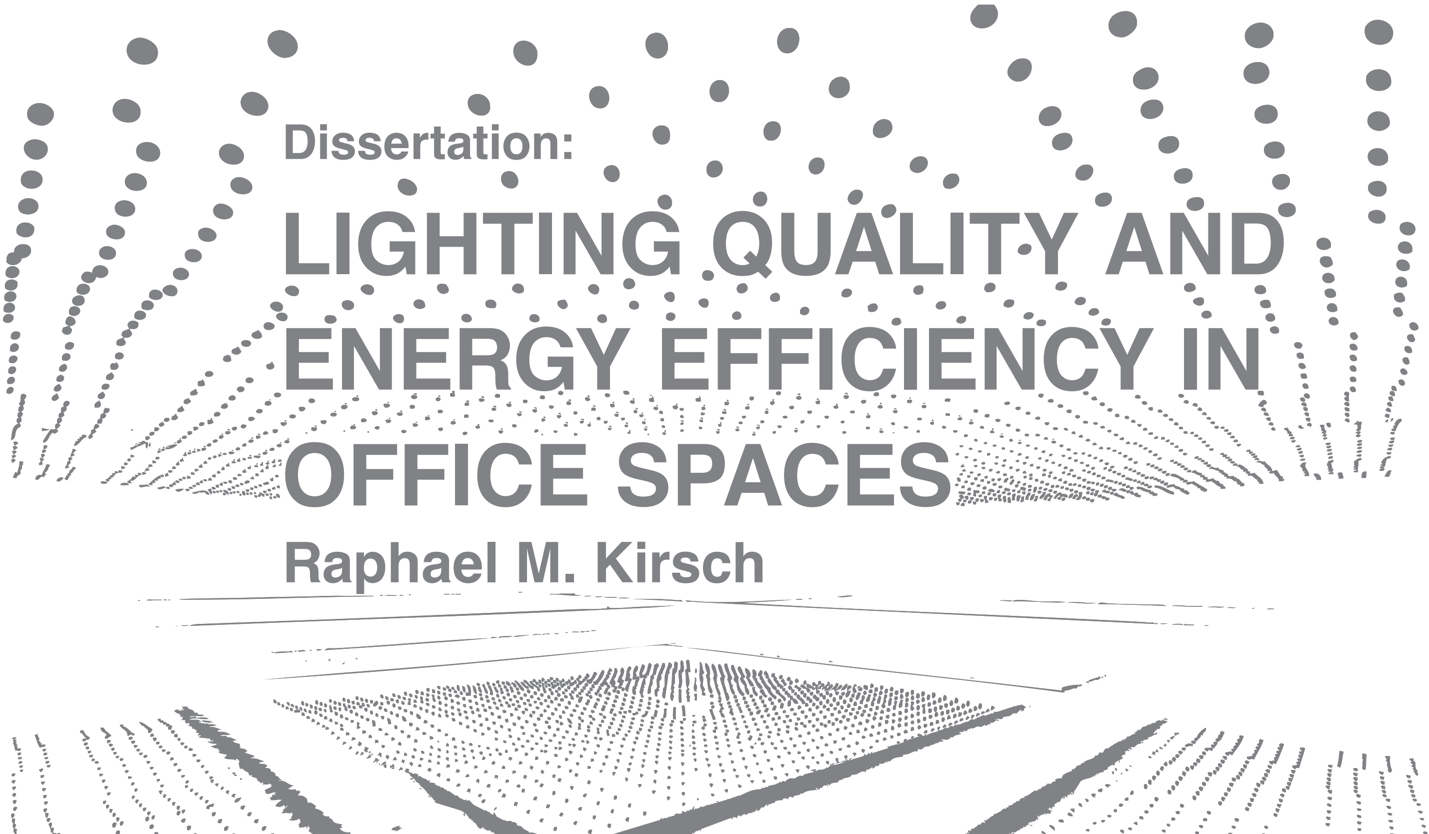

Dissertation:

LIGHTING QUALITY AND ENERGY EFFICIENCY IN OFFICE SPACES

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Lighting Quality and Energy Efficiency in Office Spaces

vorgelegt von

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Lighting Quality and Energy Efficiency in Office Spaces

Doctoral Thesis, Department of Lighting Technology, Technical University Berlin, Germany

-dedicated to my old and new family-

Abstract

The use of solid-state lighting poses new challenges for office lighting design. Efficient optical systems and lighting controls allow for highly adapted lighting installations. As a consequence, lighting designers have to consider the occupants' visual preferences and individual psychobiological differences in a more precise way. Up to now, research on lighting quality mostly exists with regard to fluorescent lighting technology. The impact of solid-state lighting characteristics on visual appearance has not been investigated extensively. The following research questions occur:

How do office lighting conditions influence room appearance?

How does a person's chronotype influence lighting appraisal of a space at a given time of day?

The research questions were investigated in a special office lighting simulator aiming at a strict separation of photometric criteria potentially influencing room appearance. The appearance of the space was rated by a total of 102 participants in two experimental sessions under different lighting conditions. Independent variables were the luminance of walls and ceiling, horizontal illuminance around the task area and background luminance distribution. Participants were divided into groups according to their chronotypes and rated the space at different times of day. Dependent measure was the subjective rating of the space on the two scales 'visual lightness' and 'visual attractiveness'.

The outcomes of this work show a marginal influence of surrounding area illuminance on the perception of visual lightness. Visual attractiveness was not affected.

Wall and ceiling luminance significantly influenced visual appearance of the office space regarding visual lightness and visual attractiveness.

The luminance distribution of walls and ceiling significantly influenced the perception of visual attractiveness and visual lightness. Coherent and relatively uniform distributions werer rated as brighter and more attractive.

The interaction between the participants' chronotype and the time of observation showed a statistically significant effect on room appearance for the first experimental session. Morning types perceived the space as lighter and more attractive in the morning than in the evening. For evening types the opposite was true.

The same effect was found to be non-significant during the second session. However, exploration of the gathered data suggested, that this might be due to the smaller sample size.

The results can help to define minimum recommendations for photometric parameters influencing visual appearance in offices with higher accuracy and to include human needs and individual differences in the lighting design process.

Kurzfassung

Der Einsatz von Solid-State Lighting in der Allgemeinbeleuchtung stellt neue Herausforderungen an die Lichtplanung in Büros. Durch effiziente optische Systeme und Lichtlenkung können Beleuchtungsanlagen an Raum und Nutzer angepasst werden. In der Konsequenz stehen Lichtplaner vermehrt vor der Aufgabe, die Beleuchtung an visuelle Präferenzen und individuelle psychobiologische Unterschiede des Nutzers anzupassen und diese schon bei der Planung zu berücksichtigen. Bisherige Forschung im Bereich der Beleuchtungsqualität bezieht sich meist auf die Leuchtstofflampen-Technologie. Die Auswirkung der abweichenden Eigenschaften von LEDs auf das visuelle Erscheinungsbild eines Raums wurde bisher nicht umfassend untersucht. Daraus ergeben sich folgenden Forschungsfragen:

Wie beeinflusst die Lichtumgebung die Raumwahrnehmung?

Wie beeinflusst der Chronotyp des Nutzers zu bestimmten Tageszeiten die visuelle Bewertung eines Raumes in Abhängigkeit von der Beleuchtung?

Die Forschungsfragen wurden in einem neu entwickelten Bürobeleuchtungssimulator untersucht, der auf eine strikte Trennung photometrischer Kriterien abzielt, die potenziell die Raumwahrnehmung beeinflussen. Das visuelle Erscheinungsbild des Raumes wurde von 102 Probanden in zwei seperaten Experimenten unter verschiedenen Beleuchtungsbedingungen bewertet. Unabhängige Variablen waren Wand- und Deckenleuchtdichte, horizontale Beleuchtungsstärke im Umgebungsbereich des Arbeitsplatzes und Hintergrundleuchtdichteverteilung. Abhängige Variablen war die subjektive Einschätzung von visueller Helligkeit und Attraktivität des Raumes. Die Teilnehmer wurden in Gruppen nach Chronotypen unterteilt und bewerteten den Raum zu verschiedenen Tageszeiten.

