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Occupant Controlled Lighting

Investigation of the Method of Adjustment

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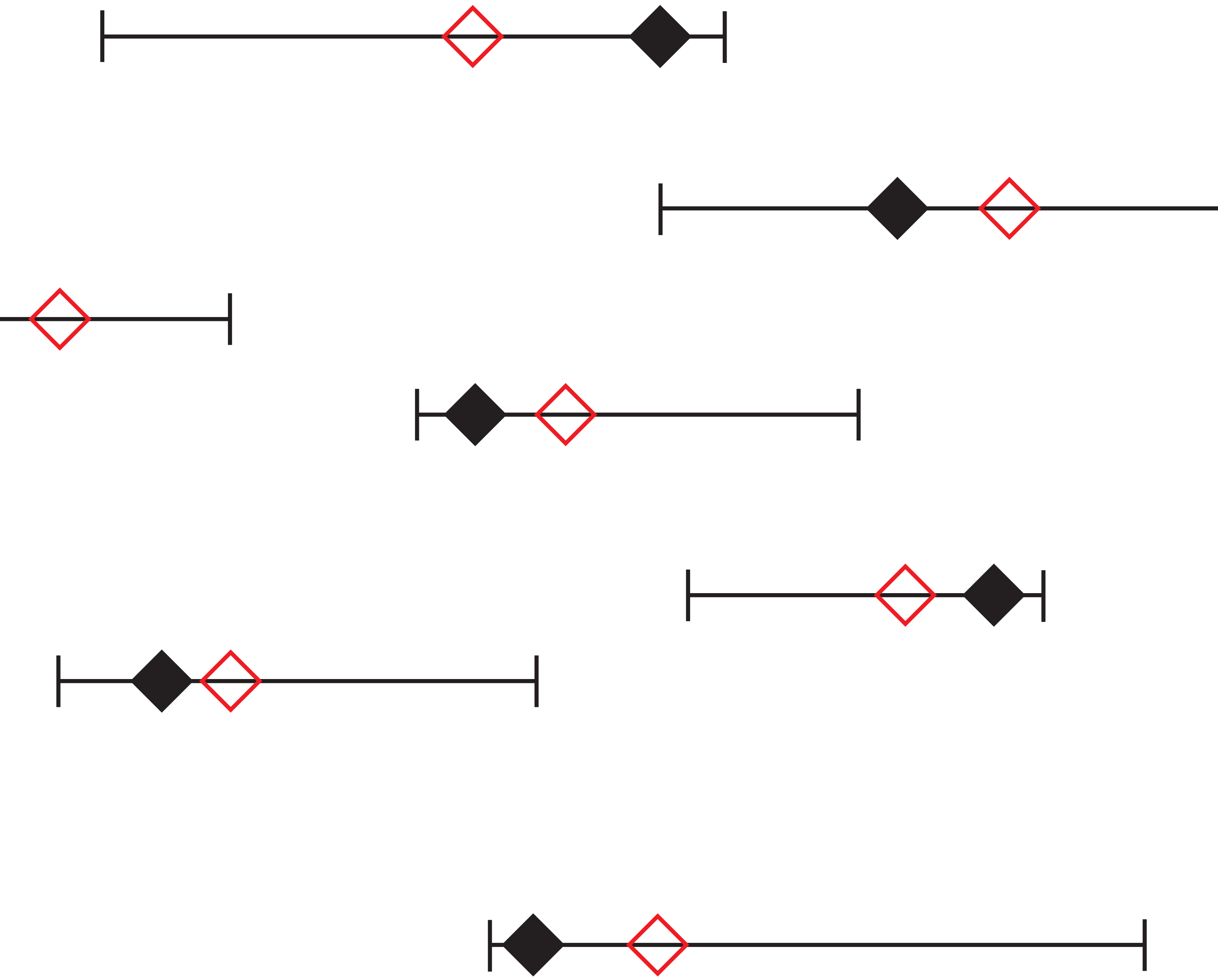

Ásta Logadóttir

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Abstract

The studies presented in this thesis explore opportunities and limitations of using the method of adjustment for occupant controlled lighting. The method of adjustment is studied with respect to occupant preferences and energy efficiency.

The work presents three types of studies using the method of adjustment. Firstly, there was preliminary laboratory study exploring the influence of daylight on occupant controlled dynamic lighting in a laboratory office environment. Secondly, there was non-daylit laboratory study on occupant preferences for illuminance, and thirdly a scale model study on occupant preferences for correlated colour temperature (CCT).

The results suggest that the method of adjustment, previously used in the lighting literature, is not adequate to generalize about occupant preferences for illuminance or CCT. Factors that influence occupants' lighting preference when applying the method of adjustment are identified as: stimulus range, pre-set anchors, adaptation time and control-output relationship of the lighting system.

Resume

Studierne, der præsenteres i denne afhandling, undersøger mulighederne og begrænsningerne ved brugerstyret elektrisk belysning, hvor brugeren har mulighed for at justere lysniveauet og/eller den korrelerede farvetemperatur indenfor et givet interval. Denne metode til lysstyring er undersøgt i forhold til brugerpræferencer og energieffektivitet.

Afhandlingen præsenterer tre forskellige studier af metoden. Først er dagslysets indflydelse på det foretrukne lysniveau og korreleret farvetemperatur ved brugerstyret belysning, undersøgt i et kontormiljø opbygget i et laboratorium. Derefter er dagslyset holdt ude og brugerpræferencer for lysniveauet er undersøgt ved elektrisk belysning alene. I det tredje og sidste studie er der opbygget en skalamodel, hvor brugerpræferencer for korreleret farvetemperatur er undersøgt.

Resultaterne viser, at metoden til justering af belysning, som hidtil er blevet benyttet i litteraturen, ikke er egnet til at generalisere i forhold til brugernes præferencer for belysningsniveau og korreleret farvetemperatur. Der er således fundet følgende faktorer, som har indvirkning på det foretrukne belysningsniveau og korreleret farvetemperatur når justeringsmetoden anvendes: intervallet der stilles til rådighed, startværdien, tilpasningstiden (adaptionstiden) og forholdet mellem indstillinger og lyskildens output.

Acknowledgements

The presented work is the result of good teamwork and great support from many people. I particularly want to thank my supervisor, Dr. Jens Christoffersen, VELUX A/S for encouraging me in so many ways and providing good guidance over the last few years. Without him this work would never have started. Jens is extremely good at pushing me and giving me a bad conscience when needed.

I am also greatly indebted to Dr. Steve Fotios of the School of Architecture, University of Sheffield, who purely out of interest and great enthusiasm for the lighting field has become a mentor to me. Without Steve, the content of this thesis would have been very different from what it is today and raised more questions than answers. This last year of working with Steve has been a great learning experience in so many ways.

I am grateful to my co-authors and colleagues from DTU Fotonik, Carsten Dam-Hansen, Søren Hansen, Dennis Corell and Peter Poulsen. Thank you for making the CCT study possible and bearing with me during stressful periods.

I am also thankful for my colleagues at SBi who have made me feel so welcome, especially my supervisor, senior researcher Kjeld Johnsen, who has involved me in general lighting activities that are of great interest. I also want to thank Karin, Mette and Harpa for being there, together with Ella, and making it fun to come to work. What I like most about SBi is that I can always be myself and be accepted for who I am.

My friends and family deserve all my gratitude for providing so much support and encouragement, and for believing in me.

I would also like to express my gratitude to my mother and father for always supporting me, no matter what, and helping me out in every way possible. You are the greatest role models.
My sister, Hrund, for her help and for all the good times we have had together.
My two lively sons, Logi and Loftur, for being the way they are, surprising me, loving me and keeping me on my toes as a mother. Without you guys I think I might have gone crazy, or at least crazier.
Last but not least, my husband Arnar for giving me support, being positive and having a beer and a conversation with me in the middle of the night when I couldn't sleep.

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Contents

List of Publications

Article I. Logadóttir Á, Christoffersen J. Energy Savings by Individual Dynamic Lighting Control. Proceedings of the 11th International Conference on Indoor Air Quality and Climate, Copenhagen, 2008.

Article II. Logadóttir Á, Christoffersen J. Dynamic Lighting Concept in Danish Office Environment with Daylight Contribution. Proceedings of the 11th European Lighting Conference LuxEuropa. Istanbul, 2009.

Article III. Logadóttir Á, Christoffersen J, Fotios SA. Investigating the use of an adjustment task to set preferred illuminance in a workplace environment. Accepted for publication in Lighting Research and Technology, subject to some revision.

Article IV. Logadóttir Á, Fotios SA, Christoffersen J, Hansen SS, Corell DD, Dam Hansen C. Investigating the use of an adjustment task to set preferred illumination colour. Submitted to Colour Research and Application.

Article V. Logadóttir Á, Fotios SA, Christoffersen J. Investigation of Occupant Controlled Illuminance. In manuscript.

List of Abbreviations

CCT	Correlated Colour Temperature
DALI	Digital Addressable Lighting Interface
LED	Light Emitting Diode
SBi	Danish Building Research Institute

Terms used in this study

This table defines terms and the way general terms are used in this thesis

Correlated Colour Temperature (CCT)	The CCT is the temperature of a Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a diagram where the (CIE 1931 standard observer based) u', 2/3v' coordinates of the Planchian locus and the test stimulus are depicted. [Schanda, 2007]
Dynamic lighting	Refers to variation in illuminance and/or CCT from the electrical lighting.
Method of adjustment	The occupant is provided with a control dial to adjust the lighting according to his preference.
Anchor	A stimulus presented before an adjustment opportunity. The stimulus is either illuminance or CCT.
Stimulus range	The range available for the method of adjustment The stimulus is either illuminance or CCT.
Control output relationship	The relationship between control settings and stimulus (illuminance or CCT)
Glare	The sensation produced by bright areas within the visual field, which may be experienced either as discomfort glare or disability glare. [EN 12464-1]

Introduction

The presented report *Occupant controlled lighting, Investigation of the method of adjustment*, completes the requirements for obtaining the Ph.D. degree at Aalborg University. The additional articles all relate to the topic of occupant controlled lighting using the method of adjustment. These are: -Energy Savings by Individual Dynamic Lighting Control, -Dynamic Lighting Concept in Danish Office Environment with Daylight Contribution, -Investigating the use of an adjustment task to set preferred illuminance in a workplace environment, -Investigating the use of an adjustment task to set preferred illumination colour, -Investigation of Occupant Controlled Illuminance. The studies were conducted at the Danish Building Research Institute (SBi), Department of Energy and Environment, in close collaboration with Dr. Jens Christoffersen, VELUX A/S, DK, and Dr. Steve Fotios, School of Architecture, University of Sheffield, UK.

