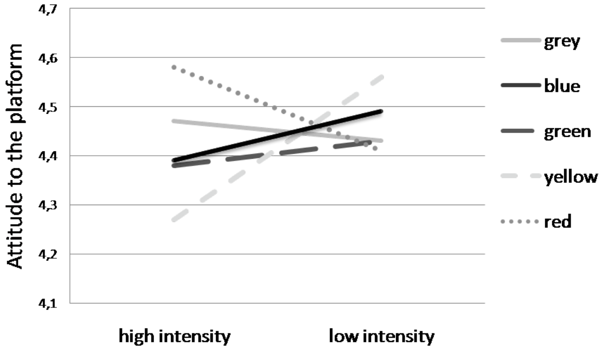


Figure 4 Interaction effects colour and light for dominance (A) and attitude platform (B)

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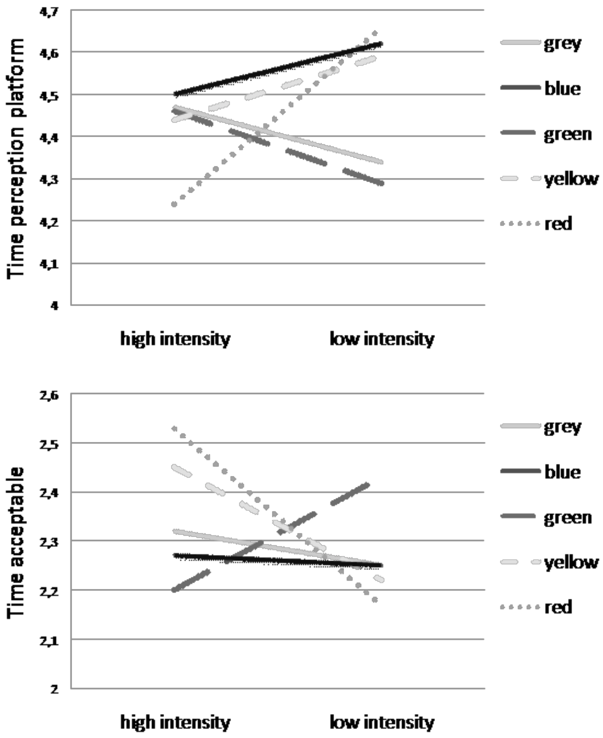
[2] Given the large d.o.f., the statistical significance of these results should be considered with caution.

Aspects of time were also included in study 2. On average respondents spent 7:09 minutes (SD=3:50) at the station, of which an average 3:54 minutes (SD=2:58) were on the platform. A t-test revealed a significant difference between the objective and subjective time on the platform (t(2244)=44,88, p<.001). The perceived time at the station appears to be significantly longer than the actual or objective time.

Again, univariate analyses of variance were conducted with objective and subjective time and time experience as dependent variables. These analyses produce a main effect for the intensity of light and applies to the time perception of the station (F(4,2329)=4,37, p=.04). This main effect demonstrates a difference between the station with the higher intensity of light (M=4,11, SD=1,52) and the station with less light (M=4,26, SD=1,49). The time spent at the station with the lower intensity of light was perceived as being significantly shorter than at the more brightly lit station. The interaction effect shows how time perception (F(4,2329)=2,41, p=.05), as well acceptability of time spent at the platform (F(4,2329)=3,18, p=.01) is influenced by the combined effects of colour x light. Panel A in Figure 5 shows that time was perceived as being shortest on the blue, yellow and red platform when the intensity of light was higher.

5A.



5B.

Figure 5 Interaction effects colour and light for perception platform (A) and time acceptable (B)

DISCUSSION

When we look at the results we can conclude that almost no main effects were found for colour and light. But we did find some interesting interaction effects for light and colour conditions. The results indicate that passenger respond more positively to warm colours in combination with dimmed (low intensity) lighting but at the same time estimate the waiting time as shorter when cooler colours and a more intense lighting are used.

As for time perceptions, most passengers appeared to overestimate the waiting time on the platform, which concurs with results from earlier work [45].

Although passengers have a definite cognitive preference for the colour blue in a well-lit environment, it appeared that only one third of the respondents could indicate which colour was dominant on the platform. In all situations the colour one thought to have seen most often was grey. Despite people indicating they also preferred well-lit surroundings, the results particularly show effects with dimmed situations. Apparently, passengers cling to the image they have of a platform. This confirms that colours and intensity of light are perceived subconsciously. For station evaluation, affective effects are thus more important than cognitive ones.

Both experiments also show the strong influence of waiting time perception in a station environment. Most people tend to overestimate the waiting time on the platform, as was also found in earlier research [25], [30], [35], [45] and can be explained by the attentional model of Zakay [49]. Zakay stated that people divide their attention in a prospective time judgment between the time and other activities. When time gets more attention, time seems to go slower [49], known as "a watched pot never boils" [36]. In a station environment especially daily commuters are focussed on the time. How the wait is evaluated and how useful passengers find it seems to be related to both the attitude to the platform and the impression thereof. In most situations, time in dimly lit surroundings appears to pass more quickly than when the lights are brighter. This confirms the results of Baker and Cameron [5]. In contrast to results found in the literature, time in a blue environment appears to pass more slowly than in a red one. One explanation might be that passengers who feel stressed not only desire cooler colours which are less arousing and distractive, but also pay more attention to the time itself, which makes it seem to pass more slowly [49].

The results show that manipulations in a virtual public environment successfully allow effects with colour, light, crowding and time pressure to be demonstrated. These findings offer an initial insight into the way colour and light work in a station. However, both experiments were conducted in a virtual station which might influence the outcome. Moreover, the significant results obtained in the online study should be considered with caution. Due to the large number of participants any difference in a dependent variable can be considered a statistical artefact evoked by large degrees of freedom. The question arises whether these findings would also be found in a real station. Recent developments in new techniques of lighting (e.g. ‘ambilight’) make it easier to study these effects of colour and light in real-life public spheres.

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Preliminary Evidence That Both Red and Blue Lights Increase Nocturnal Alertness

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ABSTRACT

Retinal blue light exposures impact nocturnal alertness, implicating participation by the circadian system, which is maximally sensitive to short-wavelength light. We investigated the impact of two levels of both blue and red light on nocturnal alertness, as measured by electroencephalogram (EEG). Exposures to both levels of the blue and red lights increased beta and reduced alpha power relative to preceding dim-light conditions. These results suggest that the circadian system is not the only light-sensitive pathway that can affect nocturnal alertness because the levels of red light used here are not effective for stimulating the circadian system.

Keywords

Circadian, alertness, light, electroencephalogram

BACKGROUND

The impact of light on alertness has gained recent attention in the scientific community because of the now well-established role that retinal light exposure plays in regulating extra-visual functions like the circadian timing system. Bright white light (greater than 2500 lx at the eye) has been shown to increase alertness at night [2, 3, 5, 7-10, 12, 17], but the mechanisms associated with the alerting effects of light have not been unambiguously established.

The human circadian system is known to be maximally sensitive to short-wavelength radiation (blue light) [4, 18, 25]; thus, the efficacy of "moderate" blue light should be comparable to that of "bright" white light for evoking measures of alertness at night [18]. Results from recent studies using blue light [6, 13] are entirely consistent with the neurophysiological evidence that neural pathways from the suprachiasmatic nuclei (SCN) affect sleep and alertness, as recently elucidated by Saper and colleagues [20-22], adding weight to the inference that the SCN, through retinal stimulation by short-wavelength light, play a role in human nocturnal alertness.

One way to test the hypothesis that the alerting effects of nocturnal light exposures are mediated only by the circadian system is to compare the impact of red and blue light on alertness at night. Long-wavelength ($\lambda > 600$ nm) light does not stimulate the human circadian system [4, 25] except perhaps at very high levels [14]. Therefore, if the light-induced stimulation of the circadian system at night is solely responsible for light-induced nocturnal alertness, then red light should be an ineffective stimulus.

The present experiment was designed to look at the impact that two "moderate" levels (10 lx and 40 lx) of both narrow-band blue (λ_{max} = 470 nm) and narrow-band red (λ_{max} = 630 nm) light might have on electroencephalogram (EEG) recordings during the night. Electrodes affixed to the human scalp are able to sense changes in brain activity when subjects engage in different types of mental tasks. The relative electrical power recorded at these different frequencies (from 1 to 50 Hz) is used to infer mental states in these subjects. Changes in the power at specific different frequency bands have been used as markers of mental alertness. Alertness is associated with lower levels of power in the alpha frequency band (8-12 Hz) and is associated with higher levels of power in the beta frequency band (12-30 Hz). If the circadian pathway is solely responsible for light-induced alertness at night, then only the blue light should reliably evoke an alerting response. Further, there should be a graded response in the EEG recordings with increasing levels of the blue light, as long as their irradiances are above threshold and below saturation for the circadian system response.

METHODS

Procedures and apparatus

Sixteen subjects (21 to 33 years of age) were recruited to participate in the study from an electronic posting at Rensselaer Polytechnic Institute in Troy, N.Y. All subjects were screened for major health problems and except for women taking birth control pills, subjects reported not taking any pharmaceuticals or medications. Every subject completed a Munich Chronotype Questionnaire (MCTQ) prior to the study [19]. In order to have a more homogenous sample of subjects, those who were late or extremely late chronotypes were excluded from the experiment. All subjects provided an informed consent approved by Rensselaer's Institute Review Board. Subjects were asked to refrain from alcohol and caffeine on the days of the experiment and were asked not to sleep after awakening for the day. Of the sixteen subjects, nine males and five females completed the entire experiment, and the results of their EEG data are reported here.

Four experimental lighting conditions, two spectra (blue and red) each at two light levels (10 and 40 lx) were delivered to individual subjects from 0.6 × 0.6 × 0.6 m light boxes, each fitted with arrays of light-emitting diodes (LEDs). The arrays (ICove, Color Kinetics) were located behind the front box apertures to be outside the subject's direct view, thereby creating a uniform, non-glaring distribution of light within the box. During light exposures, subjects placed their chin on a chinrest mounted near the front of a box, ensuring delivery of the prescribed light exposure. When sitting at the light box, the subject's head was aligned with the aperture of the box, so that subjects were always exposed to full-field, diffuse light. The spectral emissions of the blue LEDs peaked at 470 nm with a full width at half maximum (FWHM) of 25 nm. The red LEDs peaked at 630 nm with a FWHM of 25 nm. Before the experiment, each of the light boxes was calibrated using a Gigahertz illuminance photometer to provide the prescribed corneal illuminance levels when the subjects were positioned on the chinrest. The spectral irradiance of the red and blue conditions were measured prior to the experiment with a calibrated spectroradiometer (Photoresearch model PR705a) and diffuse white reflectance standard (Labsphere model SR 099) and used to calibrate the Gigahertz illuminance readings. Two boxes provided blue light (40 $\mu W/cm^2$ at 40 lx and 10 $\mu W/cm^2$ at 10 lx) and two emitted red light (19 $\mu W/cm^2$ at 40 lx and 4.7 $\mu W/cm^2$ at 10 lx); light levels could be adjusted with an electronic dimmer to reach the prescribed light levels without significantly affecting the relative spectral distributions of the LED emissions. Measurements of pupil area completed after the experiment with a different group of subjects (N = 5) were: red at 10 lx, 34 mm^2; red at 40 lx, 22 mm^2; blue at 10 lx, 10 mm^2; blue at 40 lx, 6.5 mm^2.

Groups of four subjects participated in two sessions separated by at least one week. Subjects were asked to arrive at the laboratory at 22:00 to receive instructions and be fitted with scalp electrodes for EEG recordings. Because only one EEG machine was available, data collection was staggered. The first subject in a session started at 23:00, the second at 23:10, the third at 23:20, and the last at 23:30; the last subject completed the experiment at 03:45. During every session, each subject was presented a high (40 lx) and a low (10 lx) light exposure condition of the same spectrum (blue or red). The presentation order of the light levels was counterbalanced across sessions for a given subject; light spectra were counterbalanced across subjects within sessions. Every 45-minute experimental lighting condition was preceded by a 45-minute period of inactivity in a dim-light anteroom (< 1 lx of red light at the cornea). During the inactive, dim-light periods, subjects remained quiet and were not allowed to perform any task (e.g., talk, read, or computer work) except for the prescribed data sampling specified in the experimental protocol. Each nighttime session consisted of four, 45-minute light-and-dim conditions (a dim-light condition always preceded one of the four experimental lighting conditions), plus a 15-minute period for data collection prior to each lighting condition (in addition to EEG recording, performance measures and saliva melatonin were also collected, but are not reported here).