Die Ergebnisse dieser Arbeit zeigen einen geringen, aber signifikanten Einfluss der Umgebungsbeleuchtungsstärke auf die Bewertung der visuellen Helligkeit. Die visuelle Attraktivität des Raumes wurde nicht beeinflusst.

Wand- und Deckenleuchtdichte hatten einen deutlichen Einfluss auf das visuelle Erscheinungsbild des Büroraumes in Bezug auf visuelle Helligkeit und Attraktivität.

Die Leuchtdichteverteilung auf Wänden und Decke beeinflusste die Raumwahrnehmung signifikant. Dabei wurden kohärente, gleichmäßige Verteilungen als heller und attraktiver bewertet.

Die Interaktion zwischen Chronotyp und Tageszeit hatte in der ersten Versuchsreihe einen signifikanten Einfluss auf die Raumwahrnehmung. Morgentypen bewerteten den Raum am Morgen als heller und attraktiver als in den Abendstunden. Für Abendtypen war das Gegenteil der Fall.

Dieser Effekt hatte in der zweiten Versuchsreihe keinen signifikanten Einfluss. Die Begutachtung der gesammelten Daten deutet darauf hin, dass dafür die kleinere Stichprobengröße verantwortlich war.

Die Ergebnisse können dazu beitragen, Mindestempfehlungen für die photometrische Größen, die die Raumwahrnehmung beeinflussen mit höherer Genauigkeit zu definieren. Menschliche Bedürfnisse und individuelle Unterschiede können so in die Lichtplanung einbezogen werden.

List of abbreviations

Cohen's *d*, *f*	measures of effect size
df	degrees of freedom
$E_{eye\ level}$	vertical Illuminance measured at eye level
EMM	estimated marginal means
E_{sur}	average surrounding area illuminance
E_{task}	average task area illuminance
$L_{40°}$	average luminance in a 40° horizontal band
$L_{60°}$	average luminance in a 60° horizontal band
$L_{visual\ field}$	average luminance in the visual field
$L_{walls/ceiling}$	average luminance of walls and ceiling
MANOVA	multivariate analysis of variance
PCA	principal component analysis
R^2	coefficient of determination
SD	standard deviation
SE	standard error

Contents

Introduction

Office lighting, after residential lighting, forms the second largest share of the general lighting sector, accounting for 15% of the total market volume (McKinsey & Company, 2012). According to current studies, lighting in office buildings is responsible for 40% to 50% of the overall electricity usage ((US Department of Energy, 2008), (Schmidt, 2011)). At the same time, electric lighting installations only account for 3.6% of an office building's capital costs (Cundall, 1972). Modern lighting installations reduce CO_2 consumption and introduce the potential for large energy savings at a relatively low cost. Thus, the lighting industry has a major role in green building standards and energy efficiency legislation (e.g. ASHRAE standard 189.1 (2010) and LEED (2009) in North America, EN 15193 (2008) and DIN V 18599 (2011) in Europe).

In recent years, an increasing number of solid-state lighting systems have been designed and installed in offices. Solid-state lighting systems accounted for 6% of new office lighting installations in 2011; a study by McKinsey & Company, Inc. (2012) predicted that this figure will grow to 30% by 2016 and nearly reach 55% by 2020. Solid-state lighting potentially introduces new degrees of freedom to the office lighting design process, permitting more efficient control systems and more detailed luminous intensity distributions. Light distributions that are not feasible with conventional light sources are developed and can be adapted to a given space with high accuracy. Efficient optical systems and highly controllable drivers with low power dissipation are a promising development to enhance the energy efficiency of new lighting systems. LEDs, which are effectively point light sources, allow for a better directional control of light and less stray light compared to conventional technologies. If required, light can be focused almost exclusively on the desired surfaces in the space.

The potential for energy savings associated with solid-state systems is undisputed. However, current lighting standards use fluorescent lighting as a reference technology. This practice is outdated, as solid-state technologies can serve the same purpose as fluorescent technologies with dramatically different and enhanced photometric characteristics. Standards like EN 12464-1 (European Committee for Standardization (CEN), 2011) only aim at ensuring visual performance and avoiding visual discomfort. Nevertheless, these standards represent standard practice in lighting design. Research by Kirsch (2013) and Kirsch and Völker (2013) indicated discrepancies between recommended lighting standards and office workers' lighting quality demands. Energy savings realized at the cost of lighting quality cannot be regarded as energy efficient. Thus, an accurate description of photometric criteria influencing lighting quality is needed to develop minimum quality standards for LED lighting installations that can then be accomplished with minimal energy usage.

Aim of this Work

According to current research, cognitive and/or perception based lighting quality criteria including acceptance of the work place, room appearance, apparent brightness, architectural integration, pleasantness and lightness are influenced by photometric quantities including desktop luminance, background luminance and illuminance, luminance distribution and average luminance in different parts of the field of view. The aim of this work is to contribute to a holistic approach to enhanced visual appearance and energy efficiency in offices. The first general research question of this study is:

- How do office lighting conditions influence room appearance?

Psychological mechanisms, such as appraisal and affect, determine human judgements of a lit scene. However, these mechanisms not only depend upon lighting conditions, but also upon the individuals experiencing the scene. Previous research addressed the effect of individual differences such as age and gender (e.g. Boyce, 1973; Knez & Kers, 2000). However, little is known about the impact of biological effects of lighting on subjective human responses to their environment. An individual trait potentially influencing one's judgment of a lit environment is the relationship between the occupant's chronotype and the time-of-day. Thus, the second general research question of this work is:

- How does a person's chronotype influence lighting appraisal of an office space at a given time-of-day?

Conclusively observed, the answers to these research questions can lead to a better understanding of how photometric criteria and individual differences influence visual appearance in office spaces. This investigation can serve as a basis for lighting designers and lighting industry to adapt products and lighting applications to human needs and preferences, enabling the creation of attractive and visually effective work places.

Overview

A brief introduction of the motivation and aim of this work has been given in the previous section.

Section 1 of this thesis describes the current state of research in the field of visual appearance in office spaces. Based on the characterization of psychological and psychobiological processes influencing the appearance of a scene, two important factors, 'visual lightness' and 'visual attractiveness', are identified to describe the subjectively experienced lighting quality of a lit environment.

Several decades of research indicate that some of the main influencing factors for the appraisal and aesthetic judgement of a scene include various photometric criteria and individual differences between occupants. In section 2, photometric criteria based on illuminance and luminance on different surfaces throughout the visual field are investigated regarding their influence on the perception of lightness and attractiveness in an office space. More specific research questions are proposed here and are investigated in this thesis.

Individual differences such as age, sex, and assigned role in the lit environment are briefly considered in section 3, but are not in the main scope of this work. Closer attention is paid to individual differences regarding chronotypes and internal time. Related fields of research and missing areas in the state of research are identified. Section 4 explores different methods to measure visual appearance. Previous experimental settings and quality indices are critically discussed.

In chapter 5, the first of two conducted experiments is described and discussed. Focus of the experiment is the influence of work plane illuminance and background luminance on visual appearance. Individual differences are included in the investigation to examine possible effects on the experimental outcomes.

In the second experiment described in section 6 the influence of luminance distributions in the visual field are investigated. Again, the influence of individual differences is included in the survey to verify possible effects found in the previous experiment.

In chapter 7 possible sources of error and measurement uncertainties are discussed; an overall discussion of results is given in section 8.