A great deal of resources have been put into the development of advanced lighting systems considering the limited knowledge and understanding we have of what people prefer and are comfortable with. Promising approaches have been made to establishing relationships between different lighting aspects and psychological effects, as well as an occupant's assessment of lighting quality. With consideration for the occupant's needs and preferences, lighting controls represent a great opportunity for high quality, energy efficient lighting. This thesis focuses on occupant preferences for illuminance and correlated colour temperature (CCT) in office environments. Preferences were explored in controlled laboratory situations using the method of adjustment. Figure 1 presents the course of the work presented in this thesis. First, there is a preliminary laboratory study exploring the influence of daylight on occupant controlled dynamic lighting in a laboratory office environment. Article I [Logadóttir and Christoffersen, 2008b] describes the first part of the preliminary study on an occupant-controlled dynamic lighting concept for winter season and Article II [Logadóttir and Christoffersen, 2009] reports the findings for the same study performed in autumn. Following the preliminary study Fotios' and Cheal's [Fotios and Cheal, 2010] work on stimulus range bias associated with the method of adjustment has been published, online ahead of print, resulting in collaboration with Dr. Steve Fotios. The collaboration results in the second part of the thesis, an investigation on the method applied in the preliminary study and tests were performed on the method with respect to bias potentials (method studies). The three remaining articles present the results of the method studies: Article III [Logadóttir et al., submitted to Lighting Research and Technology] focuses on biases for illuminance preference using the method; Article IV [Logadóttir et al., submitted to Colour Research and Application] focuses on biases for CCT preference; and Article V [Logadóttir et al., in manuscript] explores the use of the method of adjustment in illuminance preference research and application.

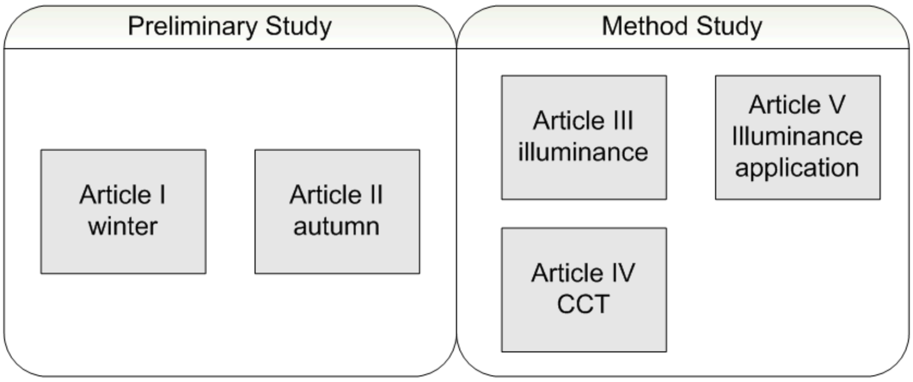

Figure 1: The course of the work presented in this thesis

Objectives

The objective of this work is to examine the method of adjustment with respect to occupant preferences for illuminance and correlated colour temperature (CCT) in an office setting. The influence of daylight on occupant control is examined in a preliminary study. The preliminary study is followed by a more detailed study where attention is focused on the method of adjustment and potential biases that accompany the method in illuminance and CCT preferences. The information gathered in this work is important for a better understanding of occupant preferences when applying the method of adjustment.

State of the art

Dynamic Lighting

There are various ways of defining dynamic lighting. In scenes and façade lighting the concept usually includes changing colours, intensity and sometimes forms. Focusing on an office environment in this thesis, we narrow the definition down to occupant-induced variations of illuminances and CCT.

Effects on humans

Lighting can affect people in different ways. Studies of the biological effects of lighting on people have focused mainly on the stimulatory effects on different aspects of human behaviour. Gifford [Gifford, 1988] and Biner et al. [Biner et al., 1989] found that lighting stimulates arousal, and Hanifin and Brainard [Hanifin and Brainard, 2007] stated that bright light exposure appears to have an acute stimulatory "alerting" effect on healthy humans. In a literature review, they conclude that higher CCT lamps induce stronger neurobehavioral effects than lower CCT lamps in healthy subjects. Viola et al. [Viola et al., 2008] found that higher CCT light sources improve self-reported alertness and performance, while Górnicka [Górnicka, 2008] did not detect non-visual effects for CCT during the day and further observed that lighting with very high CCT (17000K) does not seem to be suitable for use in offices. Górnicka did however find that bright light affects self-reported alertness during early office working hours. Furthermore, Boyce [Boyce, 2003] and Veitch et al. [Veitch et al., 2008] find that the luminous environment may also affect task performance via mood and motivation. However, research on a pre-programmed dynamic lighting concept in a well-daylit field study did not establish the concept as a good means of improving office workers' health, well-being or performance [Kort and Smolders, 2010].

Occupant control over lighting may also have an affect on people. Boyce et al. [Boyce et al., 2000] discovered that offices with lighting control had higher ratings of lighting quality, and tasks were rated as less difficult. Newsham and Veitch [Newsham and Veitch, 2001] reported that occupant control over lighting leads to improved mood and satisfaction by allowing individuals to attain their preferred luminous conditions. In another study, improved performance on a measure of attention, and improvements in mood, dominance and arousal were found to be due to the positive effect of receiving and utilizing lighting control [Newsham et al., 2004]. Boyce et al. [Boyce et al., 2006a] find that people with dimming control show more persistent motivation over the workday, and Newsham et al. [Newsham et al., 2008] reported satisfaction with the light level among their subjects who were provided with occupant controlled lighting.

Energy efficiency

Lighting controls can be used to achieve energy savings. According to Newsham [Newsham, 2007], all control types save energy, and individual controls save the least compared to occupancy sensors and daylight harvesting.

Estimates of energy savings depend to a great extent on reference conditions. Moore et al. [Moore et al., 2003] and Boyce et al. [Boyce et al., 2000] estimated savings by comparing the average percentage of energy consumption adjusted by users to the maximum installed load, which led the authors to suggest that there was a significant saving opportunity when average energy consumption was 54% of maximum installed load for the Moore et al. study, and 35-42% for the Boyce et al. study. Newsham et al. [Newsham et al., 2008] and Veitch and Newsham [Veitch and Newsham, 2000] compared the energy consumption of the tested systems to the consumption of the system if it was set to provide illuminance levels according to fixed recommended values. The savings for these two systems were estimated to be 25% and 10-15%, respectively.

Occupant control behaviour

Previous work suggests that the adjustment of electrical lighting controls is concentrated at the start and finish of the day [Love, 1998]. People entering a room at the start of the day will switch on the light and adjust it based on the visual environment that confronts them. There are indications that people are not motivated to adjust or turn the lights off until the end of the day. Field studies show that individual lighting controls are rarely used, but when they are, they are used to set a preferred light setting, and usually this is only done at the beginning of the day [Galaciu et al., 2007, Jennings et al., 2000, Boyce et al., 2006b, Moore et al., 2002, Moore et al., 2003]. Moore et al. [Moore et al., 2003] compared user behaviour for four types of lighting control in a field study. They did not find a statistically significant relationship between external illuminance and occupant controlled luminaire output. In 2001 Newsham and Veitch [Newsham and Veitch, 2001] discovered that preference for change is driven by experienced glare from the computer screen, desktop illuminance and the luminance ratio, and Newsham et al. [Newsham et al., 2008] found that when using the method of adjustment, the illuminance measured on the desktop is the best predictor of illuminance adjustment in office environment.

Illuminance data from method of adjustment

Several studies have used the method of adjustment to explore occupant control in office environments or office laboratories. Table 1 presents some of these studies. These studies are both private and open plan offices, with and without daylight, with one or more adjustable light circuits, with and without cubicle partitions and generally differently furnished. The table presents the available electrical lighting range, pre-set anchor (when reported) and the mean value set in the studies.

One of the studies presented in table 1 is Tenner et al. [Tenner et al., 1997] who performed two studies with the objectives of identifying a lower limit of an acceptance band for desktop illuminance. They concluded that occupant preference for illuminance was very high (on average 800 lux on desktop from electric lighting), and that an acceptance band was a better approach to enhancing energy efficiency. The lower acceptance band limit was estimated by slowly decreasing the set illuminance until the user reacted and increased the level again. The maximum available illuminance was set by the experimenter as 830 lux. If the subject complained or adjusted frequently to maximum, the available range was increased to 1660 lux and if the same behaviour continued, the range was increased further to 3100 lux. The lowest available range (maximum 830 lux) resulted in average acceptance of 400 lux, the middle available range (maximum 1660 lux) resulted in 700 lux, and the maximum available range of 3100 lux resulted in 1200 lux from electrical lighting. Tenner et al. [Tenner et al., 1997] conclude that in order to satisfy the needs of office workers, high illuminances should be installed, in combination with a lighting control system in order to achieve maximum flexibility.

Table 1 Overview of studies applying the method of adjustment in office environments or laboratories. The studies are arranged according to estimated middle of provided range. When the minimum illuminance is not reported, it is assumed to be zero. The table informs of office type, if the setup is in a laboratory or a field study, number of adjustable lighting circuits (Nr) and whether daylight was provided. Anchors, maximum (Max) and minimum (Min) settings are provided as illuminance measures, the middle of the range (Middle) is estimated from minimum and maximum values and the mean adjusted illuminance (Mean) is shown.