Data Collection

The Biosemi ActiveTwo system with active electrodes was used for EEG recordings. This system is battery powered, minimizing electrical interference from alternating current (ac) during recording sessions. Electrodes were placed on subjects' scalps according to the International 10-20 system at Oz, Pz, Cz, and Fz [1]. Two additional electrodes serving as virtual reference electrodes for those attached to the scalp were attached to the right and to the left earlobes.

Near the end of each 45-min dim light and each 45-min light exposure period, the scalp electrodes on each subject were attached to the EEG recording system. Six minutes of data were collected: three one-minute periods with the subject's eyes closed alternating with three one-minute periods with the eyes open. When the eyes were open and subjects were not sitting at the light box (dim-light condition), the subjects were asked to fixate on a specific marked point approximately one meter away. Similarly, when sitting at the light box, subjects fixated on specific point on the far wall of the box approximately 0.6 m away. Subjects were visually monitored by an experimenter to ensure compliance with the protocol.

The EEG signals were sampled at 16384 Hz and then low-pass filtered and downsampled to 2048 Hz for electronic storage by the Biosemi system. All subsequent EEG data processing and analyses were performed with Matlab version R2008a by The Mathworks^{TM}. The signals recorded from the two reference channels were averaged and these values were subtracted from those obtained from all of the other channels. The direct current (dc) offset of each channel was eliminated by subtracting the mean value of each channel from itself. A low-pass finite impulse response (FIR) filter (f_{-3dB} = 50 Hz) was applied and the data were downsampled to 512 Hz. Then a high-pass, third-order Butterworth filter (f_{-3dB} = 4 Hz) was applied to the downsampled signals from each channel to eliminate slow trending in the data.

Another program divided the filtered data into 5-second epochs, segregated by periods when the eyes were open and when they were closed during the six-minute recording period. Eye blink artifacts were eliminated by removing epochs from all channels where voltage fluctuations of any epoch exceeded ±100 μV. A Blackman window followed by a fast Fourier transform (FFT) was then applied to the data segments. This process yielded spectral power distributions from 1-50 Hz. The power spectra for each one-minute segment were then combined to give an average spectral power distribution for each trial. The relative power levels for eyes open in the alpha (8-12 Hz), beta (12-30 Hz), gamma (30-50 Hz), theta (5-8 Hz), and alpha-theta (5-9 Hz) ranges were calculated as a percentage of overall power from 1-50 Hz. These calculations were not performed for those intervals when the eyes were closed. Reported here are the results from the percentages of power in the alpha and the beta range of frequencies because they have been used as measures of alertness in previous studies (e.g., [6]).

RESULTS

Two-way (eight light-and-dim conditions and four recording channels), repeated measures ANOVAs were employed using the percent power in the alpha frequency range (8-12 Hz) and using the percent power in the beta frequency range (12-30 Hz) recorded from four scalp electrode channels (Oz, Pz, Cz and Fz) in the EEG recordings. Both the main effects of light-and-dim conditions and of recording channels were significant for alpha (respectively, $F_{7,91}$ = 2.15, p = 0.046 and $F_{3,39}$ = 44.7, p <0.0001) and for beta (respectively, $F_{7,91}$ = 3.91, p = 0.0009 and $F_{3,39}$ = 5.36, p = 0.0035); the interaction between the light-and-dim conditions and the channels was not statistically significant for either the alpha or the beta frequencies, indicating that the alpha and the beta frequencies from every channel exhibited similar patterns among the eight light-and-dim lighting conditions. Post-hoc, paired two-tail t-tests were performed for the alpha and for the beta frequencies using the combined data from all four channels.

As illustrated in Figure 1, relative alpha power recorded from all channels after light exposure decreased compared to relative alpha power recorded in the dim light just prior to the light exposure. Alpha power after exposures to both levels of blue light (i.e., 10 lx and 40 lx) and to red light at 10 lx was statistically significantly lower than alpha power recorded in the previous dim-light condition. Consistent with Figure 1, Figure 2 illustrates the increase in relative beta power following light exposures compared to relative beta power recorded in the dim light just prior to the light exposures. Mirroring the statistical inferences for the alpha frequencies, there was a significant difference between the previous dim-light condition and the two blue-light conditions and for the red-light condition at 10 lx.

It was hypothesized that the blue light conditions would follow a dose response such that relative alpha power would be lower for the 40 lx condition than for the 10 lx condition. It was also expected that the relative beta power would be significantly higher for the blue-40 lx condition than for the blue-10 lx condition. This expectation was met for the alpha frequencies, (p = 0.01) but, although in the right direction, not for the beta frequencies (p = 0.1). Although the red-light condition resulted in dose intransitivity for both the alpha and the beta frequencies (i.e., the red-10 lx condition produced *lower* relative alpha power and *higher* relative beta power than for the red-40 lx condition), this difference was not statistically different for either frequency band (p = 0.21 for alpha power and p = 0.13 for beta power).

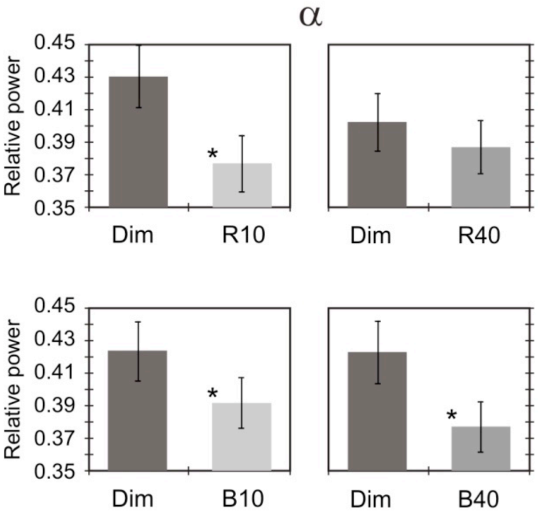

Figure 1. Relative alpha power after the four dim and the four experimental lighting conditions. Statistically significant (*) lower levels of relative alpha power were associated with blue-10 lx (B10; p = 0.007), blue-40 lx (B40; p<0.0001), and red-10 lx (R10; p< 0.0001), than with the previous dim-light exposures. There was no significant difference in alpha power between red-40 lx (R40) and the previous dim-light exposure which must, in part at least, reflect the significantly lower (p < 0.05) alpha power level associated with the dim condition preceding the R40 condition than with any of the other the dim condition.

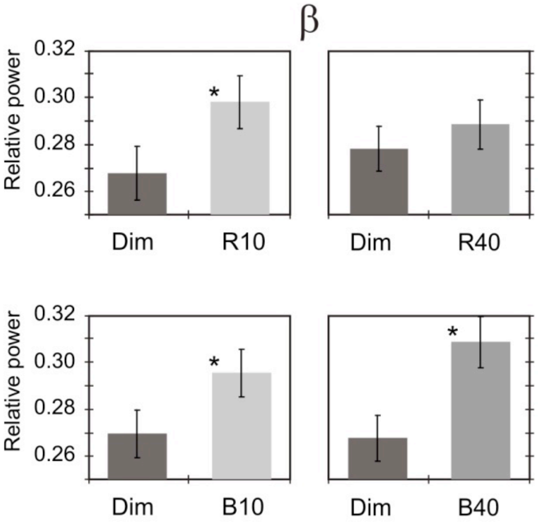

Figure 2. Relative beta power after the four dim and the four experimental lighting conditions. Statistically significant (*) higher levels of relative beta power were associated with blue-10 lx (B10; p = 0.0006), blue-40 lx (B40; p<0.0001), and red-10 lx (R10; p< 0.0001), than with the previous dim-light exposures. There was no significant difference in beta power between red-40 lx (R40) and the previous dim-light exposure.

DISCUSSION

Nocturnal alertness as measured by EEG is affected by light, but it does not seem to be affected only by light stimulation of the circadian system. Exposures to both red and blue light reduced alpha power and increased beta power levels relative to their preceding dim-light condition. However, there was only an apparent dose response for the blue light. That is, as levels of blue light increased from 10 lx to 40 lx, alpha power decreased and beta power increased (although not statistically significant), as would be expected if blue light served as alerting stimuli. Quizzically, the reverse was true for the red light. Although not significant, alpha levels were higher and beta levels were lower for 40 lx than for 10 lx of red light. If in fact reliable, the dose intransitivity for the red-light conditions remains unexplained and, indeed, somewhat implausible. It is conceivable that there is an optimum irradiance of red light for alertness (i.e., red-10 lx), but this inference seems rather unlikely and these results definitely demand further study. Nevertheless, these results indicate that colored light of ”moderate” corneal irradiance levels can induce alertness at night, but that light-induced alertness at night is not mediated only by the circadian system.

It is not completely clear, however, how light-induced alertness can arise from other neural pathways. Some evidence suggests that red light, which is ineffective for stimulating the circadian system at “low” and “moderate” light levels, can be more stimulating than blue light [15, 24]. Studies have reported that perception of red color prior to executing an important task impairs performance relative to the perception of green or achromatic color [11, 15]. Elliot et al. [11] performed a series of studies to investigate the impact of color red on performance in achievement contexts, that is, in situations in which competence is evaluated and positive and negative outcomes are possible. They hypothesized that red color is associated with danger of failure, and therefore, an automatic, unconscious decision to avoid the object, situation or event occurs. According to their hypothesis, red color impairs performance because it evokes motivational tendency to avoid failure, which, according to the authors, undermines performance. The results of their experiments supported their hypothesis that perception of red color prior to an achievement task impairs performance compared to a green and an achromatic color. Similar findings have been reported by Stone [23]. These results are not consistent with findings by Hill and Barton [15], however, who reported that red enhances performance of athletes who wore red color. In general, the studies of color on emotions and performance are conflicting and not well-grounded in neurophysiology. The explanation for this lack of consistency may be due to random, non-systematic effects of color on human perception or psychology or to individual differences in preference and cultural associations [16]. Notwithstanding this last point, these results are then, to a limited extent, consistent with some previous studies suggesting that red light acts as a stimulant through some unspecified neural pathway. It is important to note, however, that these earlier studies (e. g., [11, 15, 23, 24]) were probably conducted in the daytime, not at night, although the times for these studies were not documented. Further, these studies do not always provide quantitative descriptions of the colored stimulus. Clearly, more research is needed to elucidate the light-sensitive mechanisms affecting alertness during the day and during the night.

CONCLUSIONS

The present results are consistent with previous findings showing that light of sufficient corneal irradiance increases alertness at night. There is previous compelling evidence that light-induced stimulation of the circadian system increases alertness at night, but the present results implicate other mechanisms through which light can also increase alertness. It is important then to determine if these inferred mechanisms are independent of the circadian system or interact with it by conducting more systematic studies of light spectra and light levels during the night as well as during the day.

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Reducing Light Intensity and Changing its Spectral Composition: Effects on Human's Sleep Characteristics and Melatonin Suppression Under "Natural Conditions"

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ABSTRACT

Light has a great impact in our everyday life for vision, but also for non-visual processes. The recent discovery of photosensitive retinal ganglion cells triggers new studies on the non-visual effects of light's spectral composition. In the present study via the use of soft orange contact lenses we investigated how, under natural conditions, a reduction in exposure to the short wavelengths (blue) light affects sleep and the suppression of melatonin concentrations to a standard light stimulus in healthy young subjects. The orange lenses were effective in reducing light input. If worn only during the light pulse melatonin suppression in response to a 2h 600 lux white light pulse was reduced from 29% in the control condition to 17.3% ($p<0.05$). No significant differences in melatonin suppression were observed between the control condition (29%) and after wearing the orange lenses for 16 days (34.1%). These results indicate that the non-visual response of melatonin suppression to light adapted. While wearing the orange lenses the amount of sleep was reduced, somewhat similar to the sleep changes that occur with ageing.

Keywords

Light intensity, Light spectral composition, Melatonin, Sleep, Humans.

INTRODUCTION

Due to the earth's daily rotation around its axis a temporal pressure is imposed on almost all organisms; a 24h day with light and dark cycles (day and night). In order to anticipate the temporal changes along the 24h day, organisms have evolved circadian clocks. The circadian clock generates cycles with an approximate period of 24h that needs to synchronize with the external environment. Light is the signal that sets the phase of our biological clock, which in turn synchronizes our physiological and psychological rhythms to the 24h rhythm of the environment [1, 2]. Furthermore, light has acute alerting and activating effects and acutely suppresses melatonin at night [3,4,5]. Synchronization of the biological clock depends on several aspects related to the light signal; its intensity and the time of exposure. The recent discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs, maximal sensitive to short wavelengths) [6] has triggered new studies on the role of not only light intensity but also its spectral composition. Suppression of melatonin has been shown to be higher to light pulses of short wavelengths than to light pulses of other wavelengths [7,8,9]. Alertness was also shown to be more sensitive to short wavelengths [9]. These studies however, compared the effects of monochromatic light sources, which although informative to understand mechanisms is far from being a natural situation.