1 Processes Influencing Visual Appearance

The CIE standard 'International Lighting Vocabulary' defines appearance as the "aspect of visual perception by which things are recognized" and, in psychophysical studies, as the "visual perception in which the spectral and geometric aspects of a visual stimulus are integrated with its illuminating and viewing environment" (Commission Internationale de l'Éclairage (CIE), 2011, p.8). According to CIE 175:2006 visual appearance impacts on recognition but does not necessarily result in recognition. Appearance is defined as the "visual sensation through which an object is perceived to have attributes such as size, shape, color, texture, gloss, transparency, opacity, etc." (CIE, 2006, p.7)

In contrast to a simple stimulus-response system often used in lighting engineering research, visual appearance includes the perception of an image of the outside world and the application of 'inner concepts' such as pre-learned rules and experiences related to the image. Only then, can a scene be seen and interpreted. After the process of using the receptor mechanisms of the eye to get a final image in the cortex, "inherited and learned response modifiers" (CIE, 2006, p.12) are connected 'downstream' as a series of filters modifies the image and forms the two types of images described by Hutchings (1995):

- The impact image can be described as a first impression of a scene including initial perception and initial judgement

- The sensory image's dimensions are perception, emotion and intellect. Through these "hedonic descriptors" (CIE, 2006, p.11) questions about the context of the scene arise.

The appearance of a scene is generally difficult to measure since it is perceived naturally and partially subconsciously. Therefore it is impossible for us to tell which characteristics of a scene contribute to our perception of appearance. However, appearance does not only have an impact on subjective preferences but also on the visual effectiveness of a space. Rea (1982) described a high correlation (R^2~0.9) between subjective ratings of a space and a visual performance measure in the same space under the same lighting conditions. Research also indicates that work performance can be influenced by the conditions of the workplace (Baron, Rea, & Daniels, 1992).

1.1 Behavioural Processes

Fulfilling human needs in the best possible way is one of the main tasks of high quality lighting installations. Naturally, these needs vary depending on the environment itself and the persons in that environment. It is commonly agreed that lighting quality is achieved not only by ensuring visual task performance and avoiding discomfort, but also through consideration of economical and architectural factors, and the creation of a pleasant and attractive environment (e.g. Goodman, 2009; Loe, 2009; Pellegrino, 1999). The most important mechanisms through which occupants experience the luminous working environment, such as office spaces or spaces of similar use, are compliance with task performance and the visual appeal of the space (Loe, Mansfield, & Rowlands, 1994; Veitch, Newsham, Boyce, & Jones, 2008; Wymelenberg, Inanici, & Johnson, 2010). Veitch and Newsham (1998) defined behavioural-based measures of office lighting quality as:

- visual performance
- post-visual performance
- social interaction and communication
- mood state (happiness, alertness, satisfaction, preference)
- health and safety
- aesthetic judgments (assessments of the appearance of the space or the lighting)

Mood, satisfaction and well-being are strongly affected by the way a lit space is perceived within the framework of the task performed and the role a person is assigned to in that space. Thus, lighting designers strive to create high-quality luminous conditions by applying adequate photometric criteria to the space. Together with the occupants' individual characteristics, these quantities can positively affect people at the workplace. In general, this happens through the mechanisms and processes shown in Figure 1-1 (Schierz, 2004; Veitch, 2001). The chart is simplified from its original form to only describe processes relevant for this work. Group processes and social and organizational context also influence the appraisal of a scene, but are not considered in this work, and are therefore not included in the chart.

Figure 1-1: Simplified chart of processes influencing perceived lighting quality (cf. Veitch, 2001)

The model distinguishes between psychobiological processes and psychological processes. Psychobiological processes describe brain-behaviour relations causing biological processes that affect mental functioning (Watts, Cockcroft, & Duncan, 2009, p. 437). The American Psychological Association (APA) refers to psychobiology (also: behavioural neurosciences) as the science of the biology of behaviour.

Psychobiological processes through which people experience a luminous environment include visibility, biological effects of lighting, and arousal (Veitch, 2001). These processes often work as a stimulus response system (Schierz, 1999). Using stimulus response systems to determine human responses to light is a common approach in lighting engineering research. However, to investigate human appraisal of a lit scene it is necessary to consider psychological behavioural processes influencing lighting quality and room appearance. These processes are the main subject of this work. Veitch (2001) classified the psychological processes that influence the response to the luminous environment as perceived control, attention, environmental appraisal and affect. These processes are a function of both lighting conditions and individual differences between occupants. People evaluate a scene following an 'appraisal path' as part of the linked mechanisms approach introduced by Veitch, Newsham, Boyce and Jones (2008), where occupants appraise lighting design and resulting luminous conditions. Through 'preference' mechanisms (Veitch, Newsham, Boyce, & Jones, 2008) (or: room appearance (Veitch, Newsham, Mancini, & Arsenault, 2010) luminous conditions influence the affective domain in the form of mood, well-being, health and, when taking into consideration organizational factors, affect motivation, creativity and job satisfaction. Lighting design also falls into Maslow's hierarchy of needs (Maslow, 1943), where in addition to the most basic physiological needs the luminous environment can address human needs for safety (health), esteem (confidence, feeling competent) and self-actualization (creativity).

A similar approach was found by Gregory (1971) and Schierz (2004), who refer to these psychological processes as 'look-up perception' or 'look up-predict system' in case the process does not only involve a simple stimulus-response system and sensory information, but also includes mechanisms where a person applies personal experience and subjective analyses to 'filter' a visual stimulus. We use the response from our visual sense to process the complex patterns of light around us into objects, space, location and movement. This information is then used to make judgements eventually leading to a particular course of action. This was also described by Krueger (1994) in a model where the objective world represented by a visual stimulus is projected into the subjective conceptual space via search-, analysis- and synthesis-strategies. Environmental characteristics lead to perception of the appearance of a scene (Figure 1-2).

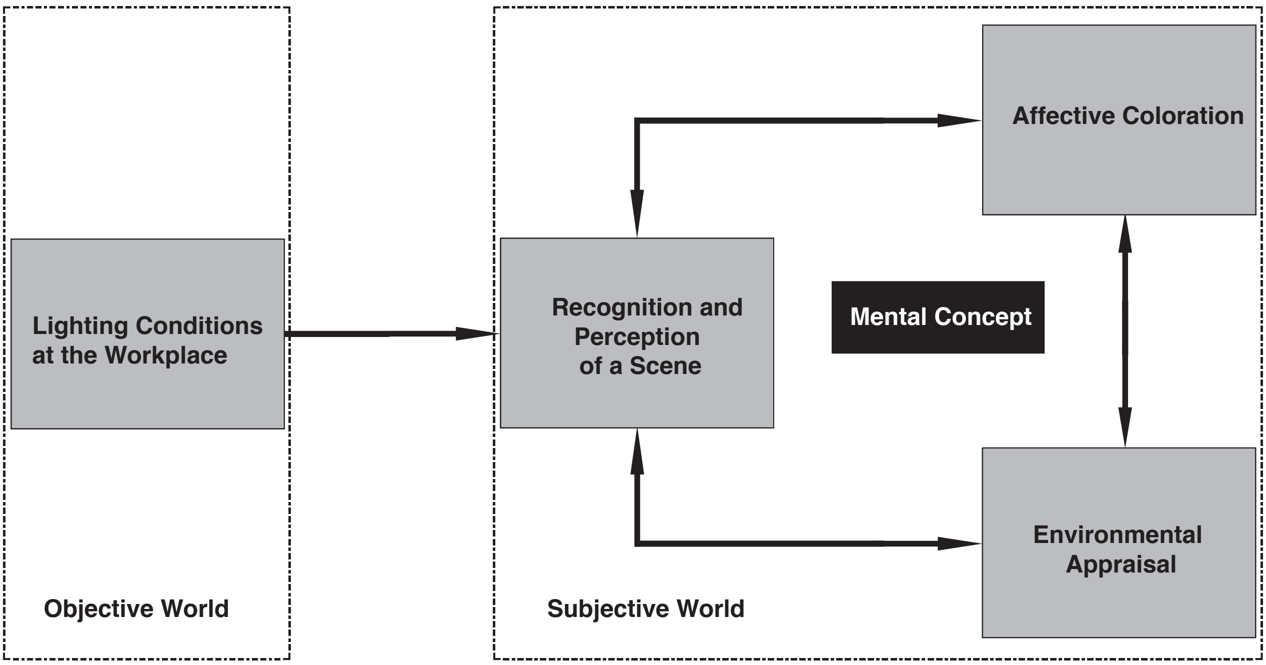

Figure 1-2: Mental concept of a scene (cf. Schierz, 2004, p. 78)