					Illuminance [lux]				
Study	**Office type**	**Setup**	**Nr**	**Daylight**	**Anchor**	**Max**	**Min**	**Middle**	**Mean**
Boyce et al., 2000 low	Private	Laboratory	1	No	-	680	7	344	398
Newsham et al., 2008	Private	Laboratory	1	Yes	320	700	0	350	355
Veitch and Newsham, 2000	Open plan	Laboratory	4	No	500	725	83	404	423
Tenner et al., 1997 low	Private	Laboratory	1	Yes	-	830	0	415	400
Newsham et al., 2004, design 1	Open plan, cubicles	Laboratory	1	No	200/400/ 600/800	944	33	489	452
Boyce et al., 2000 high	Private	Laboratory	1	No	-	1240	12	626	518
Boyce et al., 2006b, dimming	Open plan, cubicles	Field	1	Yes	365	1176	252	714	458
Tenner et al., 2007 medium	Private	Laboratory	1	Yes	-	1660	0	830	700
Newsham et al., 2004, design 3	Private, cubicles	Laboratory	2	No	200/400/ 600/800	1478	188	833	582
Begeman et al., 1997	Private	Field	>2	Yes	-	2000	200	1100	800
Tenner et al., 2007 high	Private	Laboratory	1	Yes	-	3100	0	1550	1200

Boyce et al. [Boyce et al., 2000] applied the method of adjustment in two small, windowless, private offices. The available illuminance range was maximum 1240 lux in one room and 680 lux in another. Within these two ranges, the subjects set different illuminances. Newsham et al. [Newsham et al., 2004] performed a study on different lighting designs and two of these (the ones most relative to this literature review) are shown in Table 1. Design 1 in their study only included recessed parabolic luminaires with a range up to 944 lux, resulting in a mean settings of 452 lux. Design 3 in their study also included at task lamp raising the maximum illuminance to 1478 lux and the mean settings to 582 lux. In another study by Newsham et al. [Newsham et al., 2008] they provided subjects with an illuminance range up to 700 lux in a glare-free, daylit office laboratory resulting in subjects setting to an average of 355 lux.

In the study by Newsham and Veitch [Newsham and Veitch, 2001] they provided the first half of their subjects with occupant control over four different lighting systems, and invited them to adjust to their preference in the morning and than to perform different tasks during the day. The other half of their subjects also worked under the light set by the first half of subjects in the morning. At the end of the day, the subjects who had not set the lighting in the morning adjusted to their preference. Table 1 shows the results of the first half of the subjects who adjusted from the initial setting (anchor). Afterwards they used a regression method on the two sets of data, gathered in the morning and at the end of the day leading them to propose 392 lux as the preferred desktop illuminance within a range of 0-725 lux.

Begemann et al. [Begemann et al., 1997] provided their subjects with an illuminance range of 200-2000 lux and CCT of 2800-5000 K. They conclude that preferred lighting levels are significantly higher than today's indoor lighting standards or on average 800 lux. They further found that the average preferred CCT was around 3300 K for daylighting levels of around 500 lux (on desk) and increased to 4300 K for daylighting levels of around 1500 K.

In the search for optimum illuminance, Boyce et al. [Boyce et al., 2006b] applied the method of adjustment, providing a stimulus range of 252- 1176 lux on desktop, and the mean chosen illuminance was 458 lux. They also compared their data to that of Newsham and Veitch [Newsham and Veitch, 2001] and drew the following conclusion: that 350 lux is the optimal illuminance on desktop. The conclusions from these two studies apply to lighting systems that provide a uniform pattern of illuminance across the working area. The recommendations are that a range of 175-700 lux should be available when providing occupant controlled lighting, and that 400 lux is appropriate as a fixed light level that is close to the preferred illuminance of the maximum percentage of people. These results are not in accordance with those of Tenner et al. [Tenner et al., 1997].

Preferences

The dictionary definition of the word *preference* is the selection or choice of one thing over another or others [Hornby, 1974]. In a psychology literature review, Payne et al. [Payne et al., 1992] concludes that there is ample evidence that preferences are often constructed in response to a judgment or choice-task.

The psychological literature on judgment focuses mainly on availability, anchor and frequency and how these factors influence subjective judgment. Helson’s theory of adaptation-level [Helson, 1947] presents mathematical models for perception of a stimulus based on experience. He explains an adaptation-level as a neutral state, such as being luminance-adapted, Helson’s theory of adaptation level has been partly validated and partly criticised by his colleagues [Parducci, 1959, Parducci et al., 1960, Sarris, 1967]. However, his colleagues seem to agree that available range affects a subject’s judgment to some degree. Available stimulus range seems to be judged according to its limits (and in some cases frequency), the lower limit of a range being perceived as low or small, and the higher limit of the range as high or great [Wever and Zener, 1928].

Hunt and Wolkmann [Hunt and Wolkmann, 1937] showed how anchoring affects judgment on an affective scale. Since then, significant anchor effects have been detected in psychophysics by different stimuli [Parducci, 1954]. Tversky and Kahneman [Tversky and Kahneman, 1974] defined anchoring by saying that different starting points yield different estimates, which are biased toward the initial values. They stated that anchoring, among other heuristics, leads to systematic and predictable errors.

Occupant control and preferences

Fotios and Cheal [Fotios and Cheal, 2010] compared previous studies of determining preferred illuminances using the method of adjustment. A stimulus bias was noted within all the data they examined. A stimulus bias results in the mean preferred illuminance approaching the centre of the available stimulus range. This bias is the result of a fairly equal distribution of data across the available stimulus range. They showed that studies which provided subjects with high stimulus ranges resulted in high preferred illuminances, and that studies which provided subjects with lower ranges resulted in lower mean preferred illuminances. Fotios and Cheal [Fotios and Cheal, 2010] confirmed this bias by applying the method of adjustment in a scale model where the subjects were instructed to set their preferred illuminance using a rotary dial and were not aware that the experimenter changed the range of illuminances available in successive trials. Three different ranges were tested with pre-set anchors near the minimum and maximum limits of the provided range. Their results were that mean preferred illuminance in each range approached the centre of the range. The larger the range provided, the higher the mean preferred illuminance. They also identified significant anchor effect in their studies, where higher pre-set anchors resulted in higher preference estimates and vice versa.

Studies concerned with occupant controlled lighting seem to agree that there is a wide variance in illuminance choice between individuals [Boyce et al., 2006b, Newsham et al., 2004]. However the variance may be due to a centering bias within the data.

Table 1 suggests there may be a tendency for illuminance settings to grow with the illuminance interval and also suggests that the anchor may influence the settings. The study of Tenner et al. [Tenner et al., 2005] indicates a stimulus range bias, where the minimum *acceptance* rises with the provided range. The study of Boyce et al. [Boyce et al., 2006b] provides a large range of desktop illuminances of 252- 1176 lux where the mean chosen illuminance is 458 lux. The question remains whether the relatively low chosen illuminance within this range is the result of a low anchor of 366 lux.

Newsham et al. [Newsham et al., 2005] report a significant anchor effect where a higher anchor leads to higher mean settings. Juslén found controversial results regarding the anchor effect. Juslén [Juslén, 2005] first observed 11 subjects' preferences for the anchor control settings of 10% and 100% for four months, changing anchor settings every second week. The low control setting resulted in an average of 1340 lux and a high of 1370 lux. The stimulus range was not reported. However, in the following year Juslén [Juslén,2006] found a significant anchor effect ($p<0.01$) where anchors of 310-400 lux resulted in settings of around 500 lux and anchors of 740-990 lux resulted in settings of around 850 lux. Osterhaus and Bailey [Osterhaus and Bailey, 1992] applied the method of adjustment to identify the borderline between different glare thresholds for the brightness of a light source surrounding a PC screen. They presented subjects with different anchors, and their results show that higher anchors lead to higher estimates of the threshold luminance.

Despite these indications of methodological effects on the results due to the method of adjustment, many studies that apply the method omit information on the available stimulus range and/or anchor. This work will further investigate potential biases related to the method of adjustment.

Occupant Controlled Lighting

General introduction

Occupant preferences for illuminance and correlated colour temperature (CCT) in office environment were investigated using the method of adjustment, and considerations of energy efficiency were on the agenda. The literature presents divergent data on illuminance preferences in offices [Tenner et al., 1997, Newsham and Veitch, 2001, Boyce et al., 2006b] and therefore also suggests different approaches to achieving energy efficiency by means of preferred illuminance.

This work begins with a preliminary study based on previous work, Article I [Logadóttir and Christoffersen, 2008b], where the method of adjustment is applied to a commercial dynamic lighting concept installed in a laboratory. Occupant control dependency of daylighting was of special interest. Subjects were prompted to use the controls every half hour for one day, because previous studies have shown limited use of lighting controls [Galaciu et al., 2007, Jennings et al., 2000, Boyce et al., 2006b, Moore et al., 2003]. By prompting subjects to adjust every half hour, data was gathered according to the varying daylight contribution throughout the day. Occupant control of the lighting system was recorded and questionnaires used to obtain further information on occupant experience of the lighting system. The questionnaire data is outside of the scope of this work.

The preliminary study was reviewed according to the findings of Fotios and Cheal [Fotios and Cheal, 2010] on stimulus range bias associated with the method of adjustment. It was decided to further explore the method of adjustment with respect to occupant preferences for illuminance and CCT, focusing mainly on identifying bias potentials in the method of adjustment. Fotios and Cheal [Fotios and Cheal, 2010] discovered a stimulus range and anchor affect when using the method of adjustment to identify illuminance preferences using a scale model. In the presented work these effects were further explored in a laboratory furnished as an office, and in a scale model for CCT. Additional variables of the experimental design that were also of interest were adaptation time and control dial. As discussed in Article III [Logadóttir et al., submitted to Lighting Research and Technology] the literature regarding the CCT - illuminance relationship was considered misleading, due to the divergent data it presents, so this possible bias was also tested within this work.

According to Newsham et al. [Newsham et al., 2008] the illuminance measured on the desktop is the best predictor for illuminance adjustment in an office environment using the method of adjustment. Desktop illuminance is therefore reported in this work as the illuminance adjustment variable.