Considering the natural phenomenon of cataract (yellowish of the lens with ageing) [10], in the present study we investigate what the effects are of a reduction in (blue) light via the use of orange soft contact lenses. This situation resembles at least qualitatively what happens with ageing. We hypothesized therefore a disruption of sleep patterns and a reduction in the suppression of the nocturnal melatonin to nocturnal light exposure.

MATERIALS AND METHODS

Subjects

In total 50 subjects enrolled for the study. Only those subjects who were healthy, non-smoker, non-color blind, and with an intermediate chronotype [11, modified for Dutch population] were selected. Subjects who worked night shifts or travelled through more than 2 time zones during the 2 weeks prior the study were also excluded. Because subjects have to wear soft contact lenses during 2 consecutive weeks, 24h per day a check-up by a contact-lenses specialist was conducted at the University Medical Center of Groningen (UMCG) in order to assess subject's eyes condition. After screening, 22 subjects were selected from whom 15 completed the study (7m:8f, mean age ± sem: 24.5 ± 4.6 years old). The study was conducted between December 2007 and September 2008. The Medical Ethical Committee of the UMCG, The Netherlands, approved the study protocol. All subjects signed a written informed consent form prior to their participation.

Soft orange contact lenses (OL)

The OL (CE: 0120, with UV protection) were supplied by Oculenti at the UMCG, The Netherlands from Ultravision International Ltd., UK. In the visible range of the spectrum (from 400-700 nm), the OL reduced transmitted light for 37% (calculated as the area under the curve) while in the short wavelengths (400-530 nm) the reduction was 56%. The reduction in light transmission through the OL can be seen in Figure 1.

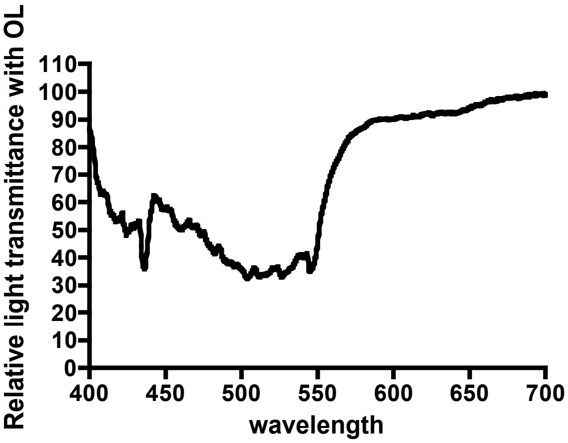

Figure1: Relative light transmittance through the OL from a halide light bulb (MDS 200.2, Philips).

Experimental design

A control condition (subjects wore their own contact lenses n=13, or no lenses n=2) and an experimental condition (subjects wore the OL) were assigned to each subject in a randomized order. The OL were worn 24h per day. Each condition lasted for 16 days, they were planned at least 2 weeks apart to avoid any potential carry-over effects, and they started on the same day of the week in order to have a similar pattern of behavior within each subject.

Measurements

During the 16 days that each condition lasted, subjects wore an actiwatch® (Cambridge Neurotechnologies, UK) to measure sleep-wake cycles and filled in sleep diaries. During the last two nights of each condition, subjects came to the lab in order to assess a dim light melatonin profile on the first night and melatonin suppression on the second one. During the first night, in order to assess melatonin profiles, light levels were dimmed (<10 lux) and saliva samples were taken using cotton swabs (Sarstedt BV, Etten-Leur, The Netherlands) hourly from 19:00 to 00:00 h, every half hour until 2:00 h, and 2-hourly from 3:00 until 9:00 h. On the second night the same protocol was followed until 00:00. From 00:00 until 2:00 h subjects were asked to sit in front of 2 light boxes with full spectrum white light (600 lux, Pharos Max, Osram Dulux-L tubes, ©Lumie) to investigate the suppression of melatonin. During these two hours subjects watched a movie on a TV situated in between both light boxes so that they could keep their level of gaze constant. Light intensity at eye level was regularly checked during the 2 hours light pulse and adjusted if necessary. On a separate night from each 16-days session, subjects came for an extra night at which the acute effect of the OL on suppressing melatonin was measured (S-OL). For this purpose, the protocol of the second night was repeated but in this session subjects put the OL in only 30 minutes before the light pulse (in contrast with 15 days of continuously wearing the OL; L-OL). Subjects were carefully instructed about the collection of saliva samples for melatonin assessment. Eating was restricted to the 15 minutes after each sample, chocolate, bananas, coffee or black tea were not allowed during the whole time. Samples were centrifuged immediately after its collection and stored at -20ºC until its analysis.

Analysis

Melatonin concentration measured in saliva was determined by means of radio-immunoassay (RK-DSM, Bühlmann laboratories AG, Siemens Medical Solutions Diagnostics, Breda, The Netherlands). The area under the curve was calculated from time point 00:00 until time point 2:00 for the control profile, and the control (CL), the L-OL and the S-OL suppression conditions to estimate the nocturnal melatonin suppression by light. A repeated measurements ANOVA was used to test the effects of these conditions.

Sleep parameters were assessed by means of actiwatches and sleep diaries. For this purpose only the first 14 days of each condition were used since sleep during the last two nights in our lab was disturbed by the sampling protocol. Actual sleep (the percentage of assumed sleep minus the time being awake), sleep efficiency (percentage of time spent asleep while in bed) and sleep fragmentation (the percentage of immobility phases of 1 minute as a proportion of the total number of immobility phases) were calculated. The effects of the OL were tested with Paired-T test.

RESULTS

The suppression of melatonin during light exposure measured as the area under the curve relative to the control profile condition (= 0 level in figure 2) can be seen in figure 2. The repeated measurement ANOVA revealed a significant effect of condition (F (4,9) = 5.694, $p < 0.05$). Post hoc comparisons showed no significant differences between suppression after wearing the OL for 16 days (L-OL) with the control suppression (CL) (F (1,13) = 0.26 p = 0.62). However, when compared to the control suppression the acute suppression achieved in the S-OL condition was significantly different (F (1,12) = 10.427, $p < 0.01$).

Wearing the lenses for 16 days lead to a small but significant reduction in the actual sleep percentage ($t = 3.41$, $p < 0.01$), no significant differences were found however in the sleep efficiency nor in the fragmentation index (table 1).

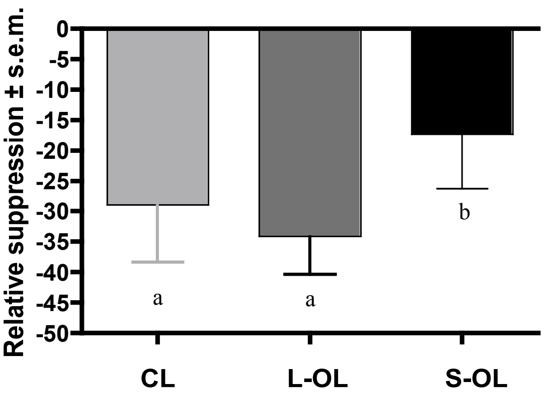

Figure 2: Melatonin suppression (calculated as area under the curve) ± s.e.m. relative to the control profile (0 level). No significant differences in suppression were found between the control (light grey bar) and the OL (dark grey bar) condition (denoted by a), while the acute suppression of the OL (black bar) was significantly different from the control condition (denoted by b).

	Control	L-OL	p-value
Actual sleep %	85.05 ± 1.49	83.64 ± 1.44	< 0.01
Sleep efficiency	80.77 ± 2.05	80.10 ±1.68	ns
Fragmentation Index	27.54 ± 3.13	28.71 ± 3.00	ns

Table 1: Mean ± s.e.m. and p values of the sleep parameters measured in this study for both conditions.

DISCUSSION

The aim of this study was to investigate the effects of diminishing the light input, in particular in the short wavelengths range of the visible spectra. In order to do this and trying to simulate a natural situation [10], subjects wore soft orange contact lenses (OL) for 16 consecutive days, 24h per day.

Melatonin suppression by light is a way to estimate the effects of light input to the biological clock [12]; the smaller the suppression to the same stimulus the less sensitive the system is. In the present study we clearly showed that wearing the OL only during the light pulse (S-OL) reduced the light input to the system; the suppression of melatonin to a white light stimulus was less then without the lenses (CL). When the OL were worn for 16 days (L-OL) the suppression of the nocturnal melatonin was not different from the suppression without the OL (CL). It can be concluded that the system has become more sensitive after 16 days of reduced (short wavelengths) light input by wearing the OL. It has already been shown that exposure to dim light during one week by staying inside and using dark goggles (2% light transmission) increased the suppression of the nocturnal melatonin due to a higher sensitivity of the system [13]. Our study represents a more realistic situation in terms of both the reduction in light intensity as well as the "bright light exposure" condition. In Hébert *et al.*[13], subjects exposed themselves to bright light boxes in the bright light week condition while in the present study they exposed themselves to natural and artificial light in accordance to their personal behaviour. The mechanisms by which adaptation occurs and at which level in the circadian system it happens is not know. At the retinal level several possibilities could be hypothesized. Photostasis, gradual changes in the retina to keep a constant number of photons absorbed per day, has been already shown in rats [14], although there is still no proof of such processes happening in the human retina. A shift to the responsive form of the bistable melanopsin molecule due to a reduction in exposure to short wavelengths and a relative increase in exposure to long wavelengths while wearing the OL is another possibility [15].

Regarding sleep parameters a reduction in the actual percentage of time that subjects spent sleeping was found as a result of wearing the OL. Although also sleep efficiency and fragmentation index showed minor changes in the direction of a more disturbed sleep pattern while wearing the OL these differences were not significant. Obviously the reduction of light exposure due to the OL was not big enough to induce sleep disturbances in these young people, or the adaptation process was fast enough to normalize the overall sleep pattern over the 16-days period.

The present study does not support the idea that the changes seen in the circadian system with ageing can be explained by the development of cataract in the elderly. However, the present study has been conducted in young healthy subjects and probably extrapolating these data to the elderly might not be possible. With ageing the circadian input system might become less flexible and looses its capability of adapting to the different situation.

In conclusion short wavelengths do play an important role in the suppression of melatonin [7,8,9, and the present study], but exposure to changes in the spectral composition of "natural light" on the long-term lead to adaptation of the non-visual responses to light in young subjects. These results are important both for understanding individual differences in non-visual responses to light, and for artificial indoors lighting developments.

ACKNOWLEDGMENTS

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Reflections on the Eyelid: Experiencing Structured Light through Closed Eyes

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ABSTRACT

It is generally taken that closure of the eyes for periods longer than a blink blocks visual perception due to the presumed diffusion of image structure by the eyelids. Although as much as 14.5% of the light incident at the eyelid may reach the retina, a capacity to visually perceive meaningful structure has not previously been proposed. We report on visual experiments through the closed eyelid, demonstrating the presence of both spatial and temporal sensitivity. By Rayleigh's criterion, we found a mean spatial resolution of 21° for the closed eye (N=17), in comparison with optimal open eye resolution of approximately 0.008°. In addition, we found that motion direction discrimination was qualitatively comparable to performance with an open eye that was perceptually matched with the closed eye for blur and brightness (N=8). Confidence in making closed eye observations was significantly lower than with open eyes, and subjects' mean blur and brightness matching using the open eye overestimated (based on previous measurements of transmission through the eyelid) the attenuation of light in the closed eye by more than 50 times. A further observation indicates that colour naming can also be made accurately through closed eyes. Applications of the findings are considered in the context of how light and pattern may be experienced on the *dark side* of human vision.

Keywords

Closed eyes, eyelid, motion sensitivity, direction discrimination, Rayleigh's criterion, colour naming

INTRODUCTION

The present investigation challenges the widely-held assumption that the world cannot be perceived visually when the eyes are closed. Closing the eyes attenuates significantly the characteristics of the retinal image affecting the consequent reception by conscious (i.e. perceptual, cognitive, cortical) and non-conscious (i.e. circadian, reflexive, subcortical) neural mechanisms. The factors leading to the attenuation of the retinal image when the eyes are shut may be broken down into the spectral filtering and diffusion applied by the skin of the eyelid prior to the light reaching the retina. We examine experimentally the extent of the spatial and temporal attenuation. We consider whether, under controlled lighting and display conditions, perceptual processing may still take place through closed eyes, and if thus, what are the implications, and what advantage can be made for lighting and well being applications.

Spectral Filtering

Sensitivity when the eyes are closed is heavily reduced, especially at short and medium wavelengths, with most of the uniform light reaching the retina radiating in the 'red' region of the spectrum [2, 9, 13, 14]. Subjective observation confirms readily the band-pass nature of the eyelid filter at long wavelengths: for example, looking at an intense, broad spectral light source (such as the sun) normally produces an appearance through closed eyes of a broadly homogenous field of light with a reddish hue.