Note that in the original chart by Schierz (2004) the bottom right box contains the German word 'Attribuierung', which literally translates to attribution. However, the psychological meaning of the term vary across languages. Thus, the mechanism is referred to in this work as 'environmental appraisal' (Gifford, 2007). Instead of merely seeing (in the sense of the word) the scene, we build a mental concept including generalization and judgements to the perceived scene. What we see is judged and analyzed using individual experiences, expectations, and interpretations within the specific context of the scene. This mechanism is part of the perception of a scene (Veitch, 2001). Additionally, appearance is judged following a more emotional, affective evaluation (or: affective coloration (Schierz, 2004)). The interconnections of these factors form a mental concept within our subjective perception. An example for environmental appraisal is the evaluation of 'lightness' of a space when a concept-based appraisal of brightness beyond a merely stimulus-response based mechanism is existent. A scene's 'pleasantness' is an example for an emotional, affective evaluation. Appraisal of a scene is both sufficient and necessary for an emotional (affective) response (Siemer, Mauss, & Gross, 2007). That is, both processes are interrelated and cannot exist separately. Thus, the appraisal of a lit scene always results in an affective response. In appraisal theory, these mechanisms can be measured as differences in emotional response due to individual differences in a controlled environment or as differing emotional responses due to differing scene characteristics.

Regarding the aesthetic judgement of the environment, researchers have defined dimensions of appraisal. Kaplan (1987) stated that two affectively important factors are 'understanding' and 'exploration'. 'Understanding' is related to comprehension and determination of a scene. Dimensions of appraisal that fall into the 'understanding' category according to Kaplan are labeled 'coherence' and 'legibility'. 'Exploration' attends to the human affectation of problem solving (Maslow, 1943) and is closely related to both the information available and not available in the scene. Kaplan assigns the dimensions 'mystery' and 'complexity' to the 'exploration' category. These dimensions are strongly related to the affective attractiveness of a scene since they can create a state of "being held by the setting, being attracted by or pulled toward sources of additional information" (Kaplan, 1987, p.10). Osgood, Suci, and Tannenbaum (1957) labeled this affective domain as 'evaluation'.

In summary:

One mechanism of appraisal is strongly related to the subjective comprehension of a scene and a categorization beyond a merely emotional reaction. Judgements are made connecting mental concepts on the scene with predetermined concepts and hypotheses. In the following, this mechanism is labelled as subjective comprehension or environmental appraisal.

A second mechanism addresses the more emotional appraisal of and satisfaction with a scene and how a user feels about that scene. Judgements on this level apply an affective filter or coloration on an otherwise rational appraisal.

1.2 Environmental and Emotional Appraisal of a Lit Scene

The previously described appraisal factors, 'environmental appraisal' and 'emotional appraisal', can be found in different investigations of lighting quality (Table 1-1).

Table 1-1: Factors/dimensions identified in environmental appraisal experiments

Investigation	Factors
(Flynn, Hendrick, Spencer, & Martyniuk, 1979)	visual clarity, spaciousness, complexity and 'evaluative factors' regarding interest and attractiveness
(Loe *et al.*,1994)	visual interest, visual lightness, (tense-relaxed)
(Veitch & Newsham,	visual attraction, complexity, brightness
1998)(Pellegrino, 1999)	performance, satisfaction, interest, comfort, uniformity
(Boyce, Veitch, Newsham, Myer, & Hunter, 2003)	comfort, attractiveness, visibility, spaciousness

Visual Lightness

In all investigations shown in Table 1-1, a factor regarding the visibility and brightness of a scene can be identified ('visual clarity', 'brightness', 'visual lightness', 'performance' and 'visibility'). The CIE standard 'International Lighting Vocabulary' refers to brightness as an "attribute of a visual perception according to which an area appears to emit, or reflect, more or less light" (CIE, 2011 p.16). According to the Lighting Handbook of the Illuminating Engineering Society of North America, brightness is the perceptual response to a source of light and thus, to luminances and related quantities. Influencing factors on a stimulus level are: object luminance, surround (background) luminance, state of adaptation, gradients and spectral content (Illuminating Engineering Society, 2011, p.4.9). Regarding a mathematical luminance-brightness relationship, Marsden's investigation (1969) supported Stevens' power law (1957) where perceived brightness is a power function of luminance if the observed areas are simple ('psychophysical power law'). In a different paper (1970) Marsden explicitly described the brightness-luminance relationship for room surfaces and objects with no strong colors as a power function:

$$B = a \cdot L^n \qquad \textbf{(1-1)}$$

with apparent brightness B, surface luminance L and matching coefficients a, n.

The coefficient n lies in the order of 0.3 for single surfaces and in the order of 0.6 for several stimuli presented at the same time. Marsden described participants rating apparent brightness on a ratio basis compared to a (personal) standard brightness. Therefore, in his study a ratio scale was used to quantify brightness sensation. The power function approach was supported by further investigations (e.g. Bodmann & La Toison, 1994). Völker (2006) used a different approach derived from the Weber-Fechner-law:

$$B = a \cdot \ln(L) + b \qquad \textbf{(1-2)}$$

with apparent brightness B, surface luminance L and matching coefficients a, b.

The coefficients *a, b* were empirically determined as 5.2 and 4.7 respectively. Both functions vary significantly and cannot be compared directly. While Völker used a bipolar 18-point-scale, later reduced to a 9-point-scale, with the endpoints marked as 'too dark' and 'too bright', Marsden's participants rated brightness using a series of numbers (1-2-3-4-5-8-10-15-20-30-40-50-80-100).

The closely related perception of lightness goes one step further including a stimulus-response system (luminance-brightness relationship) and additional judgements about properties and composition of the reflecting, transmitting or emitting surface (cf. IES, 2011, p.4.9). Jay described the difference between brightness and lightness as "brightness is perceived as the result of the lighting, while lightness is perceived as an innate property of a surface" (Jay 1971, p.142). Applying the concept of lightness to a lit scene includes the interaction of brightness perception of the scene and mental concepts projected into the subjective space (cf. Figure 1-2). Visual lightness accounts for absolute brightness, a concept of visibility, visual safety and assumed support for task performance, even if no task is actually performed or the ability to perform the task is not affected by changes in lighting.

A number of visual needs recommended by CIE 175:2006 'A Framework for the measurement of visual appearance' are attributed to visual lightness (CIE, 2006, p.8):

- visually assessed safety (that is, safety of our existence within the scene)
- visual identification of the scene
- visually assessed utility or usefulness of the scene

Thus, visual lightness can function as an environmental appraisal since it includes an emotional response and the application of a mental concept ('I can/cannot perform tasks in this scene/in this lighting'). The visual lightness factor investigated in this work can also be regarded as a part of the 'potency' dimension found by Osgood *et al.* in their analysis of the semantic space (1957). A higher judgement of visual lightness derives from a higher estimated potential to see and work in the lit environment.