Preliminary study

(Detailed description in Article I [Logadóttir and Christoffersen, 2008b] and Article II [Logadóttir and Christoffersen, 2009])

Introduction

An experiment was designed with the intention of identifying an energy-efficient, user-accepted approach to a dynamic lighting concept. This was done by exploring occupant control for one type of dynamic lighting concept in two different seasons. The first part of this study, done in winter, had already been performed and documented in a master's thesis [Logadóttir, 2007, Logadóttir and Christoffersen, 2008a, Logadóttir et al., 2008b]. The objective of the first part of the study was to obtain knowledge of how occupants applied the concept and how the concept was experienced, as well as accounting for energy use. The study was performed from December 2006 to March 2007. Fifty subjects spent one working day each in a laboratory test room where they performed ordinary office work and chose their own light setting, using the method of adjustment, every 30 minutes throughout the day. The illuminance range provided on desktop was 57 to 1270 lux, and CCT measured vertically at the estimated eye-level position was 2900-5500K. At start of the day, the lighting was set at 500 lux and 3500K. The results showed that controls were utilized to some extent to vary light levels according to daylight contribution, with a mean illuminance value on desktop extending the recommended practice value. CCT was chosen depending on personal preferences. Most of the subjects recorded using the controls, depending on daylight condition and their task. Subjects found it important to have the opportunity to adjust light levels as well as the illumination colour. The study did not achieve energy savings compared with a fixed light level of 500 lux on desktop according to recommended values.

There were three main focuses in the second part of the study. In the first place, to explore whether there were different ways of applying the dynamic lighting concept between seasons. Secondly, whether energy savings would be achieved for autumn compared to winter, and thirdly to confirm diversity within individual illuminance and CCT preferences. For further details, see Article I [Logadóttir and Christoffersen, 2008b] and Article II [Logadóttir and Christoffersen, 2009].

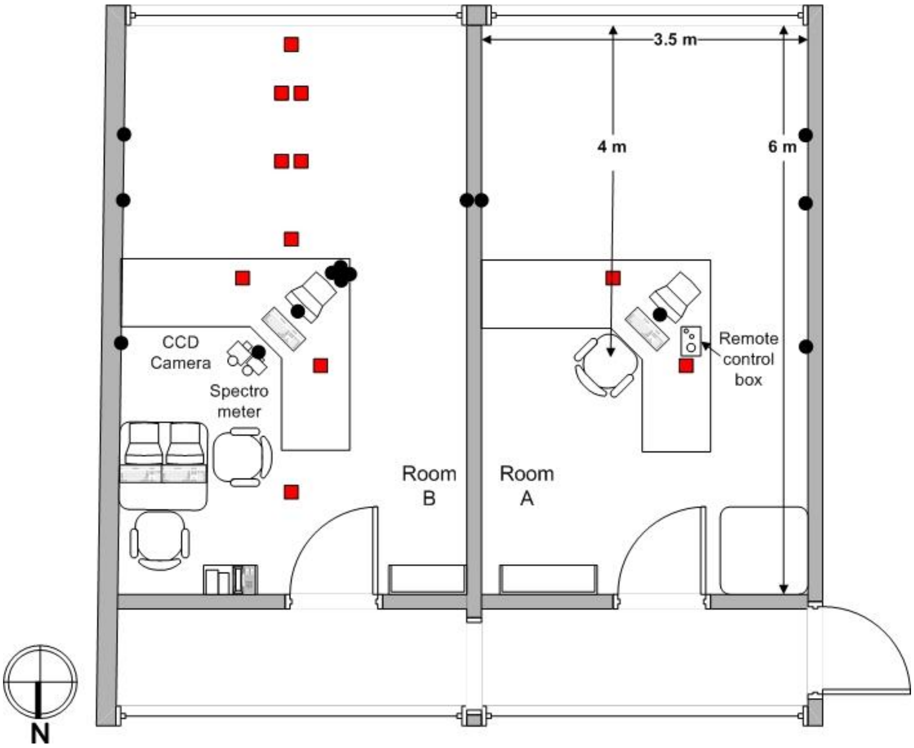

Figure 2: Experimental set-up in the laboratory. Subjects are placed in Room A and photometric recording instruments in Room B. Symbols indicate the location of illuminance meters, horizontal (squares) and vertical (black dots). [Logadóttir and Christoffersen, 2009]

Study Setup

Both the winter and autumn trials were performed in SBi's daylight laboratory (see Figure 1) in Hoersholm Denmark, 56°N and 12°E. Inside the laboratory there were two identical, experimental rooms located side-by-side, one room for subjects (Room A) and the other for researchers and photometric measuring equipment (Room B). This allowed detailed lighting condition data to be collected. The experiment was carried out for autumn from 4 September to 24 October 2008. Figure 3 shows a subject in room A participating in the study. The window dimensions and position were 3.5 m wide and 1.4 m high, with a sill height of 0.78m. White venetian blinds were controlled by the researcher in both rooms simultaneously in order to prevent glare from the windows.

Lighting system

The lighting system was identical in both rooms. In each room, three luminaries (ceiling-mounted direct) were installed, each containing three TL5 tubes with a general colour rendering index of R_a 85. Of the three tubes, two were 6500 K tubes and one was a 2700K tube. The voltage of the electricity supplied to these lamps was stabilized at 230V throughout the study. The lamps were operated on electronic dimming ballasts by a commercial lighting control system [Multidim]. The subjects were provided with a control box to adjust the illuminance and/or CCT by controlling the output from the two types of tubes, either simultaneously by means of a rotary control dial or individually with a double slider. The rotary dial provided an illuminance range of 3% to 100% in one complete turn, but this was open ended so that there were no obvious physical limits to the range. The double slider was adjusted for the same range, and the physical limits of the range were apparent.

The control box was placed on the desktop in front of the subjects, who adjusted the light setting in both rooms simultaneously. The illuminance conditions in the two rooms were identical to within 3%. The lighting system provided 57 to 1270 lux on the desktop; a maximum of ~ 860 lux when using only the 6500K tubes and maximum ~ 400 lux when using only the 2700K tubes.

Subjects

A total of 22 subjects participated in both seasons (11 male and 11 female), their age ranging from 22 to 36 years. This was a repeated measures design. During the autumn season, 22 of the 50 subjects (participating in the winter trials) returned 18 months later to perform exactly the same procedure in the same set-up as before. In the data analysis, subjects who did not participate in the autumn trials were excluded. All subjects reported having normal or corrected-to-normal vision, and only one subject occupied the laboratory on each test day.

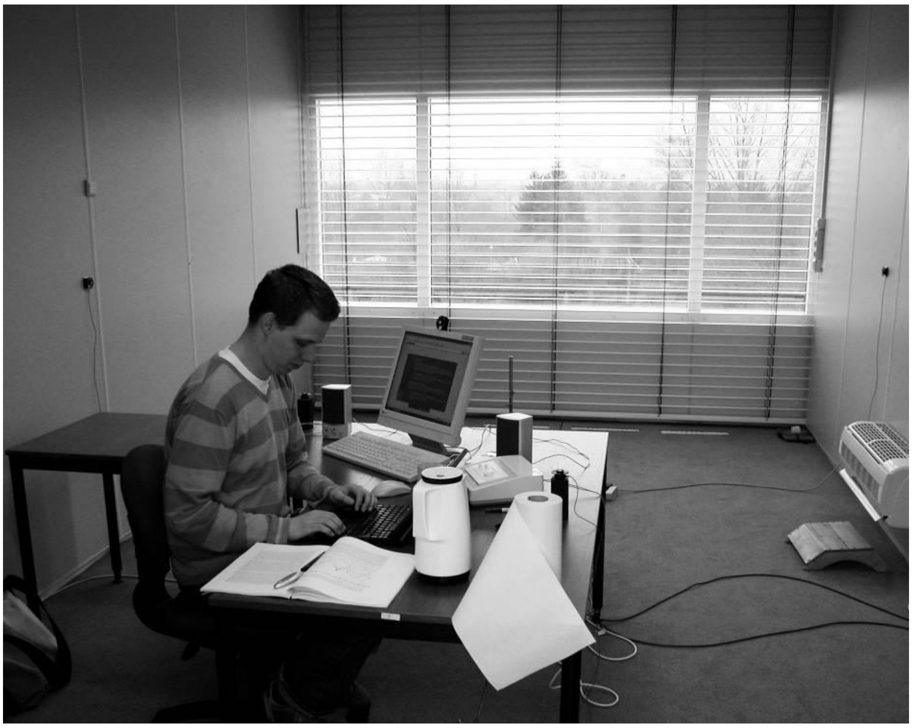

Figure 3: subject participating in the preliminary study

Measurements

Global total and diffuse illuminance and irradiance measurements were recorded by an exterior meteorological station located on the roof of the laboratory. The interior position of illuminance meters is shown in Figure 1. The photometric equipment in Room B was mounted on a tripod at the approximate level of the occupant’s eyes (1.2m). The equipment included a vertical illuminance sensor, a spectrometer and a digital camera calibrated as a luminance camera (yielding pixel-by-pixel luminance measurements). The energy use for lighting, luminance and light spectrum was recorded 23 times during the day, immediately before and after subjects changed the light setting by means of the remote control box.

The light spectrum measurements were presented by the CCT of the spectrum. Mixing two different CCT fluorescent tubes and the reflection from different surfaces in the room resulted in a CCT value outside the definition for

CCT [CIE, 2004]. Nevertheless, CCT values were used because the CCT values made it easier for the reader to relate to warm or cold colours rather than u' and v' chromaticity coordinates. Borbély et al. [Borébly et al., 2001] state that CCT is nothing more than a shorthand description of whether the light is bluish white, neutral or reddish white. In this study, the CCT values were used as a rough estimate of cold or warm colours only.

To distinguish between measured illuminance and CCT, which includes electrical lighting and daylight contribution, a model had been made for control-setting position and luminaire output. The model was based on measurements after blocking out daylight. In the illuminance data, the daylight component was the difference between the measured values during tests and the measured electric lighting component for the corresponding control setting.

Procedure

This project was carried out in cooperation with National Research Council Canada (NRC) and Lawrence Berkeley National Laboratory (LBNL), USA. The method applied was the method of adjustment, and the procedure was adapted to the Newsham et al. [Newsham et al., 2008] study on occupant lighting control in a daylit space.