The observation favouring a red coloured filtering effect by the eyelid has also been confirmed by formal investigation. Ando & Kripke's [2] threshold measurements for the detection of light passing through the eyelid indicated that there was 94% attenuation for monochromatic red light, compared with 99% for blue and green light. Physical measurements find spectral characteristics for the eyelid that are similar to other blood-bearing biological tissue. Robinson et al [13] delivered monochromatic light through a fibre-optic that was mounted onto a contact lens, with the output detected on the outside skin of the eyelid using a photodiode. Their data from 5 adult subjects indicate that the eyelid acts as a predominantly red-pass filter with mean transmissions at 700nm and with as much as 14.5% of the light transmitted across the skin of the eyelid. Similar measurements with 9 preterm neonates indicated the transmission of 21.4% if the light.

Diffusion

In addition to heavy spectral filtering, a second attenuation factor present when closing the eyes is the diffusion of the spatial structure of the image incident at the eyelid, blurring the retinal image prior to photoreception. The extent of the blur is assumed implicitly in the literature, and commonly by lay people, to be total and therefore the main cause for blocking visual perception with closed eyes. It has never been measured, to our knowledge, probably for this reason Our first objective, therefore, is to estimate the blur due to the eyelid by measuring spatial resolution to determine if it is instead finite in extent and quantifiable under controlled conditions.

Spatio-temporal Structure

Whether or not meaningful visual perception can take place with closed eyes can be determined by measuring the psychophysical performance of human observers in spatial and temporal visual tasks. Comparing the results to appropriately matched open eye equivalents would indicate whether the underlying mechanisms are the same for open- and shut-eye vision. Spatial resolution is often measured in optical studies by the Rayleigh criterion [16], which is defined as the minimal retinal angle subtended for which the separation between two point sources can be resolved. The minimal resolvable angle thus measured defines the line-spread function (the inverse of the modulation transfer function), which is readily converted to spatial resolution (see, for example, Fig. 1).

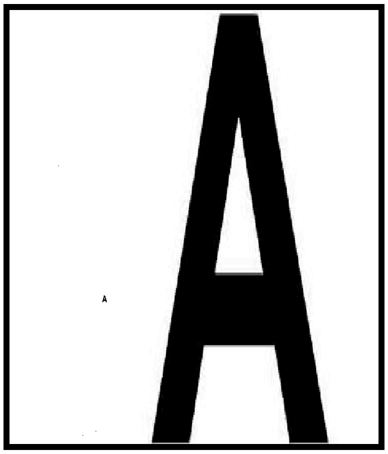

Figure 1. Illustration comparing the Snellen optometric chart visual acuity for an open eye (barely visible ‘A’, left) to the theoretical Snellen acuity of a closed eye through the eyelid (large ‘A’, right). The relative letter sizes are derived from the ‘worst’ Snellen acuity (open eye), and ‘best’ Snellen acuity (closed eye) calculated from the mean Rayleigh resolution (see Experiment 1).

Our second objective is to assess whether vision with closed eyes can include functional perceptual properties in the temporal domain. Motivated by the evolutionary need for predator avoidance, perhaps the simplest task to examine for temporal sensitivity across the eyelids would be direction discrimination during motion. With closed eyes under bright illumination - conceptually, for instance, for predator avoidance, a shadow cast on the eyelid would firstly need to be detected, and secondly, its direction of motion would need to be discriminated (e.g. in order to take the correct evasive action). This was addressed experimentally by testing our subjects’ ability to detect motion direction for the brief presentation of a vertical bar drifting to the left or right, measured separately for the shut and open eye, with brightness and blur perceptually matched beforehand.

Our final objective, if visual perception can be shown to take place through closed eyes, is to consider what use can be made of the reported visual property, especially for the benefit of human health and wellness. We consider in our discussion categories of eye closure and discuss possible directions for applying the finding within each of them.

METHODS

Experimental methods are described below for the overall setup, and separately for the spatial resolution (Experiment 1), perceptual matching (Experiment 2) and direction discrimination (Experiment 3) experiments.

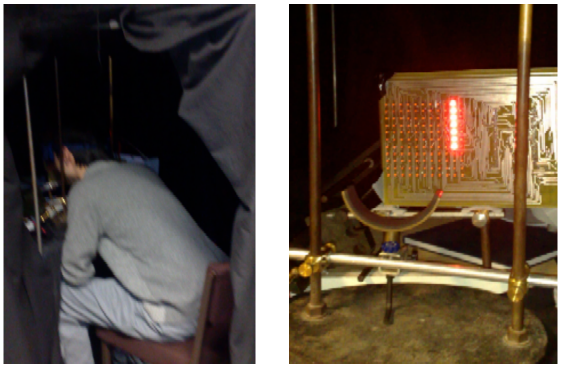

Figure 2. The experimental setup. Left: A subject is seated in the experimental booth; during experiments the curtain would be drawn for complete darkness. Right: The subject’s chin rest and stimulus display array. An illuminated vertical column of the red LEDs is shown. For Experiment 1, the viewing distance is changed by moving the display array along calibrated track (partly visible on the lower left).

Experimental Setup

Physiological optics generally neglects the optical properties of the eyelid (or treats it as opaque), though it is rightly the first stage of the visual pathway when the eyes are closed. The eyelid can be modeled as a spectral filter, attenuating light differentially across the visible spectrum, placed in series with a diffuser that blurs the image. Spectral attenuation by the eyelid is highest at the blue and green regions of the spectrum, with most of the energy at the photoreceptors remaining in the red (due to the optical properties of skin and blood) [2, 9, 13, 14]. As our objective for obtaining resolution thresholds was to measure the blur that includes the degrading effects of the eyelid we maximised effective transmission in the apparatus by restricting stimuli to light in the red region of the spectrum. We used a custom, computer controlled stimulus grid designed and built in-house consisting of 9 rows by 9 columns of bright, red LEDs spaced 1.0 cm apart along each of the vertical and horizontal axes of the grid (see Fig. 2, Right Panel).

The spectral peak of each LED in the display array was 635 nm with a bandwidth of 45nm at half height. Experimental observation was done monocularly, with one eye closed and the other patched to full darkness at a given trial, using a chin-rest for stability and a Maxwellian view that allowed subjects to sit at comfortably close distances to the stimulus grid centred at the eye (see Left and Right Panels of Fig. 2). LEDs that were lit were displayed at equal, high brightness levels. The total luminance flux per area was determined by measuring, with a photometer, the luminance of a single LED (269 cd/m^2), multiplying this by the area of an LED (circular, 3mm diameter) to get the amount of luminous flux that the LED would contribute to the display. The single LED's value is then multiplied by the number of LEDs illuminated in a given stimulus configuration to obtain the total flux, which is then divided by the area encompassed by the illuminated cluster. In Experiment 1, the 4 x 7 LED display (Fig. 3, Left Panel) has a luminance of 30.0 cd/m^2, while the respective luminance values for the display in Experiments 2 and 3 (see Fig. 4) is 33.3 cd/m^2.

Informed consent was obtained from subjects prior to their participation; all subjects were between the ages of 20-23 years and had normal or corrected to normal vision through contact lenses. Subjects first dark adapted for at least 20 min prior to the commencement of trials and were allowed at least 10 min of practice to become familiar with the nature of the apparatus and the experiments. Measurements for spatial resolution were made using the method of limits (the viewing distance was manually manipulated by the experimenter in order to vary the size of the retinal angle subtended by the test stimulus), while those for directional discrimination were done using a 2-alternative, forced choice (2AFC) paradigm by randomly varying the motion direction of the stimulus. Subject responses were made verbally in Experiment 1 and 2, and by button presses corresponding to 'left' or 'right' direction with a hand-held keyboard in Experiment 3.

Experiment 1 – Rayleigh resolution

Spatial resolution thresholds were determined on the basis of the Rayleigh criterion [14], defined as the minimum resolvable detail, as limited by factors such as diffraction, blur and noise. Functionally, the Rayleigh criterion is measured as the smallest retinal angle at which a gap is resolved between two adjacent point sources. To enable better performance through brighter stimuli, we used columns of LEDs rather than point sources, thus obtaining resolution based on the alternative 1-D optical line-spread function rather than the 2-D point-spread function [see 5}. The Rayleigh criterion was thus taken as the maximal distance between the eyelid and the array at which a 2.0 cm gap between two vertical LED columns was resolved and discriminated from 1.0 cm gap (see Fig. 3). The two frames were presented alternately for a 1.0 s duration each interleaved by a dark frame of the same duration. Viewing distance was used to estimate thresholds for resolving the fixed stimulus gap, owing to the limitations in the range of resolutions possible with our custom built bright LED display apparatus. A confound with stimulus luminance therefore occurs owing to light attenuation with increasing distance; superior resolution values are likely to be achieved using more advanced displays with higher luminance values that are held constant, while varying stimulus resolution directly. 17 subjects participated in this experiment and each subject's testing session required approximately 30 min.

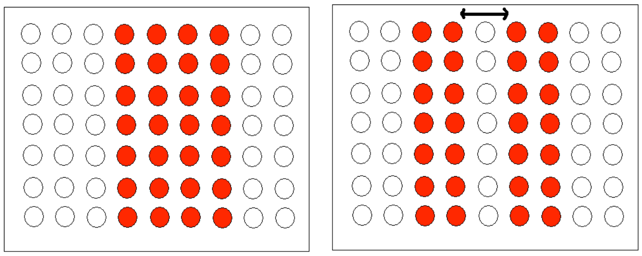

Figure 3. The display frames used for measuring Rayleigh criterion for Experiment 1. The two frames were alternated repeatedly, interleaved at 1 Hz by a blank frame (not shown). The physical gap between adjacent columns was 1cm (which was not detectable at the range of viewing distances used), thus the gap to be resolved in the second frame was 2cm wide (see arrow, right frame). The subjects were required to correctly identify and verbally confirm the visibility of the gap, with viewing distance manually adjusted to the largest distance, and therefore the smallest retinal angle, for which subjects correctly named the frame containing the gap.

Experiment 2 – Perceptual matching

Quantitatively comparing open and closed eye vision required that the stimulus properties of the former be perceptually matched to that of the latter. Subjects were asked to wear a custom-made facemask to which layers of neutral density (ND) filters and sheets of tracing paper could be attached in front of each eye's view, for light attenuation and, in addition, blur. Each ND filter attenuated light intensity by 75.0%, while tracing paper attenuated light intensity by 97.0% per sheet. We then presented subjects with a bright, steady LED array stimulus consisting of three vertical columns, asking subjects to match the percept seen in the closed left eye with that of the open right eye, by covering each eye alternately while observing the stimulus with the other. We added and removed filters and sheets of tracing paper to the open eye's view until the subject reported no difference between the percepts for both eyes.

A subject's settings therefore consisted of a finite number of ND filters and tracing paper sheets, from which the viewed luminance may be computed for the open eye as the perceptual match to the closed eye. If settings were based on veridical luminance perception, as measured for light transmission through the eyelid by other studies [2, 13], then we would expect filter settings for the open eye's view that achieve between 5% and 14.5% light transmission.

13 subjects participated in this experiment and each subject's testing session required approximately 15 min. One additional subject reported difficulty doing the matches and also produced extraordinary results. These data were therefore excluded from the sample as an outlier.

Experiment 3 – Direction discrimination

Directional discrimination thresholds were determined as the percentage of correct responses ('left' or 'right') for three vertical columns of illuminating LEDs drifting in the horizontal direction over a sequence of three 400 ms frames (2.5 Hz), as illustrated in Fig. 4. The viewing distance used to present the stimuli was 2.0 cm, resulting in a temporal drift velocity of ±70 °/s. Stimulus brightness was varied by placing the appropriate number of layers of ND filters in front of the LED array.

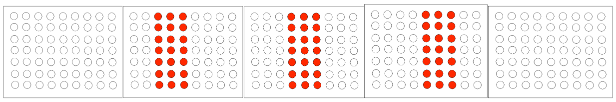

Figure 4. The display frames used for discriminating direction of drift in Experiment 3. The frames were presented in sequence at a rate of 2.5 Hz from left to right, as above; the illustrated sequence corresponds to rightward motion. Blank frames appear as shown at the start and end of each presented sequence.

RESULTS

Experiment 1 – Rayleigh resolution

Spatial resolution thresholds were obtained from one-dimensional Rayleigh criterion judgments. Expressed in degrees of visual angle at the nodal point of the eye, the mean (± SD) Rayleigh resolution was 20.95° (±8.44°). The viewing distance values across all subjects are normally distributed, as shown in Fig. 5. The mean Rayleigh resolution may be compared to the equivalent resolution for open eyed vision. Under optimal conditions, the diffraction-limited, optical resolution [e.g. 5] has been shown to match that of the neural pathways [6] to a value of approximately 0.0083°.