Visual Attractiveness

Regarding affective appraisal it can be noted that a number of factors from Table 1-1 are connected to the diversity of the scene (complexity, uniformity) and its attractiveness (visual interest, visual attraction, satisfaction). Knowing that the factors were obtained from a number of semantic differentials using principal component analysis (PCA) or correlation analysis, the naming of the dimensions was restricted to the items rated by the participants and implemented according to the researcher's understanding of the component composition. Table 1-2 and Table 1-3 show some of the common items used to retrieve factors from PCA or correlation analysis.

Table 1-2: Items used by Loe (1994)

Items	Factor
non-uniform - uniform	
interesting - uninteresting	
pleasant - unpleasant	visual interest
stimulating - subdued	
dramatic - diffuse	

Table 1-3: Items used by Pellegrino (1999)

Items	Factor
non-uniform - uniform	
unbalanced - balanced	uniformity
dramatic - diffuse	
unpleasant - pleasant	satisfaction
subduing - stimulating	

It becomes clear that, although both researchers used the same items among a few others, the resulting factors are quite different. The same impression can be received when comparing the items used in (Schierz, 2004) or (Boyce *et al.*, 2003) and others. However, according to Kaplan (1988), these factors might be different sides of the same dimension concerning the visual attractiveness created by the diversity and intricacy of a scene. Attractiveness, pleasure and interest are parts of the affective domain also described in (Duncan-Hewitt & Hall, 2005). As stated by Kaplan (1988), pleasure and interest often occur together but are independent of each other. As a result, there is a strong possibility that the concept of visual interest is not a necessary condition for the attractiveness factor and thus, is not covered by this work. Affective components for the evaluation of visual attractiveness are typically 'like-dislike' or 'attractive-unattractive'. Visual attractiveness of a scene or a space covers visual expectations defined in CIE 175:2006 'A Framework for the measurement of visual appearance' (CIE, 2006, p.8):

- visually assessed pleasantness of the scene
- visually assessed satisfaction that we predict we shall get from the scene.

Visual attractiveness in this work functions as an affective response or coloration of the perceived scene. The two components *'visual lightness'* and *'visual attractiveness'* are the main subject of this work and are further explored in the following chapters.

2 Photometric Criteria Influencing Visual Appearance

As described in the previous chapter, lighting conditions at the work place influence different behavioural processes that lead to the appraisal of a scene, and thus, impact on visual appearance. Important photometric criteria include luminances and illuminances, spatial and spectral distribution of light, flicker and glare. In this work the influence of luminances and illuminances is investigated regarding absolute values in different areas of the space and their spatial distribution on and between different room surfaces.

2.1 Photometric Criteria Based on Illuminance of the Work Plane

Illuminance is the most important quantity used in lighting calculations and planning today. Due to its quasi-independence from surface reflectance and texture, it is implemented in lighting calculation software and the basis for current lighting standards ((CEN, 2011), (Illuminating Engineering Society of North America, 2004), (Chartered Institution of Building Services Engineers, 2005)). To some extent, illuminance is an adequate instrument to give recommendations ensuring task performance. However, using illuminance as the only measure and recommendation for brightness perception and visual appearance is insufficient. Flynn, Hendrick, Spencer, and Martyniuk (1979) as well as Butler and Biner (1987) stated that appearance and human responses to a complex lit environment cannot be described adequately by illuminance effects on task performance. In this work, only illuminances on horizontal planes and surfaces are considered. Vertical illuminances on surfaces delineating the room are, if possible, converted to luminances. Lighting installations in cell offices usually consist of two components, task and ambient lighting. Ambient lighting provides seamless lighting coverage of the whole work plane. It is usually lower than the desired task illuminance. Task lighting often addresses a specific 'task proper' (IES, 2011) or task area. Both systems usually work in conjunction, however, if the size and position of the task area are unknown, ambient lighting systems may also provide uniform horizontal illuminances at task area level throughout the whole space (general lighting).

Task Area Illuminance

Illuminances in task areas are an important factor assisting with task performance. The task area is defined as the "partial area in the work place in which the visual task is carried out" (CIE 2011-p. 169); in many offices the whole desktop is considered the task area. There is extensive research on task area illuminance in offices and its impact on task-performance and visual comfort. Illuminances higher than the standard recommendations are often found to be preferred for both task performance and visual appearance in subject experiments (e.g. Begemann, van den Beld, & Tenner, 1995; Halonen & Lehtovaara, 1995; Saunders, 1969). Preferred task area illuminances derived from experiments with participant-control over the lighting depended on the adjustable range (Fotios, Logadóttir, Christoffersen, & Cheal, 2011).

Still, there exist a number of investigations where standard practice illuminance levels of the order of 300-750 lux were supported (e.g. Boyce, Eklund, & Simpson, 2000; Katzev, 1992; Veitch & Newsham, 2000). Tregenza, Romaya, Dawe, Heap, and Tuck (1974) found a mean preferred desk illuminance of 2297 lux in an experimental office, representing the largest deviation from 500 lux found in research. Participants rated different pre-set lighting conditions. Since the lighting consisted of different lighting systems it was possible to control different room surfaces separately. However, when the illuminance on the desk was set to a 10 times higher level, mean wall illuminance changed by about factor 9. The results of the preference study were most likely strongly biased by the luminance of the background that strongly influences brightness perception of the space (cf. Houser, Tiller, Bernecker, & Mistrick, 2002). Also it was found that preferred working plane illuminance depends on the luminance of the walls (van Ooyen, van de Weijgert, & Begemann, 1987).

Task area illuminance has also been one of the most important figures in lighting standardization. The modern recommendations of 300-500 lux for office tasks were developed over time (Osterhaus, 1993), (Table 2-1).

Table 2-1: Evolution of ANSI/IES recommendations for task area illuminances over time

	1913	1921	1930	1942	1947	1960	1982
E_{Task} [lux]	20-40	50-100	100-250	250-500	750	1000-1500	500

With an increasing usage of computers and a stronger need for energy efficiency, the recommendations decreased after the 1960s. The relevance of task area illuminance for task performance is undisputed. However, this work does not focus on visual performance but rather on room appearance and perceived lighting quality. Thus, in this work task area illuminance is not manipulated but kept at a constant 500 lux throughout all experiments.

Table 2-2 shows preferred task area illuminances derived from research and recommended task area illuminances from current lighting standardization.

Table 2-2: Preferred and recommended task area illuminances in research and standards

Investigation/Standard	Preferred or recommended task area illuminance [lux]
(Balder, 1957)	1770[1]
(Bodmann, 1967)	~1000[1]
(Saunders, 1969)	~1000[1]
(Tregenza *et al.,* 1974)	2297[1]
(Katzev, 1992)	460-810[1]
(Begemann *et al.,* 1995)	700-1100[1]
(Halonen & Lehtovaara 1995)	230-1000[1]
(Berrutto, Fontoynont, & Avouac-Bastie, 1997)	100-600[1]
(Boyce *et al.* 2000)	398-518[1]
(Veitch & Newsham 2000)	~500 (458)[1]
(IESNA, 2004)	300-500[2]
(CIBSE, 2005)	300-500[2]
(Boyce *et al.,* 2006)	458[1]
(CEN, 2011)	300-750[2]

1: preferred
2: recommended

Ambient Lighting and Surrounding Area Illuminance

Ambient lighting and background/surrounding area illuminances are important factors in lighting standardization. The spatial definition for this photometric quantity varies depending on the standard or research. The CIE standard 'International Lighting Vocabulary' defines a surrounding area as "a strip surrounding the task area within the field of vision" (CIE, 2011, p. 167). A different approach is used in lighting standards (e.g. CEN, 2011; CIBSE, 2005; IESNA, 2004), treating horizontal and vertical surfaces separately by giving separate recommendations for horizontal illuminances on the work plane and vertical illuminances or ratios on room surfaces.