The experimental session in the laboratory started between 8:45 and 9:15 am. During this period, the lighting equipment was introduced, the subjects answered Part 1 of a questionnaire (which is outside the scope of this work) and tested the remote control box. Before the subject's arrival, the electric lighting was set by the researcher to provide a desktop illuminance of ~500 lux and CCT of ~3500 K. The subjects were told that they could only change the lighting scenario when invited to do so by the researcher; the invitation came every 30 minutes, beginning at 9:15 am. The researcher took luminance photos, measured the light spectrum at eye level and registered the energy use immediately before and after the subjects chose their preferred light setting. There were no breaks other than the lunch break (from 12:00 – 12:30). When subjects returned from lunch, the light level on the desktop was adjusted by the researcher to maintain a maximum of 500 lux, and the CCT value was kept as far as possible at the same level as that chosen before lunch. The final control opportunity occurred at 15:15. At the end of the day, the subjects completed Part 2 of the questionnaire, which included questions on how they used the controls and on their satisfaction with various aspects of the indoor and lighting environment. Information on light sensitivity and chronotype was collected but is also outside the scope of this work.

Results

The results on illuminance and CCT are not statistically tested due to the strong relationship between the illuminance and CCT adjustment. We do not know which variable the subject was aiming to adjust (or if he intended to adjust both), and therefore a descriptive report of the results is provided instead of statistically testing a presumably meaningless variable rather than a dependent variable. The highly variable daylight contribution would also have been a difficult confound within the statistics.

An average illuminance value for all 11 trials per day for all 22 subjects amounted to 1098 lux for winter trials and 1381 lux for autumn trials, thus relatively 26% higher in autumn than winter. The electric lighting contributed 629 lux of this measure during the winter season and 630 lux during the autumn season, and was thus seasonally independent. Figure 4 shows a trend line for the average of all 22 subjects where the measured illuminance throughout the day is split into an electrical lighting component and a daylighting component for both seasons. The figure shows the difference in the daylight contribution, the electrical lighting chosen being fairly stable between seasons.

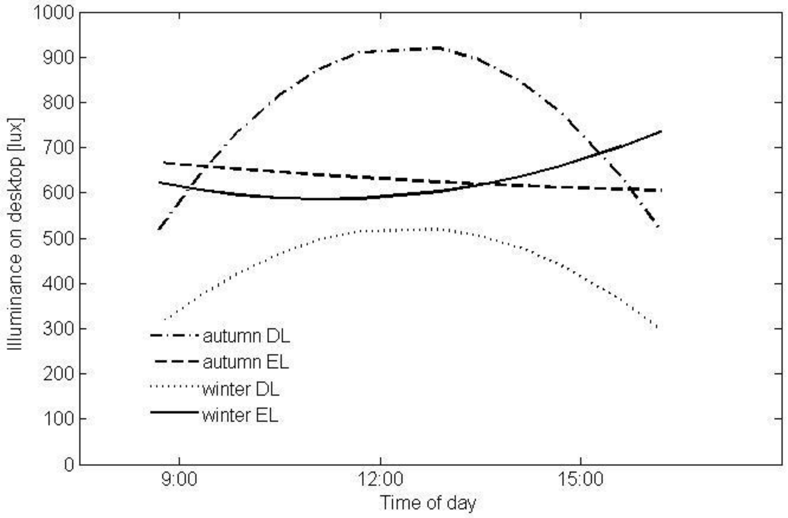

Figure 4 Illuminance measured on desktop for winter and autumn seasons split between electrical lighting component (EL) and daylighting component (DL).

An average CCT value for all 11 trials per day for all 22 subjects amounted to 4700 K for winter trials and 5080 K for autumn trials. The average CCT value for all trials for the electric lighting component was 4060 K during the winter season and 4030 K during the autumn season, and was thus seasonally independent.

The installed lighting power density was 26 W/m^2, which was much higher than the recommended installed lighting power density in office environments in Denmark. The average lighting power density amounted to 13.1 W/m^2 for the winter trials, compared to 13.3 W/m^2 for the autumn trials, and was thus independent of season.

Discussion

According to the electrical lighting results, users preferred the same mean illuminance and CCT, independently of the daylight contribution for the two different seasons. Daylight contribution was on average 469 lux on desktop in the winter trials, while it averaged 751 lux for the autumn trials. The results therefore did not result in energy savings in autumn compared to winter. The same interval and pre-set anchor was used in the two trials, and according to Fotios and Cheal [Fotios and Cheal, 2010] the results show strong indication of stimulus-range bias, both within the illuminance range and the CCT range. It is not known whether one is the result of the other due to dependency between the two variables using this lighting system. Further work therefore focused on possible biases within the method applied.

Illuminance preferences using the adjustment task

(Detailed description in Article III [Logadóttir et al., Lighting Research and Technology] and Article V [Logadóttir et al., in manuscript])

Introduction

According to Fotios and Cheal [Fotios and Cheal, 2010] the preliminary study indicated a stimulus range bias when determining preferred illuminance. The psychology literature [Parducci et al., 1960, Tyversky and Kahneman, 1974] supported Fotios' and Cheal's findings in different ways. Preference is based on judgment [Payne et al., 1992], and Parducci puts it well when he refers to the relativism of absolute judgment [Parducci, 1968]. This gave reason to further explore the influential parameters for preference when applying the method of adjustment.

This test was designed to investigate the effect of stimulus range, pre-adjustment anchor, CCT, adaptation time and internal consistency when applying the method of adjustment to determine occupant preferences for illuminance in an office setting (see Article III [Logadóttir et al., submitted to Lighting Research and Technology] for detailed information). Of further interest was the satisfaction rating for an energy efficient application using the method of adjustment (see Article V [Logadóttir et al., in manuscript] for detailed information).

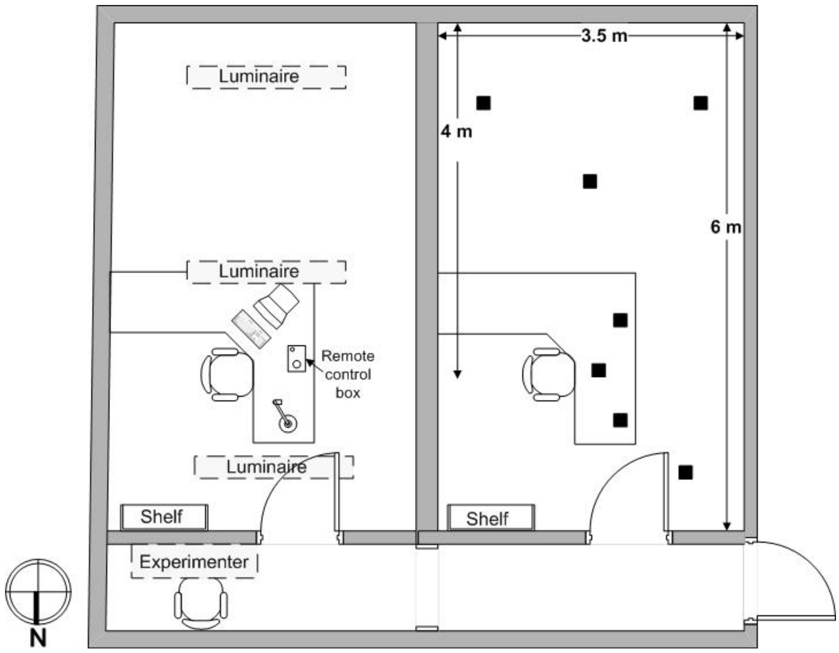

Figure 5: Plan of the test rooms used for the illuminance adjustments. The left room shows the locations of the luminaires; the right room shows the location of the seven illuminance measurements used to compare spatial distributions. All windows were shielded and the doors closed during the study to exclude daylight and external views. [Logadóttir et al., submitted to Lighting Research and Technology]

Study setup

The test was carried out in the same laboratory as described in the section on the preliminary study, and the setup inside the room is shown in figure 5. Daylight was excluded by shielding the windows. Figure 6 shows a subject using a mask between trials. During trials, the mask was removed, and reading task and control dials were their assignment. The computer and task light were turned off during the study.

Figure 6: Subject wearing mask between trials. Reading task and controls are placed in the immediate vicinity, computer and task light were turned off during the study.

Lighting system

The lighting systems in each room were identical and the same as used in the preliminary study, however this time all three luminaires in a room contained the same CCT fluorescent tubes. Each room was lit by one CCT at a time, nominally 3000K, 4000K and 6500K, all having a general colour rendering index of R_a 85.

The researcher set the anchors and changed the stimulus range (i.e. the number of tubes being adjusted) by means of the DALI based lighting-control software [Multidim]. Subjects adjusted the illuminance within the provided range with the same rotary dial used in the preliminary study (see Figure 6), the double slider was not idle in this study.

Subjects

A total of 36 naïve subjects took part in the study. These were 16 males and 20 females, aged 20 to 67 years (mean 27.7 years, std dev 9.9) and were either university students or office workers. All subjects reported normal colour vision except one, who reported red-green colour deficiency. Subjects were instructed to wear vision-correcting lenses if they were normally worn in office work situations.

Measurements

Desktop illuminance was measured for all three CCT, and there were three measurements for each CCT (3x3) for control settings from 3% to 100% within all three ranges (3x3x3xcontrol setting). The reported illuminance measurements are the mean of all these parameters. The maximum difference in illuminance between the two rooms at any one point was 6.8%. The measuring points are shown in Figure 5. The maximum CCT difference between the two rooms was 2% for lamps of nominally the same CCT. The measurements were performed using a reference white on task location.

Procedure

A detailed description of the procedure is presented in Articles III [Logadóttir et al., submitted to Lighting Research and Technology] and V [Logadóttir et al., in manuscript].
The following is a summarized description of the way the different parameters were tested:

CCT
To investigate interaction between CCT and illuminance preference, the adjustment task was carried out using lamps of three different CCT (3000K, 4000K and 6500K). Only two test rooms were available, so the researcher changed the tubes in one of the rooms during the break. The different CCT tubes were installed randomly in the two rooms.