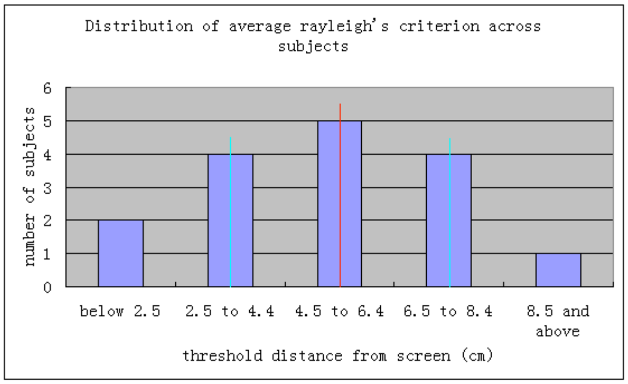

Figure 5. The distribution of viewing distance for spatial resolution measured according to Rayleigh's criterion in Experiment 1. The mean, shown at the vertical red line, is 5.409cm, which is equivalent to 20.95°±8.44° of visual angle subtended at the nodal point of the eye. The standard deviation, shown by the blue lines, is ± 1.96,. N=17.

Experiment 2 – Perceptual matching

Perceptual matching was obtained, as explained in Methods, between the percept from a bright light as viewed by an open eye through filters to that seen in the closed eye. The filter settings (also used for Experiment 3) show a considerable mean ((± SD) over-estimation of the amount of brightness attenuation taking place across the closed eyelid of 0.09% (± 0.21) transmission (i.e. 99.01% attenuation); this may be compared with published estimates of approximately 5% transmission (i.e. 95% attenuation) for similar perceptual measurements [2]. This is more than a 50-fold over-estimation. In addition, there are large differences in subjects' individual perceptual settings. (see Table 1, column 3).

Sub ID	Matched filters (ND & TP)	Transmission (%)
1	4 & 3	1.05E-05
2	2 & 2	5.63E-03
3	2 & 2	5.63E-03
4	2 & 1	1.88E-01
5	4 & 2	3.52E-04
6	1 & 8	1.64E-11
7	1 & 4	2.03E-05
8	2 & 6	4.56E-09
9	2 & 2	5.63E-03
10	1 & 1	7.50E-01
11	2 & 2	5.63E-03

12	2 & 2	5.63E-03
13	2 & 1	1.88E-01

Table 1. Subjects' individual filter settings in Experiment 2 selected for the open eye to match the perceived appearance of a bright light source seen through the eyelids in the closed eye. The first number in the middle column indicates the number of neutral density filters, each with 75% light transmission. The second number in the middle column indicates the number of sheets of tracing paper, each with a 97% light transmission. The mean transmission percentage (± 1 SD) through the matched open eye filter for all subjects was 0.09% (± 0.21), a large overestimation of the attenuation (compared to earlier reports), or equivalently, an underestimation of brightness through the eyelid.

Experiment 3 – Direction discrimination

Directional discrimination thresholds for 8 subjects for open and closed eye conditions are shown in Fig. 6. Results show clearly that motion direction can be discriminated through a closed eyelid. This appears to take place in a qualitatively similar manner as a function of stimulus luminance as it does through a perceptually matched open eye. However, it is also clear that performance in the open eye remains superior to that of the closed eye by approximately 15-20% under the conditions in the present experimental setup. The quantitative difference is seen despite the filtering applied individually for each subject (see Table 1, and Experiment 2) to match the percepts in the two conditions. As indicated earlier, the matching made the open eye's view darker than would have been expected from previous measurements [2, 13]. So the difference in direction discrimination between closed and open eyes may have been under-estimated in this experiment.

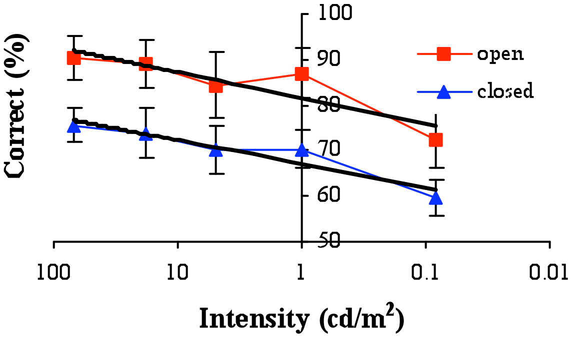

Figure 6. Mean subject performance (% correct) in discriminating the direction of motion monocularly through an open or closed eyelid. In the open eye condition subjects viewed the stimulus through tracing paper and a series of neutral density filters, selected individually as a perceptual brightness and blur match to their closed eye percept. Discrimination is easier through an open eye despite the matched percept and probable overestimation of attenuation in the perceptual matching (see Table 1), though performance appears qualitatively similar in the two conditions. Errors bars are shown as ± standard errors of the mean. N=8.

A Colour Naming Observation

The spectral filtering of the eyelid is well known and although colour perception behind the closed eyelid has not explored, the filtration is thought largely to impoverish the retinal image of chromatic information except in the red. The experiments we report make use of a band limited red LED display panel in order to maximize the brightness at the most effective spectral range, namely in the red. However, we also make the following observation. We presented single, bright (uncalibrated) LED key-chain type flashlights in red, green, white and blue, applied in random order at the surface of the eyelid to one closed eye (the other eye was patched). The five subjects tested, with 10 or more presentations of each colour, were able to name the colour to near complete accuracy. Thus, human perception of colour, and thus the presence of cone vision, is not precluded when the eyes are closed.

DISCUSSION

The investigation began with questioning the commonplace presumption that active visual perception is extinguished when the eyes are shut. Indeed, in basic psychophysical, neurophysiological, and applied vision research, a closed eye condition is often used as the controlled 'no-vision' condition. There undoubtedly is extensive attenuation of visual information through closed eyes. However, casual observation (through introspection) of a small uniform light source through closed eyes has motivated us to consider whether structural spatiotemporal image information may be detected and perceived under certain circumstances; and if this is so, whether such shut-eye visual processing may serve to benefit novel applications in medicine, lighting and imaging research, as well as improve our understanding of visual processing.

Our preliminary survey of visual capacity through closed eyes of two visual spatiotemporal parameters, spatial resolution and directional discrimination, demonstrate that spatiotemporal structure can be perceived in visual images seen through the closed eyelids. The novelty of making conscious observations with closed eyes, and probably the reduced control of eye position sense [1], leads subjects to report a reduced confidence in their judgments. When questioned at the end of experimental runs, subjects reported mean (± SD) confidence[1] in their direction discrimination of 7.63 (±1.97), with the eye open, compared with only 4.76 (±2.48) with it closed, a reduction in confidence of 38%. The reduced confidence cannot

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[1] Confidence scale 0 to 10; 0 = 'no confidence', 10 = 'complete confidence.'

explain the underestimation of perceived brightness through the eyelid (see Table 1), as uncertainty would more likely lead to a large variance but not necessarily an order of magnitude or two of underestimation in perceived brightness of the closed-eye.

Subject accuracy, particularly for direction discrimination, is nevertheless good. Percentage correct for the most visibly (i.e. brightest) stimulus is only 14% lower for the closed eye (see Fig. 6). A likely reason for the inferior direction discrimination of the closed eye is the absence of position information due to the severe loss in spatial resolution through the eyelid. Indeed, the discrimination of motion direction despite such severely impaired spatial resolution, provides a clear instance of objectless motion perception [15], as also observed for blindsight patients [3]. There is no indication, however, that performance would not continue to improve with further increases in image brightness.

Spatial resolution, as measured by the Rayleigh criterion, is extremely poor compared with open-eye vision (see Fig. 1), yet surprisingly good compared with what might be expected, namely, an absence of any resolvable detail when the eyes are shut. The poor resolution is due to the blur and brightness reduction of the eyelid caused by diffusion. The expected dominance of lower-resolution, rod-mediated vision operating at the eyelid-attenuated light levels following dark adaptation would not be expected to be a significant factor, as the rods perform poorly for red light. In addition, we found that colour perception, the hallmark of cone-mediated vision, can take place with closed eyes. Our estimates are therefore conservative, given the greater resolving power of the cones, and we believe that significantly higher resolutions than reported here are likely to be detected with improved conditions.

Extended periods of eye closure are normally associated with sleep, when only relatively large and abrupt changes in ambient light level seem to affect behaviour (e.g. by waking or stirring the sleeper). On the other hand, sufficiently slow, gradual changes in ambient level are not likely to be perceived consciously through closed eyes (or even open eyes), although some light transmission through the closed eyelid would presumably be advantageous to assist circadian training as dawn approaches. For structured light, it may be important, for ecological reasons of predator avoidance for instance, to collect at least the edges and direction of movement of an approaching shadow cast on the eyelids. It is therefore not unreasonable on first principles to expect that eyelids should be designed through evolution to allow for transmission of light and some images.

It is promising and attractive to learn that a richer and more complex appreciation of the environment can be obtained from light incident on the closed lids of the eyes. While the underlying mechanisms for visual perception during eye closure are not fully understood, our finding that structured spatiotemporal light is perceptible behind the eyelid could have applications in medicine, architecture, education or entertainment.

In relation to our final objective for this study, we therefore consider that people close their eyes within three categories of experience, and suggest possible thinking on applications within each. Naturally, each will present its own challenges and unanswered questions on implementation are outside the scope of this paper.

1) Reflex and maintenance, as with natural blinks for moistening the eye surface, and protection from bright light or physical objects nearing the eye. The prospect that useful visual information can be delivered to the eyes during brief periods of closure could be applied to high-speed physical and informational activities, for instance in sports, battle, or other time-critical safety monitoring scenarios, such as car racing or air-traffic control.

2) Communications and emotions, as in facial expressions, or responses to enjoyment, fear etc. Within this category, one could envisage additional modalities of communicative information conveyed visually during eye closure, for instance, to enhance or modify the emotional state or convey more subjective information during these intervals during video telephony (e.g. Skype) type communications.

The third category to consider is 3) Sleep, relaxation and related states of longer duration eye closure. During eye closure brain activity is distributed differently, and eye movement velocities are greater, as reported by. Marx et al [8]. Interestingly, they also argue from brain imaging (fMRI) results concerning the presence of two distinct mental states: an ‘exteroceptive’ state when the eyes are open, characterized by attention and oculomotor activity, and an ‘interoceptive’ state during extended periods of eye closure, dominated by imagination and multisensory activity. Perhaps applying custom-structured light displays during eye closure to awake individuals could cross such normal boundaries, by instigating a mixture of perceptual processes and unusual experiential effects?

Differences are found for certain medical conditions that may support this view. For example, the eye movement patterns of schizophrenics are different when their eyes are open compared to when their eyes are closed [10]. Applications in this category may thus include visual stimulation during eye closure for schizophrenic patients, for epilepsy patients [7], who demonstrate abnormal brain patterns during eye closure [4], fro coma patients, who have abnormal sleep-awake patterns, and for other patients with ‘disorders of consciousness’ (i.e. coma, vegetative state and minimally conscious state) [11, 12]. It is conceivable that stimulation during eye closure periods for such patients could stimulate different brain areas and trigger alternative pathways to facilitate diagnosis or treatment.

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Evaluation of Today's Research Methods for Assessing Light-Induced Alertness

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ABSTRACT

Daytime alertness has not established the same type of research routines as nighttime alertness. This paper evaluates today's research methods to provide help in choosing suitable methods for assessing light-induced daytime alertness in future research. The evaluation is done according to two main criteria; the method's ability to reflect alertness physiologically and its suitability for use in a lighting study. The methods under evaluation are subjective ratings, reaction tests, brain imaging, pupillometry, measurements of heart rate and skin conductance, and the use of an electro-oculogram and electroencephalogram. On the basis of a literature review and practical testing of some of the methods, the writers suggest that in low-cost studies, where detecting the effects is enough, autonomic nervous system activation should be measured. To gain broader knowledge of the mechanisms, central nervous system responses need to be studied.

Keywords

Alertness, sleepiness, central nervous system, autonomic nervous system activation, lighting research

INTRODUCTION

With growing interest in the impact of light on health [60, 70] and wellbeing [84], accelerated by the introduction of the novel photoreceptive melanopsin-containing retinal ganglion cell [10], the relation of light and alertness during nighttime hours has been the subject of considerable examination [for a review, see 17]. Daytime alertness, on the other hand, has not yet attracted the same amount of research interest. In general there are two approaches to this field of interest. One aims at detecting the effects of light [6] so that the current lighting standards used in the building business could be updated so as also to consider wellbeing instead of only the visual performance [81]. This type of research is clearly application-oriented and of high commercial value [79], which can be seen from the high level of interest in e.g. bright light treatment. The other type of research tries to reveal the mechanisms behind the detected effects [4]. This can be thought to be a more rigorous approach, trying to find out the scientific basis for the phenomenon.