There is extensive research on surrounding or ambient lighting and the ratios of task to ambient illuminance. Task to surrounding illuminance ratios found to be preferred ranged from 1:1 (Bean & Hopkins, 1980) to 1.7:1 (Tabuchi, Matsushima, & Nakamura, 1995), the former suggesting a preference for general lighting with equal illuminances throughout the whole work plane. However, research also shows that ambient lighting illuminances lower than task area illuminances can be acceptable depending on the overall illuminance and the lighting setup. Boyce (1979) found that it is possible to create a surrounding to task area lighting ratio that is too high in contrast. Still, a horizontal background illuminance of about 150 lux under normal task illuminance conditions was found likely to be satisfactory. Bean and Hopkins (1980) found the adequacy of surrounding illuminance levels to be dependent on task area illuminance. Nonetheless, a decrease from a task to surrounding illuminance ratio from 2:1 to 1:1 resulted in a rapid increase of observers satisfied with the lighting. Tabuchi Matsushima, and Nakamura (1995) found, that at higher overall illuminance levels, higher task to ambient ratios were accepted by participants. Inoue (2010) asked participants in a test laboratory to adjust ambient and task illuminance to the point where it was just possible to work comfortably changing task to ambient ratios. The acceptance of a setting varied depending on task area illuminance and the initial light setting. At a task area illuminance of 750 lux a task to ambient illuminance ratio of 8:1 was rated 'acceptable' by 75% of the participants. McKennan and Parry (1984) found that localized task area lighting from both the ceiling and from task lamps were rated satisfactory, despite producing illuminance ratios lower than standard practice. Van Ooyen *et al.* (1987) found a task to work-plane luminance ratio of 10:4 to be preferred by participants in the study. However, since floor and task area reflectance is unknown, corresponding illuminance ratios cannot be calculated. According to Cuttle (2008), a task to ambient ratio of 1.5:1 is perceived as uniform, and ratios higher than 10:1 have a negative effect on room perception. In a different paper (2013), Cuttle defined a target to ambient illuminance ratio (TAIR). This ratio describes the ratio of a local illuminance to its surrounding ambient illumination. However, the ambient illumination is determined by the 'mean room surface exitance (MRSE)' which includes reflected illuminances and therefore is a quantity related to luminances on room boundaries and other surfaces. Vertical surfaces are closely examined in the next chapter.

In this work, surrounding area illuminance defines the horizontal illuminance of the work plane excluding the task area. Measured from the walls, an additional 0.5 m boundary area is subtracted from the surrounding area (Figure 2-1).

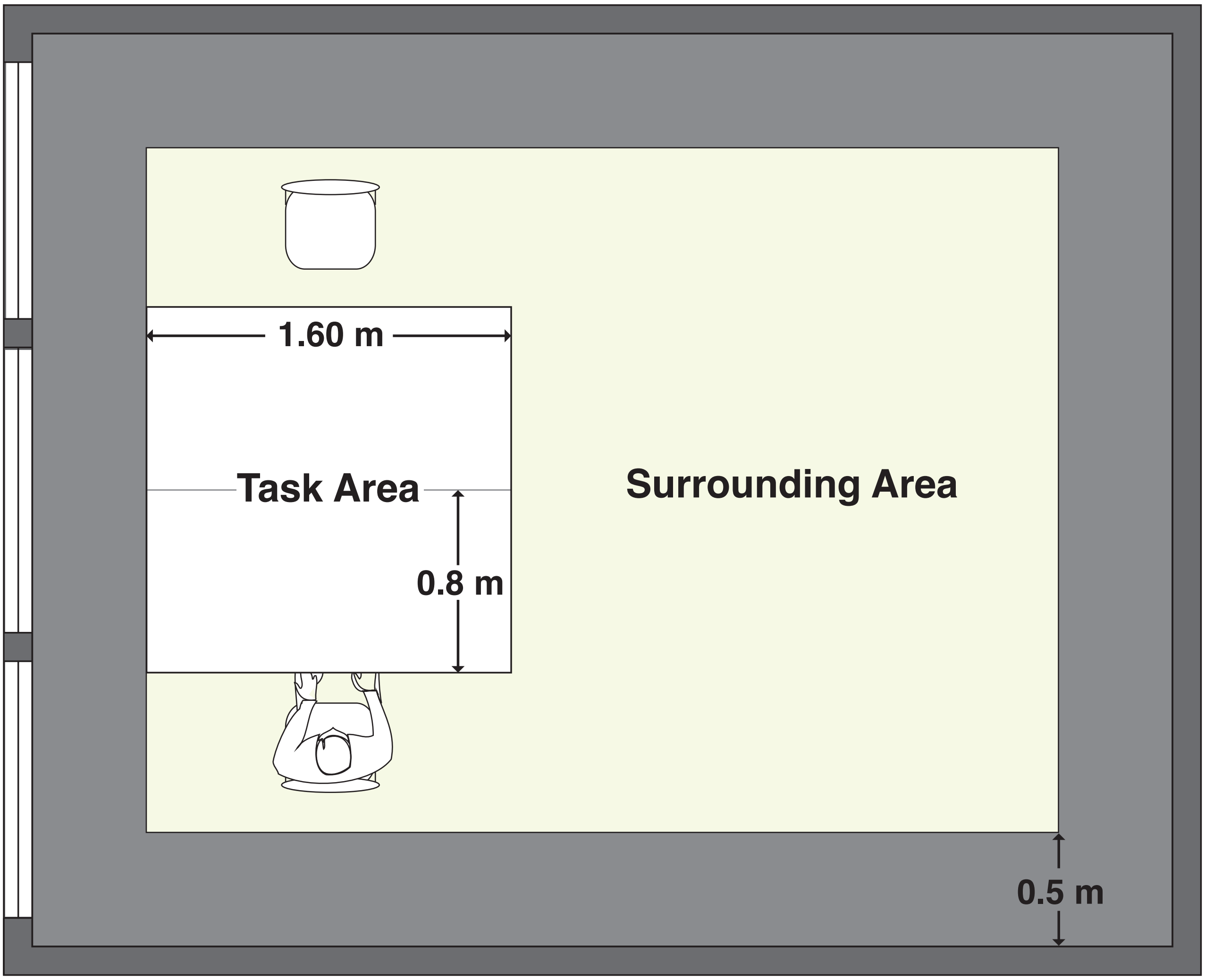

Figure 2-1: Definition of surrounding area and task area

This is standard practice in lighting planning for offices and corresponds to several German guidelines and standards (e.g. Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2011; Zentralverband

Elektrotechnik- und Elektronikindustrie, 2011). To separate relevant factors, in this work ambient lighting is defined as the fraction of luminous flux on the work plane exclusive of the task area. Luminances of other surfaces are described separately in the next section. In a pre-test to this work (Prella, 2013) participants rated surrounding area illuminances (as defined in Figure 2-1) of 300 lux slightly brighter than 100 lux, if wall luminances were low (~11 cd/m^2). With higher wall luminances (>30 cd/m^2) there was no significant difference between surrounding area illuminances of 50, 100, 200 or 300 lux.

The IESNA Lighting Handbook (2011) recommends that ambient lighting is, to some extent, responsible for the overall brightness impression of a space. However, this is not necessarily valid for illuminances restricted to a horizontal plane. The European standard DIN EN 12464-1 recommends surrounding area illuminances related to task area illuminances. Immediate surroundings should provide "a well-balanced luminance distribution in the visual field" (CEN, 2011, p.11). Naturally, these horizontal illuminances on a virtual plane do not have a strong impact on the adequacy of luminance distributions in the space. If an office worker remains at the working position, the surrounding area defined in Figure 2-1 only contributes to a small part of the visual field. Moreover, the usually dark floor linings absorb most of the light and, thus, make the work plane an inefficient area to enhance luminance distributions. Additionally, research by Flynn (1977), Loe, Mansfield, and Rowlands (1991) and Houser *et al.* (2002) indicated a lower correlation of apparent floor brightness with the overall brightness perception of a space than for other surfaces.