Stimulus range
To confirm the presence of a stimulus range bias in the current study, the adjustment task was repeated using different stimulus ranges. Three different stimulus ranges were created by varying the number of active lamps in each luminaire, i.e. one lamp (range R1, the central tube), two lamps (range R2, the outer two tubes), or all three lamps simultaneously (range R3).

Anchor
To confirm the presence of anchor bias in the current study, the adjustment task was repeated using different anchors within the stimulus ranges. Three anchors within a range were chosen.

> A low anchor (A1) was approximately the same across all three sizes of stimulus ranges. This presented an opportunity to compare an anchor across stimulus ranges.
>
> A middle anchor (A2) was set at a 50% control setting position within all three ranges a method previously used by Boyce et al. [Boyce et al., 2006b]
>
> A high anchor (A3) was set at 90% control setting position. 90% was chosen instead of 100% in order to avoid giving the impression that a downward adjustment was the only preference option available, thereby determining a subject’s preference to some degree.

In an attempt to minimize a sequential anchor bias (a subject comparing his perception of the previous adjustment task to the anchor set by the researcher), subjects were asked to use a mask while the researcher set the next anchor (see Figure 6).

Internal consistency

In order to establish whether subjects were consistent in their choices within one context, the researcher set the middle anchor (A2) twice within all stimulus ranges.

Adaptation time
Two levels of adaptation were used, and they were examined between subjects. Half of the test subjects (luminance adapted subjects) were instructed to wait for five minutes after removal of the eye mask before attempting the adjustment task. The other half of the test subjects (non-adapted subjects) were instructed to carry out the adjustment immediately after removing the mask.

Satisfaction with estimated preference
At the end of each CCT session, the test subject was presented with a fixed light level and asked to report his satisfaction, thus giving 36 subjects x 3 CCT's judgements of satisfaction. This illuminance was the mean illuminance which they had set in a total of four anchor trials (the three anchors and the repeated one) with the lowest of the three illuminance ranges. One half of the test subjects were informed that this was the mean of their settings (informed subjects), the other half were not (not-informed subjects). Satisfaction was reported using a three-category response scale: (1) they would prefer less light, (2) they were satisfied with the light level, or (3) they would prefer more light.

Test subjects were informed that they were participating in a study of user preferences for light levels in an office environment. After entering the first test room and sitting at the desk, they were given instructions regarding the task and use of the eye mask between trials and were given the opportunity to try the dimming control device. The light setting at this time was the first experimental setting for that test subject and was therefore balanced across subjects. Subjects were instructed to adjust the amount of light in the test room to the level they would prefer while reading a text placed flat on the desk surface and this was done using the rotary control device placed on the desk.

This was a repeated measures design; all test subjects were presented with the 36 combinations of stimulus range (3), CCT (3), anchor (3 plus one repeat), the repeat anchor being anchor A2. When a test subject entered a room it was lit by only one CCT, and tests using all combinations of stimulus range and anchor were completed for that CCT before moving to the adjacent room set up with a different CCT. At the end of each CCT trial, the mean value of all four anchors within the lowest range (R1) was presented to the test subject, and she was asked to rate whether she was satisfied, or wanted more or less light. The three anchors were carried out in a balanced order (plus the repeat anchor), and this was repeated for the other two illuminance ranges, these being experienced in a balanced order. Subjects were not informed that the ranges or anchors were being changed.

Results

Due to non-normally distributed data, analyses were performed primarily using non-parametric statistical tests. Non-parametric tests are sometimes less effective than parametric tests in revealing differences, and therefore the analyses were repeated using parametric tests for confirmation. Data analyses were performed using SPSS version 18, and the detailed description of analysis is reported in Article III [Logadóttir et al., submitted to Lighting Research and Technology].

The main results are the following:

1 The CCT did not affect the illuminance preference results obtained in this study. All three CCT 3000K, 4000K and 6500K produced similar preference results.

2 Different stimulus ranges lead to significantly different estimated preferred illuminances. In each case, the higher stimulus range (i.e. higher maximum value available) lead to the higher preferred illuminance.

3 The three different anchors provided significantly different results within each stimulus range, which demonstrates that the illuminance immediately preceding the adjustment task within the method of adjustment influences the results obtained. The lowest anchor A1 (which was the same anchor for each range) does not suggest a stimulus range bias but rather suggests similar preferred illuminance for all three ranges.

4 Subjects displayed a reasonable degree of consistency in their preferred illuminance adjustments within a particular stimulus range, anchor and CCT.

5 The subjects who were luminance-adapted for 5 minutes did not prefer different illuminance levels to those of subjects who adjusted immediately (non-adapted subjects) except within the low range (R1), where adapted subjects preferred significantly lower illuminance.

6 The test subjects would have preferred more light than presented to them, despite the presented illuminance being derived from the preferred illuminances they had personally set. The subjects who had previously adjusted within the lowest range were those who were most pleased with their presented level. There was no difference in satisfaction between subjects who knew of their contribution to the illuminance and those who did not.

Discussion

The experimental results show that both stimulus range and pre-adjustment anchor have significant influence on preferred illuminance set by adjustment, confirming the previous results of Fotios and Cheal [Fotios and Cheal, 2010]. Stimulus ranges with a higher maximum limit yield higher estimates of preferred illuminance. Within a given range, an anchor of higher illuminance leads to a higher setting of preferred illuminance.

Different estimates of preferred illuminances within a range produce different results. If the results are estimated using only one anchor, this anchor significantly influences the preference within the range. Furthermore, if results are estimated using the mean or median of two or three anchors, these methods are also shown to significantly affect the results for this non-linear control output relationship.

The consistency in choices within CCT, range and anchor suggests that subjects do present an individual preference within the context and are not just randomly setting the illuminance.

This test confirms the context-specific results that can be expected using the method of adjustment.

CCT preferences using the adjustment task

(Detailed description in Article IV [Logadóttir et al., submitted to Colour Research and Application])

Introduction

The Preliminary study (described in a previous section) not only suggested a stimulus range bias in the illuminance adjustments, but also in the CCT adjustments. It is not clear whether the stimulus range bias indicated for the CCT was the result of the illuminance range bias. The reason for this doubt is the strong relationship between the illuminance and CCT adjustments in the lighting system used in the preliminary study. The psychological literature establishes judgment bias with different types of stimulus [Parducci, 1954], and it was therefore decided to further explore possible influential parameters when determining CCT preference using the method of adjustment in a scale model.

The test was designed to investigate the effects of stimulus range, pre-adjustment anchor, type of control dial, adaptation time and internal consistency when applying the method of adjustment to determine occupant preferences for CCT.

Study setup

The test was carried out by subjects sitting in front of a scale model as shown in Figure 7. The dimensions of the visible space were: width 1.1 m, length 1.1m and height 1.1 m, similar in size to that used by Fotios and Cheal [Fotios and Cheal, 2010]. Daylight was excluded, because the study was performed in a windowless laboratory. The internal surfaces of the scale model were painted white, and typical desktop materials were used to give the impression of an office desk. The luminaires were placed behind the front screen of the scale model, where they were not visible to test subjects, thus avoiding any significant magnitude of glare.

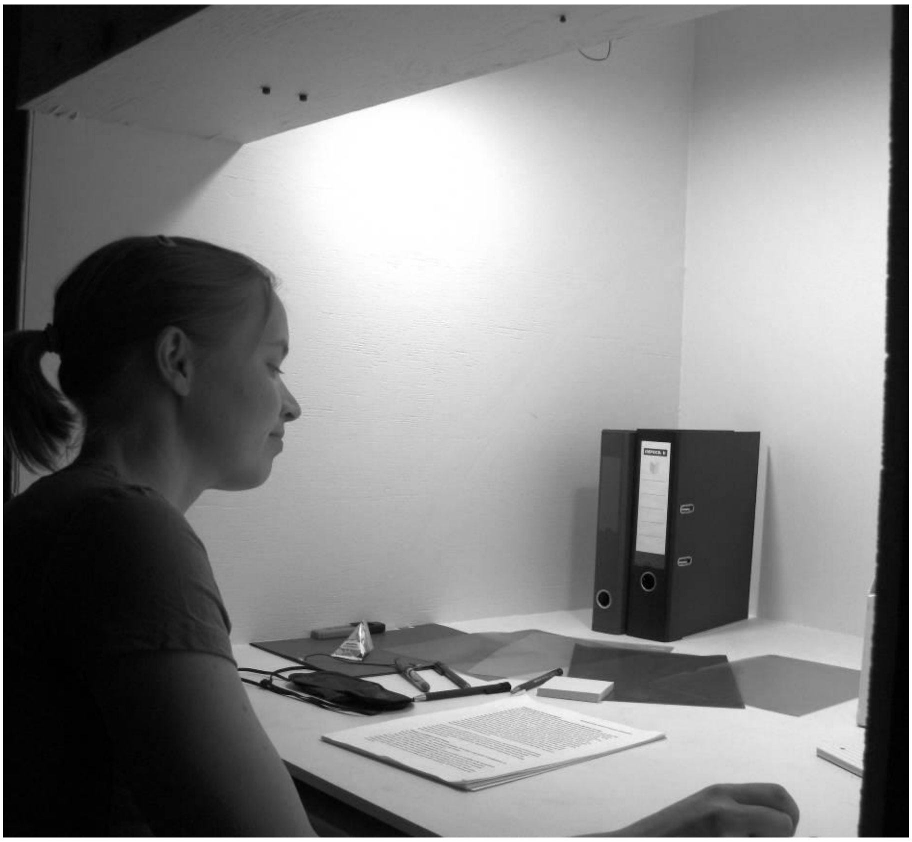

Figure 7: Subject performing the adjustment task for preferred CCT while reading a text in the scale model.

Lighting system

Lighting was provided by two identical, specially developed LED luminaires. To gain continuous variation in CCT by means of the control dial operated by test subjects, each luminaire contained an array of white and coloured LEDs that could be varied. The LED array permitted task CCT to be set in the range of 2736K to 4014K while keeping the general colour rendering index higher than 92 over the entire range.