The current weakness in both types of research is that the methods used for evaluating light-induced daytime alertness are not always suitable for such research. First of all, it is often forgotten what alertness is, physiologically, and hence which methods measure human alertness quantitatively. Second, it is not always considered that using light as a stimulus can create special demands for the method. Finding proper methods is challenging because in lighting research papers the problems related to the usability of the study methods chosen are reported too seldom.

The object of this paper is to provide help in choosing eligible methods for assessing light-induced daytime alertness by evaluating the research methods used today. This is done according to two main criteria: the ability of the method to reflect alertness physiologically and its suitability for use in a lighting study. Besides evaluating today's research methods theoretically, the paper also reports on the practical testing of some of the methods, namely subjective evaluation, and measuring pupil size, heart rate, and the skin's ability to conduct electricity. The methods are chosen for the practical testing on the basis of their potential value for alertness research and on the available resources.

EVALUATION CRITERIA

Physiology of Alertness

In 1949 Moruzzi and Magoun presented a theory of the activation system of the brainstem which suggests that stimuli travelling through the brainstem give rise to the level of alertness [58]. This was thought to be the missing explanation of why external stimuli increase alertness but a lack of them reduces it. Soon the concept of the "ascending reticular activating system" achieved wide currency.

Anatomically speaking, the activating system is located in the reticular formation. The reticular formation is a broad and netlike formation in the core of the brainstem running through the mid-brain, pons, and medulla oblongata. The ascending reticular activating system is connected to areas in the thalamus, hypothalamus, and cerebral cortex, while the descending reticular activating system is connected to the sensory nerves of the cerebellum. [31]

The regulation of alertness is based on the messages sent between the nuclei in the reticular formation in the brainstem and the cerebral cortex [68]. Of the nuclei in the brainstem, the locus coeruleus (LC) is the most essential one when alertness is considered, because it reacts easily to stimuli and improves alertness by increasing its noradrenalin secretion to the cortex. It has been said that a single noradrenergic neuron can innervate the entire cerebral cortex via its branches, mediating arousal and priming the brain's neurons to be activated by stimuli [6]. That supports the belief that the LC is one of the key components in light-induced alertness [4].

How the function of the LC is seen in practice is through the secretion of noradrenalin, which enables the body to perform well in stressful situations [8]. Noradrenalin normally produces effects such as increased heart rate, blood pressure, and sweat gland activity, and the dilation of the pupils and of air passages in the lungs. Hence, the LC is in direct connection to the autonomic nervous system (ANS). In fact, the activation of the ANS is often used as a conceptual definition of alertness. Because the activation of the ANS increases as arousal increases, it is reasonable to claim that by observing the changes in the ANS, it is possible to see how the LC reacts to stimuli and activates the body.

This section concludes that one potential way to assess daytime alertness is by observing the brain and characterising the neural correlates of the alerting effects of light. Another option is to observe the activation of the autonomic system. Although the pathways have not yet been fully identified, there is evidence that light stimulates the ascending arousal system and eventually the cortex in order to enhance alertness [65]. It should be noted that it still remains unclear whether light induces alerting effects in daytime, when the homeostatic sleep pressure is low and there is no circadian drive for sleep. Therefore the methods need to be even more sensitive than the methods used in nighttime studies.

Demands Set by Lighting Research

In general a good method for use in a scientific study is something that can be applied both in laboratory and field studies. This permits the best further use of the results in real-life applications. To gain objective and reliable data the experiment should be repeatable and as independent of the subject and the researcher as possible. Setting a baseline or altering the testing conditions often helps in analysing the data and verifying the results.

In addition to these general guidelines, lighting research sets some special demands for the study method. The most essential demand is that the method allows light to be used as a stimulus. Often it is also important to be able to alter the lighting conditions, hence changing the exposure time, light source, spectrum of the light, irradiance etc. [62]. One crucial criterion for the method is that it presents the data in such a way that the effect of light can be distinguished from effects caused by other stimuli such as caffeinated beverages [30], indoor climate [14], and auditory stimuli [27], among others. There are two ways to do this: either eliminating other stimuli from the set-up or separating them out in the analysis.

One practical factor to consider in choosing a good method is that in research done on humans there is considerable variation between individuals [65]. Therefore the number of subjects has to be big enough to gain reliability. This results in the fact that the test cannot be too complicated to conduct. Practicalities such as the costs and availability of the method may also limit the use of some methods. In studies of long-term light exposure and its effects, it is important to make sure that the lighting conditions and the method are not too burdensome and uncomfortable for the subject.

THEORETICAL EVALUATION OF METHODS

Subjective Methods

Subjective evaluation is a commonly used research method because it is easy to conduct both in laboratory and field conditions. Sleepiness is typically assessed on a Likert-type discrete scale [i.e. 32] or a continuous visual analogue scale (VAS) anchored by word descriptors at each end [76]. Perhaps the most popular subjective measure is the Karolinska Sleepiness Scale (KSS) [88], which uses a discrete scale from 1 to 9, where 1 = very alert and 9 = very sleepy, great effort to stay awake or fighting sleep. KSS has been validated to significantly correlate with EEG and behavioural variables [39] and is therefore considered a reliable measure of alertness or sleepiness. However, as Cajochen points out [17], the precise meaning of the terms alertness and sleepiness may differ between languages and situations. Furthermore, approaching alertness through sleepiness can be inadequate because alertness is not always the inverse of sleepiness [57].

The main criticism of any type of subjective assessment arises from the fact that it relies on self-reporting, leaving it open to misinterpretation, unintended bias, and falsification for any number of reasons (e.g. the act of rating itself can affect sleepiness [42]). It is possible that the subjects may evaluate their alertness differently in light than in darkness, even though there was no real difference in their level of alertness. In fact, there is no real placebo control for light, but it can only be hoped that the subject assesses his alertness time after time following the same logic. Another weakness of subjective assessment in a study of light-induced alertness is that it can only be used to point out the changes in the subject's way of responding to light, but it does not show anything about the reasons or mechanism behind the changes. Therefore it can never give as much input to the study as objective measures that are linked to physiology.

It is also hard to be sure that the effect is caused by light and not something else. Using subjective assessments thus requires a very strictly controlled test environment where there are no other factors that could affect the person's way of answering. Finally, one major disadvantage of using subjective assessment in lighting studies is that the data recording is not continuous. Because self-reports are produced after certain time periods, the information about the state of alertness between the measuring points is automatically lost. One could say that the data expire as soon as they are recorded. This is a big problem because it hinders one in detecting whether it is a question of a fast or slow response to light.

Objective Methods

Reaction Tests

Performance is often used to evaluate how alert a person is [85]. This is based on the assumption that alertness is involved with increased reactivity to external stimuli; thus an alert person reacts fast to stimuli. Using reaction tests to evaluate alertness is, however, not as problem-free and easy as it would at first seem. For example, the test itself can act as an activating stimulus and thus affect alertness.

The reaction tests need to be well designed in terms of the complexity of the test because the subject should be able to perform the test without too great an effort. Another important factor is how the subject manages to retain their motivation throughout the whole test. That depends on whether the subject is being rewarded after a successful test, but also on the duration of the test. For a long time it was thought that a reaction test should last no less than 10 minutes because studies indicated that shortening a performance task resulted in reduced sensitivity to changes in performance [12]. However, recently the study of Roach et al. [64] showed that a 5-minute test correlates well with a 10-minute test. They tested the psychomotor vigilance test (PVT) [83], which has been shown to be a reliable indicator of decreased alertness [19] and is commonly used for assessing neurobehavioural performance.

The advantage of the PVT is that it reflects the tiredness-related reduction in performance without being confounded by the learning effect, a factor that often causes bias in the experimental data. In the traditional study protocol a visual stimulus appears on the display and the subject is instructed to press the response button as fast as possible after detecting the stimulus.

Another and more modern option is to use auditory stimuli in a psychomotor vigilance test. In the auditory PVT the subject presses a button after hearing the stimuli in the same way as in the visual PVT. By using two buttons and two different stimuli instead of one it is also possible to add complexity to the test. Today there are portable, palm-held devices that make it possible to conduct experiments in real environments such as workplaces, instead of only laboratories [83]. The Walter Reed Army Institute of Research, Maryland, offers test and analysis software for this kind of field-portable reaction time tester for free [75]. However, their PalmPVT does not allow auditory stimuli to be used.

In theory, these kinds of reaction tests can be used in lighting research in two ways. First of all, if light with the specific characteristics under study acts as the stimulus, the reaction time will show how easy it is to detect that stimulus. In practice, however, this only shows that the person reacts to light but not whether the light induces any alerting effects. Another option is to use an exogenous stimulus in the PVT to assess vigilance after being exposed to light for a certain amount of time. Following e.g. Lockley's example [44], in this kind of protocol it is better to use an auditory stimulus instead of a visual one to prevent the PVT stimulus from masking the light-induced effect under study. This has potential for revealing how the exposure to light affects the reaction times.

The biggest disadvantage of using a PVT in studies of light-induced alertness is that it measures sustained attention rather than alertness and therefore it is not a proper method to evaluate the activation system in detail. Furthermore, it does not measure the functioning of the LC or other body parts that take part in light-induced alertness but instead it exhibits the circadian and homeostatic processes that take care of the natural asleep/awake rhythm. Therefore it can be concluded that a PVT can be broadly used in chronobiology research [11] but it does not necessarily make a good assessment method for alertness in lighting research.

Pupillometry

The pupil provides control over the retinal illumination and depth of focus [50]. In addition to constricting as a response to increased light flux and vice versa, the pupil also responds e.g. to accommodative changes [41] and to anticipating effects for an instructed task [87], illustrating the wide range of confounding factors involved in pupil recordings. Given that pupil size modulates the retinal illuminance, precautions are needed to control the exact retinal illuminance. These precautions include monitoring the pupil size via a video-based infrared pupillometer [73] with or without dilating the pupil to a constant size during the recording. Additionally, one can use a Maxwellian view [82], as opposed to a free view in which the stimulus sizes are smaller than the smallest physiological pupil diameter; hence pupil size has no modulating effect on retinal illuminance.

The pupil size can be measured using a direct approach with binocular light stimulation or by a consensual approach, where only one eye is stimulated and the response of the unstimulated eye is recorded. There is no vast literature on pupillometric hardware but it should be noted that many of the approaches are similar to that used in the eye tracking literature [20]. Typical temporal resolutions range from 30 Hz in low-cost setups [43] to 6-12 kHz in more customised setups [74], with spatial resolutions going down to 0.008 mm [29] depending on the sensor resolution, quality of the optics, and the signal-to-noise ratio of the video signal. The increase in temporal resolution can be achieved by using complementary metal oxide semiconductor (CMOS) sensors instead of charge-coupled device (CCD) sensors, in which this is not possible because of technical limitations [47].

Typically, the human pupillary light reflex (PLR) exhibits roughly three phases, rapid phasic constriction in response to light onset, which is followed by a steady-state pupil, and finally, depending on the light stimulus, there can be the post-stimulus persistence of a constricted pupil even after light offset [26]. Additionally, pupil size exhibits spontaneous fluctuations called hippus or pupillary noise, which is characterised by a random noise in the frequency range of 0.05 to 0.3 Hz [67]. To avoid contamination of pupillary measurements by spontaneous fluctuations of the pupil, a continuous monitoring of the pupil is preferred. The exact origin of hippus is not fully understood, but it has been suggested that it is an indicator of the state of vigilance of a person. There is evidence that if a drowsy subject spends daytime in darkness, the 'fatigue waves' start to occur with an increasing amplitude at the frequencies 0.025–0.25 Hz [45], whereas in an alert subject pupil size remains stable for a long time, oscillating mainly with a frequency of 1 Hz.

For this reason, pupillary fluctuations have been widely exploited as an easy and non-invasive measure to track changes in autonomic nervous system activity. One example of such an approach is the Pupillary Unrest Index (PUI) which measures the cumulative changes in pupil size, typically during periods ranging from 25 seconds to 15 minutes [53] in darkness or under light. PUI was used, for example, by Szabó et al. [72] to measure the changes in the vigilance levels of subjects during bright light exposure. Among others, Nikolau et al. [59] found pupillary assessment to be a promising objective tool to detect pharmacologically induced changes in alertness. However, it should be noted that the majority of studies on pupillary fluctuations have been carried out in darkness and the relationship between fatigue and oscillations in daylight requires further validation, adding some restraints to real-life lighting studies with pupillometric alertness assessment.