Table 2-3 shows the results of research and standards regarding the ratio of task area illuminance and ambient illuminance.

Table 2-3: Lighting conditions in surrounding areas derived from current research and standards

Investigation/Standard	**Accepted, preferred or recommended task to ambient illuminance ratio**
(Bean & Hopkins, 1980)	1:1[1]
(McKennan & Parry, 1984)	non-uniform installations possible[2]
(Tabuchi *et al.,* 1995)	1:1 (E_{task}=500 lux), ~1.5:1 (E_{task}=1000 lux)[1]
	3:1 (E_{task}=500 lux), ~4.1:1 (E_{task}=1000 lux)[2]
(Inoue, 2010)	6:1 (75% "allowance", E_{task}=500 lux)[2]
	8:1 (75% "allowance", E_{task}=750 lux)[2]
(IES, 2011)	≤1.5:1 (task proper to task margin)[3]
	5:1 (maximum task area to minimum work space)[3]
(CEN, 2011)	1.7:1[3]
(Prella, 2013)	1.7:1 for low wall and ceiling luminances[1]
	5:1 for high wall and ceiling luminances[2]
1: preferred 2: accepted 3: recommended	

Need for Research

The influence of ambient lighting on subjective lighting quality has been explored in many different settings and experimental designs. However, the results are inconsistent, experiments are not always conclusive and the exact areas in which ambient or surrounding illuminance is considered are seldom defined. Until recently, fluorescent lighting has been largely used in both lighting laboratories and actual offices. Achieving a high surrounding illuminance usually automatically resulted in sufficient wall and ceiling luminances due to stray light. Thus, in most cases, ambient lighting is not restricted to horizontal planes, and also provides illuminances on vertical surfaces. This was also the case in many studies on the perception of light distributions. Often, changes in surrounding area illuminance also induced a change in wall and ceiling luminance, leading to a potential uncontrolled confounding factor. Most of the studies mentioned above do not clearly distinguish between horizontal illuminances and luminances on vertical surfaces. On the one hand, due to photometric characteristics of lamps and fixtures the results of these studies may be valid enough for fluorescent lighting installation.

Current solid-state technology, on the other hand, has the ability to restrict lighting to a horizontal plane without directly illuminating vertical surfaces. This may lead to problems with the validity of the research outcomes for LED lighting installations. In the work of Tabuchi (1995) participants were presented with different task area illuminances and were asked to adjust ambient illuminance to preferred and just accepted levels. Although separate wall lighting fixtures were installed to provide constant wall illuminance they were switched off completely during the experiment. Thus, changes in wall luminances due to varying ambient lighting probably had an effect on the appraisal of the scenes. Similar discrepancies can be found in the experimental setup by Inoue (2010), where changes in wall luminances due to a variation of the ambient lighting component were not considered in the study. As a consequence, the results cannot be compared directly to the outcomes of this work. It is more than likely that in some studies the measured horizontal illuminance was not the only influencing variable. Thus, it has not yet been conclusively observed whether horizontal surrounding area illuminance as defined in this work affects room appearance.

Research Questions:

- Does a decreased surrounding area illuminance have affect the lighting appraisal of a space?

- Which dimensions (visual lightness, visual attractiveness) of lighting appraisal are affected?

2.2 Photometric Criteria Based on Luminance

Although illuminance recommendations are given in current lighting standards, the validity of illuminance as a criterion for room appraisal is questioned (e.g. Steffy, 2006). Cuttle (2010) suggested the consideration of vertical illuminances at eye level. However, this quantity is strongly correlated with the luminance in the visual field and therefore hardly achieves additional value. Luminance is the photometric quantity determining brightness perception. Several different investigations show an influence of luminances and contrasts within the visual field and the appearance of a lit scene (e.g. van Ooyen *et al.*, 1987; Loe *et al.* 1994; Veitch & Newsham, 1998; Loe, 2003) and are discussed in this section.

Desktop Luminance

Desktop luminance describes the luminance in the task area which is often the surface with the highest illuminance (around 500 lux) in the space. Moreover, desktop luminance accounts for a significant part of a 40° horizontal band first described by Loe *et al.* (1994) to strongly correlate with the subjective appraisal of an office scene. The dimensions of this band cover an opening angle of 20° above and below the observer's viewing axis. Moore (2003) stated that the desktop covers around 15% of the 40° band. Regardless, luminance strongly depends on desktop reflectance. Being an important parameter to adjust the visual appearance of a lit scene, different desktop materials and corresponding luminances were included in several investigations. The lower end of the range of findings and recommendations starts with the 'American National Standard Practice for Office Lighting' (2004) with 23.9 cd/m^2 calculated from minimum furniture reflectance and recommended illuminance assuming ideal diffuse reflection. The highest preferred desktop luminance was found by Balder (1957) in the area of 130 cd/m^2. Van Ooyen *et al.* (1987) found the preferred desktop luminance to be task-dependend. It was generally higher for reading and writing tasks (~45-105 cd/m^2) than for computer work (40-65 cd/m^2). For higher wall luminances, a lower desktop luminance was preferred while a higher desktop luminance was preferred under darker peripheral conditions. Veitch and Newsham (2000) recommended a desktop luminance in the range of current standard practice. The median of preferred luminances was around 65 cd/m^2. Despite its relevance for task performance, Collins, Fisher, Gillette, and Marans (1990) stated that "task luminance is not the critical determinant of the brightness of a space" (1990, p.35), which indicated only a marginal impact on visual lightness. Table 2-4 gives an overview on research findings and standard recommendations regarding desktop luminance.

Table 2-4: Preferred and recommended desktop luminances

Investigation/Standard	Preferred/Recommended desktop luminance in cd/m^2
(Balder, 1957)	116-144[2]
(van Ooyen *et al.,* 1987)	40-105[2]
(Veitch & Newsham, 2000)	65.7[2]
(IESNA, 2004)	23.9-64.5[1,3]
(CIBSE, 2005)	28.6-63.7[1,3]
(CEN, 2011)	31.8-111.4[1,3]

1: derived from recommended illuminances and reflectance of the furnishing
2: preferred
3: recommended

Background Luminance and Luminance Contrast Ratios

Although the term 'background luminance' is not defined in CIE S 017/E:2011, it is often used in research to describe the luminance of an area behind or beyond the task area. Similar to the term 'ambient lighting', definitions vary and can refer to both, vertical and horizontal surfaces. In this work, the term 'background' mainly refers to vertical surfaces such as walls and partition walls as well as the ceiling. Luminance contrast ratios, although defined by CIE S 017/E:2011 as the "ratio of the luminances of two active parts of a display surface [...]" (CIE, 2011, p.94), in this case describe the ratio of the average luminance of the task area and the average luminance of an examined surface in the space.

The apparent brightness of a surface depends on its luminance and its context of adjacent surfaces and objects in the space. Thus, the influence of different room surfaces on brightness perception is outlined here. Additionally, the ratio of task area luminance to background luminance is discussed. The relationship of brightness perception and the amount of light in a space has been shown in various experiments (e.g. Baron *et al.* 1992; Davis & Ginthner, 1990; Loe *et al.* 1994; McCloughan, Aspinall, & Webb, 1999), where in general spaces with higher luminances or illuminances were rated as brighter. According to Ishida and Ogiuchi (2002) the apparent brightness of a space does not depend on the luminance of lamps and luminaires but on the perceived amount of luminous flux emitted to the room. Houser *et al.* (2002) showed that wall and ceiling luminances contributed to overall brightness perception at a constant work-plane illuminance.