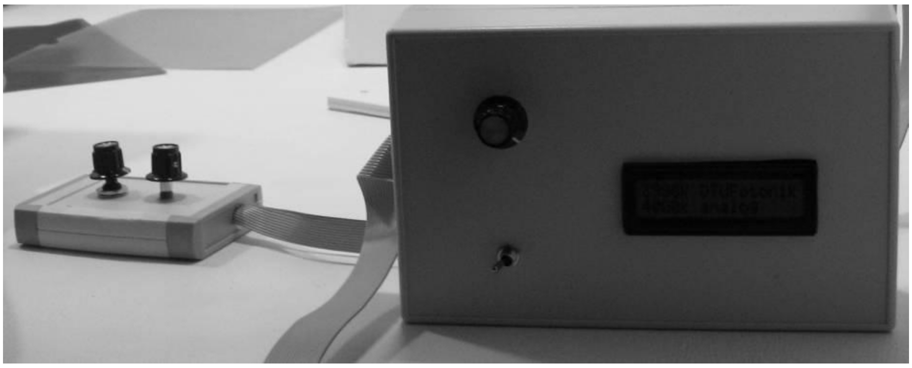

Figure 8: On the left is the subject's control box with the two rotary control dials, analogue on the left, digital to the right. The experimenter's control box was on the right.

Test subjects used a rotary dial placed on the desk in front of them to adjust CCT. Two types of dials were used, analogue and digital (see Figure 8). The analogue control dial was a one-turn potentiometer, meaning that the full variation of any range was achieved in a single 360° movement. This dial had physical limits at each end of the control action, so test subjects were aware that they could not adjust beyond the maximum and minimum points. The digital control dial was an incremental encoder, an open ended control that gave no indication of the stimulus end points, i.e. it could be turned indefinitely. It was set to cover the full variation of a stimulus range in three turns of the rotary dial.

The experimenter selected the type of control dial and the stimulus range by electric control independently of that used by the test subject (see Figure 8). The experimenter controlled which dial was activated by the pin (turning left or right) and which range was activated by the three-turn dial above. On the information screen, information about which dial was active, which range was active and the CCT provided by luminaires was displayed at all times.

Subjects

The participants in this study were the same 36 subjects who participated in the Illuminance adjustment study reported previously.

Measurements

The CCT measurements were performed 220 mm above the floor of the scale model, facing the task, and the reported values of CCT are thus the LED spectra as modified by reflectances in the test apparatus. Due to stability in control-output parameters, it was not necessary to perform as many measurements for each parameter (range, control, etc.) as it had been when measuring output from fluorescent tubes. The illuminance and CCT were measured and confirmed by Risø-DTU. Measurement data are listed in Article IV [Logadóttir et al., submitted to Colour Research and Application].

Procedure

This test examined some of the same parameters for the method of adjustment as performed previously for the illuminance preference study, such as stimulus range, anchor, consistency and adaptation time. In addition, a different type of control dials was tested. The following are the parameters tested and a summary description of how they were tested:

Stimulus range
In the current study, a different method was applied for estimating stimulus range bias than previously used in the illuminance study. Range R3 allowed test subjects to set a CCT in the range of 2736 to 4014K, i.e. the entire range available with this apparatus. If the setting of preferred CCT followed a centering bias, the mean preferred CCT in this range would be approximately 3375K. Ranges R1 and R2 provided 2736 - 3530K and 3284 - 4014K, respectively, and thus each range included the central value of R3.

Anchor
To confirm the presence of anchor bias in the current study, the adjustment task was repeated using different anchors within the stimulus ranges. Three anchors within each range were chosen.

The low anchor (A1) was set at 10% of the control setting for all three ranges

A middle anchor (A2) was set at a 50% control setting position within all three ranges

The high anchor (A3) was set at 90% for all three control ranges

A mask was also used in this study to minimize potential sequential anchor bias.

Internal consistency
To establish whether subjects were consistent in their choices within a context, the researcher set the middle anchor (A2) twice within all stimulus ranges.

Adaptation time
Two levels of adaptation were used, and this was examined between subjects. Half of the test subjects (luminance-adapted subjects) were instructed to wait for five minutes after removal of the eye mask before attempting the adjustment task. The other half (non-adapted subjects) were instructed to carry out the adjustment immediately after removing the mask.

Control type
The existence of a physical limit and the number of turns to cover the stimulus range using a control dial was tested within subjects. This experiment would therefore reveal whether differences in movement of the control dial affected settings of preferred CCT.

Test subjects were informed that they were participating in a study of user preferences for illumination colour in office environment. After entering the laboratory and sitting down in front of the scale model, they were given the opportunity to use both types of control dial to experience the control action and resulting variation in CCT. The light setting at this time was the first experimental setting for that subject and was therefore balanced across subjects. Subjects were instructed to adjust the illumination colour inside the scale model to their preferred level using the rotary control device while reading a text placed flat on the floor of the model, as in the previous study.

This was a repeated measures design, where all test subjects carried out the adjustment tasks with all 24 combinations of stimulus range (3), control dial (2), anchor (3 plus one repeat), anchor A2 being the repeated anchor. When a test subject entered the laboratory, the scale model was lit and one of the two control dials was activated. The order in which the control dials were used was balanced across subjects. Whether or not a subject was 'adapted' was also balanced between subjects. The trials using all 12 combinations of stimulus range and anchor were completed for that control dial before changing over to the second control dial. The anchor adjustment trials within one CCT range were carried out in a balanced order (plus the repeat anchor) before moving on to the next CCT range. The order in which the three CCT ranges were used was counterbalanced. Subjects were not informed that the ranges or anchors were being changed.

Results

Determination of whether the data in this study was drawn from a normally distributed population was carried out by analysis of graphical and statistical methods. The results are shown in Table 4 Article IV [Logadóttir et al., submitted to Colour Research and Application]. In the case of normally distributed data, parametric tests were used, i.e. ANOVA and the *t*-test. When the data was not considered normally distributed, it was initially analysed using non-parametric statistical tests. Conclusions were drawn by using these tests and were subsequently reviewed using parametric tests. Data analyses were performed using SPSS version 18 and in Article IV [Logadóttir et al., submitted to Colour Research and Application], the analysis is described in more detail.

The main results are the following:

1 Different stimulus ranges lead to significantly different estimated CCT preference.

2 The three different anchors provided significantly different results within each stimulus range. This demonstrates that the CCT immediately preceding the adjustment task influences the results obtained.

3 Subjects displayed a reasonable degree of consistency in their preferred CCT adjustments within a particular stimulus range, anchor and control dial.

4 Chromatically adapted subjects (5 minutes adaptation) preferred significantly lower CCT than subjects who adjusted immediately (non-adapted subjects).

5 The different control dials did not produce significantly different CCT preferences according to the method of best estimate (explained in Article III [Logadóttir et al., submitted to Lighting Research and Technology])

Discussion

The experimental results show that both stimulus range and pre-adjustment anchor have significant influence on preferred CCT set by adjustment. Higher stimulus range yields a higher estimate of preferred CCT than does a lower range, and a large range produces more variance in the results than do smaller ranges.

Different estimates of preferred CCT within a range did not produce different results in all cases. Taking a mean or a median of two or three anchors as well as comparisons to the middle anchor resulted in similar results. This is a different result from that of the illuminance preferences study and is considered to be the cause of different control-output relationships, the control-output relationship being linear for the presented test and unlinear for the illuminance test. However, if the results are estimated using only one anchor, this anchor significantly influences the preference within the range.

The consistency in choices within the control dial, range and anchor suggests that subjects do present an individual preference within the context and are not just randomly setting the CCT.

This test further confirms the context-specific results that can be expected using the method of adjustment.

Discussion

Method of adjustment

The results of the studies presented in this thesis demonstrate that the results gained from using the method of adjustment are dependent on the context of the study setup. The significant effects on the results have been identified as the stimulus range available and the anchor. Another confounding factor is adaptation time before adjusting CCT.

The context-specific results demonstrate that the method of adjustment is not adequate in research to identify a generally preferred illuminance or CCT value. The larger the stimulus range provided, the larger the variance obtained in the data, which results in the mean preference approaching the middle of the stimulus range. However, this stimulus-range bias can be used intentionally in application to design a range with an objective.

The anchor is a difficult variable when applying the method of adjustment in research. The higher the anchor is set within a range, the higher the estimated preference within the range. Different anchor treatments (mean or median values of anchors) to estimate preference can also have significant effects on the results. The results presented in Articles III [Logadóttir et al., submitted to Lighting Research and Technology] and IV [Logadóttir et al., submitted to Colour Research and Application] suggest that when using a linear control-output relationship within the lighting system, the results are more consistent between anchor treatments than for a non-linear control-output relationship. Furthermore, the middle anchor is the anchor most likely to produce normally distributed data, which is convenient for data analysis.

The effect of anchor also presents an opportunity for application. One example is given in Article III [Logadóttir et al., submitted to Lighting Research and Technology] where it is suggested that the preference results for the low anchors (70 lux on desktop) were independent of range size, presenting an opportunity for energy efficiency.

In Article V [Logadóttir et al., in manuscript], it is suggested against using the method of adjustment in research to identify the recommended illuminance levels in offices. The article further suggests that using the method of adjustment could result in occupants choosing lower light levels than recommended today while still remaining satisfied.

The results of the preliminary study on the effect of daylight on occupant preferences suggest that the stimulus-range bias exists and is independent of season. Further work on occupant controlled lighting should focus on limiting the available range, utilizing a relatively low anchor within the stimulus range and simultaneously testing for satisfaction.

User preferences

The results of the studies presented in this thesis have confirmed the findings of Fotios and Cheal [Fotios and Cheal, 2010], and the conclusion is that the method of adjustment is not adequate to determine an absolute value for user preferences for illuminance or CCT. However, Payne et al. [Payne et al., 1992] discovered that when using different methods to determine preferences (i.e. choosing from a group or adjusting to a personal preference), individuals apply different approaches when determining their preference. This is not the only cause of variance, since even when applying only one method, individuals use different strategies to determine their preference. The variance in results from applying different methods complicates the search for a small set of underlying principles that could describe the behaviour that determines preference. However, Payne et al. [Payne et al., 1992] state that using an unstructured intuitive approach to judgment may be even more biased. The authors also suggest that decisions might be improved through either more straightforward changes in information environments or more complicated methods of decision analysis, such as decision-procedure models or the provision of decision aids, where the method is matched to the individual. One example of such a model is a context-dependent model presented by Tversky and Simonson [Tversky and Simonson, 1993]. Their model provides a framework for analyzing context-dependent preferences. However, they state that the analysis of context effects in perception has produced numerous examples of individuals performing unnecessary computations and attending to irrelevant aspects of the situation under study, thereby complicating rather than simplifying the task.