Considering that the pupillometer is comfortable for the subject and the protocol does not include any tasks to be performed, it might work as a good objective indicator for light-induced alertness. The method operates with a fairly delicate apparatus and requires the subject to sit still without extra blinking and head movements. There are, however, some indications that it could be used in field studies too [78]. Recent studies suggest that pupil size measurements could offer a simpler way to estimate autonomic nervous system activity than the commonly used heart rate [54]. Therefore it is reasonable to suggest that the reactivity of the pupil could well be used in lighting-related psychophysical experiments.

Heart Rate

The heart responds to psychological stress via the autonomic nervous system [52]. Over the years a correlation between heart rate and arousal caused by light exposure has been found both with rats and with humans [56,77]. Heart rate variability (HRV) has become the conventionally accepted term to describe the variations of interbeat (RR) intervals that represent autonomic nervous activity [66].

Heart rate variability is normally recorded by placing 10 electrodes on the skin on the subject's arms, legs, and chest. They measure the activity of different parts of the heart muscle and transmit it to an electrocardiogram (ECG) machine. The machine produces an ECG tracing of these cardiac electrical impulses. In clinical studies the heart rates or cycle intervals are recorded over long time periods, traditionally 24 hours, allowing more reliable calculations of the measures. Because the analysis of HRV data is more complex than generally appreciated, there is a potential for incorrect conclusions and unfounded generalisations [25]. The experimental procedures and analysis of the results should be carried out in accordance with the recommendations of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [49]. In fact, Peña et al. [61] remind that caution should be exercised concerning the use of short recording segments, a circumstance not fully considered in several studies. Therefore, although heart rate is easily measured in the presence of a light stimulus, the method does not meet the needs of detecting the effects of short-term light exposure.

From the subject's point of view, studying light-induced alertness by observing the heart rate is an easy research method because there is no task to be performed. However, real clinical equipment contains detectors and wires that can hinder the subject from conducting other things, as is often required in field studies. Fortunately, there are commercial and cost-effective heart rate monitors that can be used in studies where it is possible to reduce accuracy in order to gain mobility. There is evidence that motion does not contaminate the signal too much [36]. It should, however, be considered that in field studies the heart rate data are even more sensitive to distractions than in laboratory studies. Hence, the effects of the light stimulus are easily masked by other unintended stimuli.

Skin conductance

Because of the connection between the autonomic nervous system and locus coeruleus, arousal has long been assessed through the skin's ability to conduct electricity [28]. In fact, activation theorists long considered skin conductance to be the most appropriate measure of a generalised arousal response [21]. Skin conductance, galvanic skin response, and electrodermal response are different terms for the same physiological measure. It is known that as a person becomes more or less stressed, the skin's conductance increases or decreases proportionally [18].

The easiest way to measure electrodermal activity (EDA) is by strapping two electrodes to two fingers, namely the little finger and pointing finger of the non-dominant hand. The skin acts as a resistor whose conductance (inverse of resistance) changes with time according to the changes in hydration in the sweat glands [23]. Changes in EDA occur with even a slight rise or decrease in the amount of sweat within the glands [69]. Therefore a typical signal recorded from a skin conductor sensor shows relatively rapid increases and slower decreases.

From the lighting research point of view measuring the skin's ability to conduct electricity can be considered a good research method for light-induced alertness because it can be used within and between light exposures with both continuous and short-term light stimuli. It has, however, not been used often in lighting studies. The recording apparatus is small and the experimental protocol does not involve any kind of task performance by the subject. One major disadvantage is that the wiring hinders its use in real-life settings.

The analysis is rather easy as long as the recordings are time-locked to specific events to allow the analyser to select the right blocks of data from the general data [40]. The analysis has the potential to show the intensity of the effect of the light on a human. However, it is important to note that changes in the signal may be elicited by external stimuli or internal events [46]. Hence, it might become hard to distinguish the effects of different stimuli from one another. Therefore, to make electrodermal activity a proper indicator of the intensity of light-induced alertness, all other emotional cues that might mask the effect of light have to be eliminated.

Electro-oculogram

Eye movements react to a decrease in alertness. The attenuation of blinking is often a marker of the fact that the person is losing interest. At the same time the duration of a blink becomes longer and the eyelids become lazier. When the eyelid closes, the eyeball makes slow roll-like horizontal movements that are called slow eye movements (SEM) [5]. From these visible neurophysiological factors it can be seen when the person is transiting from being awake to asleep. Therefore eye blink rate and SEMs are considered reliable correlates of human alertness [16].

Clinical alertness evaluation takes advantage of the knowledge that a person who is not alert finds it hard to follow targets. In the electrophysiological test called an electro-oculogram (EOG) two skin electrodes are placed as close as possible to both eyes. Moving the eyes induces a voltage between them. The voltage varies from one to several millivolts, depending on the ambient retinal illumination. The subject is instructed to look back and forth at a steady fixation rate between two fixation targets to generate consistent saccades. These saccades are amplified and registered to be considered for analysis [51]. Normally, EOG amplitude increases significantly if the eye is first kept in darkness and then in light [3]. However, it has been shown that in electro-oculogram analysis it is better to use the light-peak to dark-trough amplitude ratio instead of the actual amplitude values because the amplitude varies widely among individuals [13].

The method is well suited to use in lighting research, both during and between light exposures. However, when designing the light stimulus, it is important to make sure that the entire visual field is evenly illuminated and that there is no direct glare on the subject that could hinder the subject from focusing on the targets [51]. As the eyes alternate direction every 1 to 2.5 seconds, the test soon becomes uncomfortable and tiresome for the subject. Therefore it is advisable to record the movements in sets and let the eyes rest between the sets. According to the international standard approved by the International Society for Clinical Electrophysiology of Vision (ISCEV), one set of 10 saccades per minute is enough to recognise the relevant peaks and troughs in the EOG data. The standard for EOG technology and protocol also offers other valuable recommendations for the recording technique. facilitating the comparability of the EOG data throughout the world.

A drawback in using an EOG to study light-induced alertness is that it does not allow the subject to concentrate on other tasks at the same time. That, and the presence of skin detectors and recording apparatus, makes the method unsuitable for real-life settings. Despite its few impracticalities, the EOG technique is quite commonly used to asses alertness objectively [34], either alone or together with brain activity measures.

Electroencephalogram

A number of observations suggest that there is a possible causal link between the activity of the locus coeruleus and electroencephalographic (EEG) activation [24]. Because the activation of the LC has been shown to induce EEG signs of cortical and hippocampal activation [9], it is reasonable to claim that by observing the forebrain EEG activity it might be possible to monitor the alerting process.

Electroencephalographic activation is a direct measure of the general cortical activation level. A set of electrodes is placed on the subject's skull to detect and amplify the small electrical voltages that are generated by brain neurons when they fire. Similarly to muscle fibres, neurons in different locations can fire at different rates. The EEG is typically described in terms of rhythmic activity and transients. The rhythmic activity is divided into bands by frequency.

Jung and Makeig state that it is possible to use the EEG power spectrum to estimate alertness [38]. The spectrum Beta band (15-20 Hz) is generally regarded as a normal rhythm, which explains why changes in Beta activity are often used to reflect different levels of arousal [7]. An decrease in Alpha activity (8-13 Hz) has also been reported to be associated with a drop in alertness and cognitive performance across the waking day [86]. This means that high levels of EEG Alpha activity could indicate a high level of alertness during an eyes-open condition [15], similarly to Beta. Theta (4-8 Hz) and Delta (2-4 Hz) activity are linked to increased drowsiness and reductions in performance [48]. However, Theta and Delta activity are rarer in awake adults.

EEG has both advantages and limitations in alertness research. One of the advantages as a correlate to human alertness is that it measures the brain's electrical activity directly, while other methods record the responses of the autonomic system. Another advantage is that EEG is capable of detecting changes in electrical activity in the brain on a millisecond time scale. Compared to techniques such as functional magnetic resonance imaging (fMRI) that have a time resolution between seconds and minutes, EEG has a much higher temporal resolution. However, the spatial resolution of EEG is poor and therefore it is not able to indicate the location of the activity of the brain. One possibility is to use EEG simultaneously with fMRI, so that data with a high temporal resolution can be recorded at the same time as data with a high spatial resolution. However, there are technical difficulties associated with analysing the activity of the brain in exactly the same time frame. Furthermore, currents can be induced in moving EEG electrode wires as a result of the magnetic field of the MRI.

As a research method EEG is fairly comfortable for the subject, because it records spontaneous brain activity in the absence of tasks. Therefore light can easily act as a short-term or continuous stimulus. Despite the easiness of the study protocol, using it in real-life settings is complex because of the wiring and its interference-prone nature.

Brain Imaging

Brain imaging provides an opportunity to study what is really happening in a human as a result of light exposure. There are two techniques, namely functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), which provide an anatomical and a functional view of the brain and are commonly used for brain imaging [71].

fMRI measures changes in the blood flow to particular areas of the brain. Through a process called the hemodynamic response, blood releases oxygen to neurons, creating magnetic signal variation. This variation can be detected using an MRI scanner. PET, for one, detects radioactive material that is injected or inhaled. The material collects in the area of the brain being examined, where it gives off energy in the form of gamma rays. [63]

The procedure and analysis of both techniques is rather hard and requires knowledge of fields such as physics, psychology, neuroanatomy, statistics, and electrophysiology. That is why it is not within the scope of this paper to go deeper into the measurements. Instead, the most important characteristics of the two techniques from the lighting research point of view will be discussed.

With brain imaging it is rather easy to identify the precise areas that are activated in the brainstem as a result of the light. A conventional 1.5-Tesla fMRI scanner has a spatial resolution of 3 mm and higher-strength magners may decrease it down to 1 mm. PET is not as accurate; the effective spatial resolution of PET remains 8-15 mm when standard image processing procedures, such as a smoothening filter, are used. Temporal resolution is also superior with fMRI. However, compared to EEG, which has a time resolution of only a single millisecond, PET and fMRI are slow, because they can detect a new stimulus only some seconds after the first stimulus. As a matter of fact, with PET it is not at all possible to pick out neural activation patterns associated with individual stimuli measures, so event-related phenomena, such as the effect of a short exposure to light, can only be detected with fMRI. From the lighting research point of view this hinders the use of subsequent light pulses as stimuli.

The strong magnetic field around the functional magnetic resonance imaging scanner also causes other limitations on using light as a stimulus. The light source cannot be installed in the study room because the electricity will interfere with the magnetic field. Instead, the light stimulus has to be transmitted by an optic fibre, as was done recently by Vandewalle and his colleagues [e.g. 80]. The same problem arises when trying to measure other physiological measures during the scans to help in the interpretation of the brain imaging data. Generally speaking, it is possible to measure EEG, EOG, EMG, ECG, or skin conductance only during the scans to prevent the magnetic field from inducing a current in the electrode wires. However, several techniques are under development to deal with these issues and there are already good experiences of recording fMRI and EEG simultaneously [e.g. 55]. Positron emission tomography, for one, is free of this kind of physical limitations.

If the problems mentioned above are to be overcome there are still many practical issues that impede the use of brain imaging in a typical lighting study. First of all, there are only 100-200 MRI centres and 20-30 PET centres worldwide where the studies can be conducted. Needless to say, not only can they not be used in field studies but in laboratory studies too their use is very limited because of their huge expense, which is around $500 per session with fMRI and $1500-2000 with PET [63]. In a lighting study it is often necessary to have many subjects and run various sessions with each one, which makes the costs enormous. These two requirements can also be hard to realise for safety reasons. With fMRI the suitability of the subject for the test is very restricted (e.g. no pregnancy, tattoos, pacemaker, or claustrophobia) and with PET the repeated studies are limited by the annual permissible radiation exposure. The number or duration of fMRI tests is not limited but since the scanner is very sensitive to motion, the subject can only be expected to hold still for some hours.

PRACTICAL EVALUATION OF METHODS

Subjects

Twelve healthy young volunteers (5 women and 7 men; age range 20-28; mean age 24.4 ± 2.4 SD years) and nine healthy older volunteers (5 women and 4 men; age range 50-62; mean age 56.6 ± 3.7 SD years) participated in the study. Before the study the subjects' chronotypes were assessed using the Morningness-Eveningness questionnaire (MEQ) [33]. Extreme chronotypes that scored below 31 (Definitely Evening type) or above 69 (Definitely Morning type) were excluded from the study. The chronotypes were lower in the younger than in the older group (range, mean ±

SD: 32-56, 47.3 ± 7.6 vs. 53-63, 57.1 ± 3.3; *t* test: $p = 0.001$). The duration of sleep before the study did not differ significantly between the groups (young: 7:56 ± 0:59 hours vs. older: 7:36 ± 1:05 hours; mean ± SD; *t* test: $p = 0.240$). The subjects were instructed to avoid alcohol, coffee, energy drinks, and teas (and other drinks containing caffeine) for 3 hours prior to the study.