Scientists are still trying to understand the underlying behaviour that determines preferences. For example, Palmer and Schloss [Palmer and Schloss, 2010] present an ecological valence theory of human colour preference that is based on people’s average affective responses to colour-associated objects. The researchers performed a large-scale study aimed at understanding human colour preference in which they applied a massive repeated-measures design for different tasks related to colour affectiveness. These tasks included colour-preference, colour-appearance, and colour-emotion rating tasks.

Future research on lighting preferences should consider a multi-method approach.

Summary

The studies presented in this thesis have confirmed the findings of Fotios and Cheal [Fotios and Cheal, 2010] that stimulus-range bias and anchor influence user preferences for illuminance in laboratory office setting. Furthermore, similar effects of stimulus-range bias and anchor are detected in a scale model when testing CCT preferences, and higher CCT was chosen when subjects adjusted immediately, rather than chromatically adapting for 5 minutes.

Results from this thesis highlight the importance of reporting the range available and the anchor(s) when applying the method of adjustment, in order to place the results presented in their rightful context.

It is concluded that the results gained from using the method of adjustment are context-specific and should not be used to generalize regarding preferred illuminance or CCT.

The method of adjustment can be used to reduce energy consumption relative to a fixed recommended light level. In order to do so, the stimulus range should be limited to the recommended level, or just above it, and a low anchor set as a preset value.

The preliminary study for this thesis indicated that stimulus-range bias was independent of daylight contribution.

In the spirit of energy efficiency the term *tuning the light* instead of *dimming the light* should be implemented.

References

Begemann SHA, van den Beld GJ, Tenner AD. Daylight, artificial light and people in an office environment, overiview of visual and biological responses. International Journal of Industrial Ergonomics 1997; 20: 231-239.

Biner PM, Butler DL, Fischer AR, Westergren AJ. An Arousal Optimization Model of Lighting Level Preferences. An Interaction of Social Situation and Task Demands. Environment and Behavior 1989; 21: 3-16.

Borbély Á, Sámson Á, Schanda J. The concept of correlated colour temperature revisited. Color Research & Application 2001; 26: 450-457.

Boyce PR, Eklund NH, Simpson SN. Individual lighting control: task performance, mood, and illuminance. Journal of the Illuminating Engineering Society 2000; 29: 131-142.

Boyce PR, Human Factors in Lighting, second edition. London: Taylor & Francis 2003: 61-63.

Boyce PR, Veitch JA, Newsham GR, Jones CC, Heerwagen J, Myer M, Hunter CM. Lighting quality and office work: two field simulation experiments. Lighting Research and Technology 2006a; 38: 191-223.

Boyce PR, Veitch JA, Newsham GR, Jones CC, Heerwagen J, Myer M, Hunter CM. Occupant use of switching and dimming controls in offices. Lighting Research and Technology 2006b; 38: 358-378.

Commission Internationale de l'Eclairage (CIE). Technical Report: Colorimetry. CIE No. 15.3. Vienna: CIE, 2004.

EN 12464-1 Light and Lighting – Lighting of work places – Part 1: Indoor work places: 2003.

Fotios SA, Cheal C. Stimulus range bias explains the outcome of preferred-illuminance adjustments. Lighting Research & Technology 2010; 42: 433-447.

Galaciu AD, Newsham GR, Sauvagau C, Sandler DM. Energy saving lighting control systems for open-plan offices: a field study. Leukos 2007;4:7-29.

Gifford R. Light, décor, arousal, comfort and communication. Journal of Environmental Psychology 1988; 8: 177-189.

Górnicka, G. Lighting at Work Environmental Study of Direct Effects of Lighting Level and Spectrum on Psychophysiological Variables. Eindhoven: Technische Universiteit Eindhoven. 2008.

Hanifin JP and Brainard GC. Photoreception for Circadian, Neuroendocrine, and Neurobehavioral Regulation. Journal of Physiological Anthropology 2007; 26: 87–94.

Helson H. Adaptation-Level as frame of reference for prediction of psychophysical data 1947; 60: 1-29.

Hornby AS, Cowie AP, Gimson AC. Oxford advanced learner's dictionary of current English. Oxford University Press 1974.

Hunt W, Volkmann J. The anchoring of an affective scale. The American Journal of Psychology 1937; 49: 88-92.

Jennings JD , Rubinstein FM, DiBartolomeo D., Blanc SL. Comparison of control options in private offices in an advanced lighting controls testbed. Journal of the Illuminating Engineering Society 2000; 39-60.

Juslén HT. The influence of the preset level on the preferred illuminances in the industrial environment. Proceedings, Lux Europa 2005, Berlin, 463.

Juslén HT. Influence of the colour temperature of the preferred lighting level in an industrial work area devoid of daylight. Ingineria Ilumiatului 2006; 8, 18, 25-36.

Kort YAW and Smolders KCHJ. Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings. Lighting Research and Technology 2010; 42: 345-360.

Logadóttir A. Energy Savings by Individual Dynamic Lighting Control. Master's Thesis DTU, June 2007.

Logadóttir A, Christoffersen J, Traberg-Borup S. Elbesparelse gennem individuel dynamisk lysstyring. SBi report 2008a:18.

Logadóttir Á, Christoffersen J. Energy Savings by Individual Dynamic Lighting Control. Proceedings of the 11th International Conference on Indoor Air Quality and Climate. 2008b.

Logadóttir Á, Christoffersen J. Dynamic lighting concept in Danish office environments with daylight contribution. Proceedings Lux Europa. 2009; 1: 169-176.

Logadóttir A, Christoffersen J, Fotios SA. Investigating the use of an adjustment task to set preferred illuminance in a workplace environment. Submitted to Lighting Research and Technology, September 2010.

Logadóttir A, Fotios SA, Christoffersen J, Hansen SS, Corell DD, Dam Hansen C. Investigating the use of an adjustment task to set preferred illumination colour. Submitted to Colour Research and Application, December 2010.

Logadóttir A, Christoffersen J, Fotios SA. Investigation of occupant controlled illuminance. In manuscript, December 2010.

Love JA. Manual switching patterns in private offices. Lighting Research and Technology 1998; 30:45-50.

Moore T, Carter DJ Slater AI. A field study of occupant controlled lighting in offices. Lighting Research and Technology 2002a;34:191-205.

Moore T, Carter DJ, Slater AI. Long-term patterns of use of occupant controlled office lighting. Lighting Research and Technology 2003a;35:43-59.

MultiDim control system, details can be found at: http://www.lighting.philips.com/gl_en/global_sites/fluogear/dimming/products/multioverview.php?main=global&parent=137&id=gl_en_dimming&lang=en. Retrieved on 18.09.2010.

Newsham GR, Veitch JA. Lighting quality recommendations for VDT offices: a new method of derivation. Lighting Research and Technology 2001; 33: 97-116.

Newsham GR, Veitch JA, Arsenault C, Duval C. Effect of dimming control on office worker satisfaction and performance. Proceedings of IESNA Annual Conference Tampa Florida 2004:19-41.

Newsham GR, Arsenault C, Veitch JA, Tosco AM, Duval C. Task lighting effects on office worker satisfaction and performance, and energy efficiency. Leukos 2005; 4:7-26.

Newsham GR. Research matters – comparing individual dimming control to other control options in offices. Lighting Design + Application 2007;37:24, 26, 28.

Newsham GR, Aries MBC, Mancini S, Faye G. Individual lighting control of electric lighting in a daylit space. Lighting Research and Technology, 2008; 40: 25-41.

Osterhaus WKE and Bailey IL. Large area glare sources and their effect on discomfort and visual performance at computer workstations: Proceedings of the 1992 IEEE Industry Application Society Annual Meeting. Houston, TX. 1992.

Palmer SE, Schloss KB. An ecological valence theory of human color preference. PNAS 2010; 107:8877-8882.

Parducci A. Learning variables in the judgment of single stimuli. Journal of Experimental Psychology 1954; 48: 24-29.

Parducci A. An adaptation-Level analysis of ordinal effects in judgment. Journal of experimental psychology 1959; 58:239-246.

Parducci A, Calfee RC, Marshall LM. Context effects in judgment: Adaptation level as a function of the mean, midpoint, and median of the stimuli. Journal of experimental psychology 1960; 60:65-77.

Parducci A. Relativism of absolute judgment. Scientific American 1968; 6:84.

Payne JW, Bettman JR, Johnson EJ. Behavioral decision research: A constructive processing perspective. Annual review of psychology 1992; 43:87-131.

Sarris V. Adaptation – Level theory: Two critical experiments on Helsons's weighted-average model 1967; 80:331-344.

Schanda J, Colorimetry: Understanding the CIE system. New Jersey: John Wiley & sons, Inc, 2007.

Tenner AD, Begemann SHA, van den Beld GJ. Acceptance and preference of illuminance in offices. Proceedings Lux Europa. 1997:130-143.

Tversky A, Kahneman D. Judgment under Uncertainty: Heuristics and Biases. Science, New Series 1974; 185:1124-1131.

Tversky A, Simonsen I. Context-dependent Preferences. Management Science 1993; 39:1179-1189.

Veitch JA, Newsham GR. Exercised control, lighting choices, and energy use: an office simulation experiment. Journal of Environmental Psychology. 2000: 19-237.

Veitch JA, Newsham GR, Boyce PR, Jones CC, Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach. Lighting Research & Technology 2008; 40(2); 133-151.

Viola, A.U., James, L.M., Schlangen, L.JM., Dijk, D-J. Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. Scand J Work Environ Health 2008; 34:297-306.

Wever EG, Zener KE. The method of absolute judgment in psychophysics. Psychological Review 1928; 35: 466-493.