Protocol and Study Design

The experiment took place at the Lighting Unit of Helsinki University of Technology. The subjects were exposed to conditions of dark and lightness, the light exposure being provided by a Goldman perimeter (diameter 60 cm). One experimental session took 2 hours (15:00-17:00). As presented in Figure 1, the lighting conditions were as follows:

15:00-15:25 darkness
15:25-15:30 quasimonochromatic blue light
15:30-15:45 darkness
15:45-15:55 broadband orange-red light
15:55-16:05 darkness
16:05-16:10 quasimonochromatic blue light
16:10-16:40 minutes of darkness
16:45-16:50 quasimonochromatic blue light
16:50-17:00 minutes of darkness.

Figure 1: One 2-hour experimental session between 15:00 and 17:00. Grey = light, white = darkness, black = recording period of the pupil.

Between the recording periods the subjects were free to stretch the legs by moving around in the experimental room, which was light-proofed with dark curtains. The quasimonochromatic "standard 5 mm" blue LEDs used in the study had a peak wavelength of $\lambda_{max} = 468$ nm and a half-bandwidth of hbw = 26 nm and they provided corneal illuminance of 40 lx (corresponding to a photon density of ~1.5×10^{14} photons/cm^2/s). The broadband orange-red light that was used between the blue light pulses was a mixture of two types of Luxeon Star III LEDs: Red-Orange (λ_{max} = 617 nm, hbw = 20 nm) and Amber (λ_{max} = 590 nm, hbw = 14 nm). The corneal illuminance provided by this broadband red-orange light was 83 lx (corresponding to a photon density of 1014 photons/cm^2/s). All the LEDs were mounted on a Goldman perimeter providing uniform light distribution. The luminance distribution was measured using a Nikon Coolpix 8400 digital camera equipped with a Nikon FC-E9 fisheye lens. The acquired images were analysed using the PHOTOLUX 2.1 software [22] which had a calibration profile for the camera that was used.

Measurements

Pupil Size

The pupil size of the subject was recorded during the periods illustrated in Figure 1. It was recorded using a Unibrain Fire-I OEM (Unibrain Inc., San Ramon, California, USA) digital monochrome board camera with a resolution of 320 x 240 and a sample rate of 30 Hz. The camera was mounted at the back of the Goldman perimeter at a distance of 30 cm from the subject's eye. The camera was equipped with a telephoto lens and an IR bandpass. The minimum focusing distance was reduced with home-made extension tubes which, at the same time, made the depth of the field narrower.

The pupil was illuminated with infrared LEDs (Everlight HIR204/H0, λ_{max} = 850 nm, hbw = 45 nm, beam angle = 60°) positioned off-axis close to the eye. The pupil size was to be determined from a recorded uncompressed video file using an edge-based segmentation program developed by the authors under Matlab (Mathworks, USA). The corneal irradiance of the infrared LEDs was below the safety levels of 10 mW/cm^2 for chronic infrared exposure at λ = 720-1400 nm as defined by ICNIRP [35].

Heart Rate

Heart rate was monitored continuously during the whole experiment using a Polar Rs800sd heart rate monitor (Polar Electro, Vantaa, Finland). Heart rate was analysed with Kubios HRV Analysis Software [37] by dividing raw heart rate data into 5-minute bins. The mean of each bin was calculated for heart rate, low-frequency power (LF), high-frequency power (HF), and LF/HF ratio, which is considered to be a good index of cardiac activity [2].

Skin Conductance

Skin conductance was measured continuously using a ProComp Infiniti Encoder (ThoughtTechnology, Montreal, Canada). 256 samples were recorded per second with BioGraph Infiniti software [1]. Mean skin conductance was determined for the same 5-minute bins as with heart rate.

Karolinska Sleepiness Scale

Subjective sleepiness was assessed using the Karolinska Sleepiness Scale (KSS) [88] every 20 minutes during the experiment. The mean subjective sleepiness every five minutes was calculated by extrapolating the data.

Data Analysis and Statistics

For all the analysis, the Statistical Package for the Social Science (SPSS) was used. The significance level was set to 0.05 in all comparisons. To analyse the values in different lighting or recording conditions, the Student t-test for independent variables was used. This *t* test is a special case of ANOVA that assesses whether the means of two groups are different (if $p < 0.05$ the means are different). The correlations of different methods within the age group and of the same methods between the age groups were tested with Pearson's correlation coefficient ($r = 0.00$ = no correlation and $|r| = 1.00$ = perfect correlation). Pearson's correlation was also used to investigate the time correlation of the measures.

Results

The mean values of normalised skin conductance, normalised heart rate, LF/HF ratio, and subjective sleepiness every 5 minutes for the young and older test groups during the 2-hour test period are illustrated in

Figure 2. Unfortunately, the pupil size values could not be calculated because of the low image quality caused by an unfocused lens, camera vibration, and the absence of a fixation point of the eye.

The subjective sleepiness increased significantly by time with both the young (r = 0.74, p = 0.000) and older (r = 0.80, p = 0.000) test groups. The LF/HF ratio decreased somewhat (young: r = -0.26, p = 0.113; older: r = -0.26, p = 0.112; not significant) and normalised heart rate values decreased significantly (young: r = -0.56, p = 0.002; older: r = -0.35, p = 0.046), corresponding to reduced arousal. In contrast, the skin conductance values supported the increase in arousal with time, but only with the young subjects (young: r = 0.47, p = 0.010; older: r = 0.07, p = 0.379).

Exposure to light (either quasimonochromatic blue or broadband orange-red) did not cause any significant effect on the values in the young group (p > 0.05 with all methods; t test). In the older group there were differences in the heart rate and skin conductance values during the light period compared to darkness (heart rate: p = 0.045; skin conductance: p = 0.021; t test). However, the effect of the recording period appeared much stronger in the values. In both age groups the heart rate, LF/HF ratio, and skin conductance were significantly higher during the periods when the subject could move freely in the dark experimental room compared to the periods when he or she was attached to the Goldman perimeter (young: p = 0.000, 0.007, 0.050; older: p = 0.000, 0.022, 0.000; p = heart rate, LH/HF ratio, skin conductance; t test). Within the recording periods there was no difference in the responses to light exposure compared to darkness in any of the methods in either of the age groups (p > 0.05 with all methods in both age groups; t test). Sleepiness acted independently and did not follow the recording or the lighting conditions. The behaviour of the skin conductance correlated negatively with the behaviour of the LF/HF ratio in both age groups (young: r = -0.50, p = 0.006; older: r = -0.27, p = 0.043). With the young subjects KSS correlated with skin conductance (r = 0.54, p = 0.003), giving conflicting information about the changes in alertness. However, the negative correlation of KSS and HR (r = -0.50, p = 0.006), implied that their alertness did indeed decrease with time. These inter-method correlations were not found significant in the older test group. However, all the measures showed corresponding behaviour in both age groups (heart rate: r = 0.73, p = 0.000; LF/HF ratio: r = 0.35, p = 0.049; skin conductance: r = 0.70, p = 0.000; KSS: r = 0.99, p = 0.000).

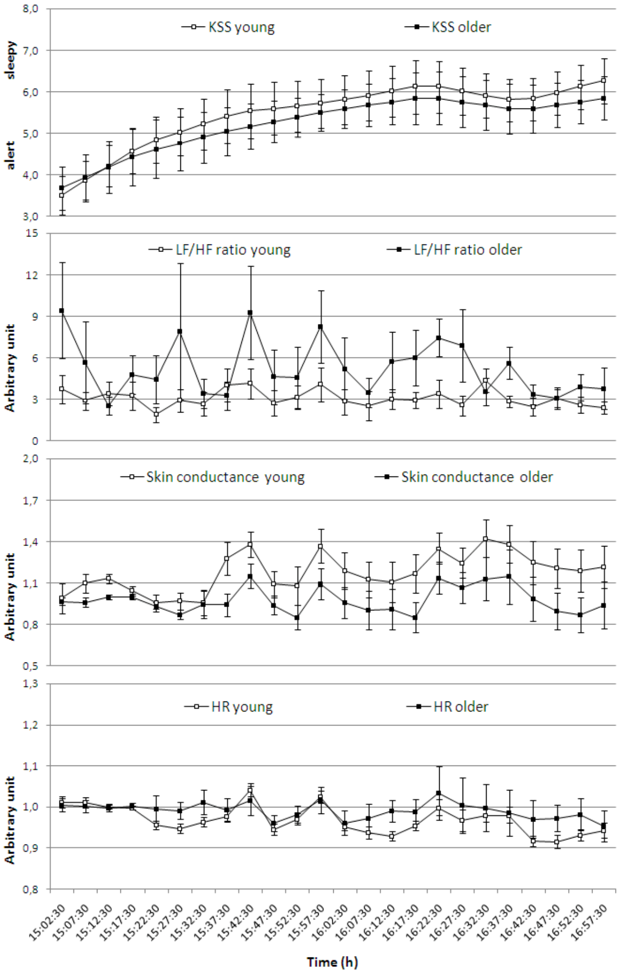

Figure 2: Time course of subjective sleepiness (top), LF/HF ratio (panel 2), normalised skin conductance (panel 3) and normalised heart rate (bottom). Mean values per 5-min bin ± SEM.

Discussion

Subjective sleepiness ratings and heart rate measures showed that the subjects became sleepier during the test. That is in conflict with the skin conductance responses, which suggest that the subjects became more aroused. It is possible that the KSS ratings reflected reduced motivation rather than alertness. However, a more likely explanation for the inconsistency is that while becoming sleepier the subjects were trying harder to fight against the desire to sleep. That appeared in the skin conductance data as arousal.

The effect of light exposure was shown in the older test group as a change in skin conductance and heart rate. However, the variations of the autonomic nervous system functions were mainly detected when the subject was able to move freely in the experimental room without having his or her head attached to the Goldman perimeter. This indicates that the presence of the pupil camera played a strong role in the ANS responses masking the effect of the light stimulus. This is a practical illustration of the sensitivity of the ANS methods to external stimuli. It shows that more effort has to be put into the study protocol to either exclude everything that could appear as external, unwanted stimuli or choose methods that can be used in the presence of such stimuli. Apparently, sitting still in front of the Goldman perimeter eye facing towards the camera was a task that did not go together with skin conductance and heart rate measurements. Hence, in this type of study setting the measurement of pupil size cannot be used at the same time as other methods recording the activation of the autonomic nervous system. Furthermore, the recording protocol has to be designed so comfortable for the subject that no difference between the recording period and the rest of the experiment can be detected.

The biggest drawback of the study was the unsuccessful recording of the pupil size, which appeared despite the fact that the protocol had been tested in a pilot study. It was not possible to adjust the focus of the camera, so the focusing had to be done manually. In future studies one could try to adjust the distance to the eye by attaching the camera to a microrail on which the camera can move back and forth. To reduce the noise in the image, more infrared light should be applied. That is challenging because the light should be kept invisible to the subject. In this study difficulties were encountered in keeping the camera still. During some of the experimental sessions the heavy camera could not be held in a constant position, causing the eye to change its position in the image. Therefore not all the data could be read and processed with the Matlab program. This could be corrected by using a separate stand for the camera instead of attaching the camera directly to the Goldman perimeter.

CONCLUSIONS

The theoretical and practical examination of the methods showed that using subjective evaluation to assess alertness is an easy method to conduct. However, it should be kept in mind that ratings on scales such as the Karolinska Sleepiness Scale (KSS) do not necessarily indicate changes in alertness. Therefore subjective evaluation should always be used together with an objective test. Objective evaluation can be done by using either central (CNS) or autonomic nervous system (ANS) variables or, in the best case, a combination of those two. Reaction tests are also often used in lighting studies, but they measure sustained attention rather than alertness. In addition, the tasks can mask the light stimulus. For measuring ANS activity through skin conductance and heart rate, there is relatively cheap, low-tech equipment available. As the practical testing showed, it is, however, very sensitive to external stimuli, which can limit its use in lighting studies. The current study encountered some difficulties in the measurement of pupils. However, it is foreseen that with more careful study design pupillometry could be a suitable method for use in light-induced alertness research.

In the current study it was not possible to test CSN variables. Previous studies show, however, that electro-oculogram (EOG) measurements could suit lighting research if the tiresome tasks did not limit their use to short recordings. The electroencephalogram (EEG) is popular because of its high temporal resolution. However, as a result of the low spatial resolution a lot of interference can occur in the data. The authors are of the opinion that of the research methods presented in this paper, the greatest potential lies in brain imaging, because it can reveal the mechanisms behind the (hypothetical) light-induced daytime alertness by spotting the neural correlates. The protocol is expensive and hard to design because of numerous restrictions. What is common to all CNS methods is that they are not suitable for field studies.

By using validated methods and designing the experiments in accordance with the standards, the data analysis and the comparison of the results with other studies can be made easier. There is already good software available for numerous methods.

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