Research has also shown that brightness perception does not only depend on absolute luminances or the amount of luminous flux in the space (e.g. Tiller & Veitch, 1995). Different room surfaces and luminance ratios were investigated to locate areas of the visual field with particular impacts on apparent brightness. Loe *et al.* (1994) identified a 40° horizontal band to significantly determine the visual lightness of a space. This was in accordance to an earlier study by van Ooyen *et al.* (1987) who indeed did not explicitly use a horizontal band, but described luminances in equivalent areas of the visual field to have great impact on perceived brightness. The influence of the 40° horizontal band was confirmed by Berrutto *et al.* (1997), later experiments by Loe *et al.* (2000), and Veitch and Newsham (2000). However, a direct comparison of the experiments is not possible without reproach. Observer positions in the space and, thus, surfaces contributing to the 40° band varied significantly. In the experiment by Loe *et al.* (1994) participants observed the scene from a point outside the actual office space and rated lighting conditions in a conference room, Veitch and Newsham used an open plan office with cubicles and partition walls.

Iwai, Saito, Sumi, and Sakaguti (2001) found that estimated room brightness strongly depended on the average luminance of the whole visual field and especially on walls and the room-corners. The particular influence of wall luminances on brightness perception was partly confirmed by Kato and Sekiguchi (2005), where lighting on walls had a higher impact on brightness perception than lighting on the ceiling. In their work it was also found that brightness estimates depend on the observer's action in the space. This contributes to the theory that brightness perception is not merely a stimulus-response process but includes mental concepts of space-usage influencing the appraisal. A major drawback of these findings is the insufficiently small sample size of ten participants.

A different approach to visual lightness of a scene is the observation of environments with theoretically sufficient illumination that nonetheless appear dark or gloomy. In the gloom studies by Shepherd, Julian, and Purcell (1992), the negative affect of gloom was defined as a phenomenon where occupants judge an interior to be under-lit even though the illuminance in the task area is sufficient for task performance. Gloom perception was investigated using adjectives of negative affect such as 'sombre' and 'dark' that are also used in this work. Results showed that gloom occurs mostly under conditions with insufficient peripheral luminances. Low peripheral luminances and low apparent brightness of peripheral surfaces can cause gloom, even if visual performance is not compromised. High task to background luminance ratios are also most likely to cause gloom due to relatively bright task areas resulting in higher adaptation levels. These results were confirmed by Collins *et al.* (1990) who found that for workstations with very bright tasks and dim surroundings, brightness perception was lower than for any other installations in the study. A similar phenomenon, the 'cave effect', was described by Cuttle (2013), where spaces with lighting installation, that exceeded illuminance levels necessary for task performance by far, were still perceived as bland and gloomy workplaces. As a countermeasure, Cuttle suggested the use of additional quality criteria in lighting design such as perceived adequacy of illumination (PAI) and illumination hierarchy (IH). IH is examined in greater detail in the chapter about background luminance distribution. PAI is closely related to the visual lightness factor used in this work since it is a measure for a space to "appear acceptably bright for the activity it houses" (Cuttle, 2013, p.24). To specify PAI, the mean room surface exitance (MRSE) briefly described in the previous chapter can be consulted. It is defined as the ratio of first reflected flux and room absorption, and therefore is related to room surface luminance. MRSE is the mean flux density exiting room surfaces averaged over all surfaces in the room. MRSE and absolute luminances are important factors in determining appropriate illumination. However, as described in the following chapters additional factors such as spatial distribution, context and position of particular surfaces also have an impact on brightness perception, and should be considered as well.

Factors influencing the attractiveness and pleasantness of a space are closely connected to factors also affecting the observer's concept of brightness. Thus, clearly distinguishing between findings on attractiveness and brightness is no easy task. Similar to the findings about visual lightness, a number of researchers found that the luminance of different parts of the visual field and background to task luminance ratios to affect visual attractiveness. Marsden (1972) stated that in a working interior with a lighting system directing light to the work plane only, even if all visibility requirements are met, the worker would be unlikely to be satisfied with the luminous environment. This was supported by the gloom studies (Shepherd *et al.,* 1992) mentioned above. Fischer (1973) found that the luminance of walls, ceiling and luminaires influences the impression of comfort and pleasantness of the lit environment. This was confirmed by van Ooyen *et al.* (1987), where wall luminances strongly affect the way a room is experienced. Higher luminances created a more stimulating environment where it was also easier to concentrate. According to the same investigation, the participants' preferred wall luminance is independent of task area luminance, but is, to a certain degree, task dependent. Regarding the task to background luminance ratio, a bright desktop in dark surroundings ($L_{\text{workplane}}>L_{\text{walls}}$) was rated by the participants as more relaxing while a darker desktop in a bright room ($L_{\text{workplane}}<L_{\text{walls}}$) had a stimulating effect.

Compared to direct lighting, a direct/indirect lighting installation usually provides higher wall and ceiling illuminances. Several studies investigate the effects of the direct to indirect lighting ratio on user acceptance. According to research, a high percentage of indirect lighting can have positive effects on the occupants' reaction to the lighting (Harvey, Dilaura, & Mistrick, 1984), as well as satisfaction and productivity (Hedge, Sims, & Becker, 1995). In the study by Houser *et al.* (2002) mentioned above, a higher indirect to direct lighting ratio made the room appear more spacious. Indirect to direct ratios greater than 0.60 were preferred. This was most likely due to higher luminances in the visual field created by the indirect part of the lighting. These ratios were approximately confirmed by Govén, Bångens, and Persson (2002) and Govén, Laike, Pendse, and Sjöberg (2008) where indirect to direct ratios of 0.56 and greater were found to be preferred. Fostervold and Nersveen (2008) did not find significant effects of direct to indirect lighting ratio on well-being. However, well-being in this case was restricted to job satisfaction, stress, anxiety and depression; room appearance and appraisal of the lit scenes were not included in the survey. In a study by Veitch, Newsham, Jones, Arsenault, and Mancini (2010a) lighting with a substantial indirect component was judged to be better and more comfortable than the control group by a larger proportion of participants. Also, the same lighting conditions with furniture of different reflectance led to different judgements. With lighter furniture (and thus, higher luminances on partition walls) the same lighting was more likely to be rated as 'better than in other similar workplaces'.

Table 2-4 summarizes findings of research and minimum recommendations of different standards. Since international interior lighting standards usually recommend illuminance levels rather than luminances, luminances and ratios are calculated from illuminances using recommended ranges of furniture and surface reflectance (Equation (2-1)) assuming ideal diffuse reflectance.

$$L = \rho \cdot \frac{E}{\pi} \tag{2-1}$$

with average surface luminance L, surface reflectance ρ and average illuminance E.

Table 2-4: Preferred and recommended background luminances and luminance ratios

Investigation/Standard	Preferred/Recommended luminance in cd/m²	Preferred/Recommended task to area luminance ratio
(Balder, 1957)	120^a, 95^b, 135^c	$3{:}1^a$, $3.8{:}1^b$, $2.7{:}1^c$
(Bodmann, 1967)		3:1c
(Collins & Plant, 1971)	71.9^c	ρ_{Task}=0.75, $3.1\ldots1.5{:}1^{a,b}$, $2.8\ldots0.94{:}1^c$
(Tregenza *et al.,* 1974)		$2{:}1^{a,b}$, $1{,}2{:}1^c$
(van Ooyen *et al.,* 1987)	20-45 (VDU work)^{a,b} 30-60 (other tasks)^{a,b}	$2{:}1^{a,b}$, $3.3{:}1^c$, $1.33{:}1^d$
(Loe *et al.,* 1994)	>30d	
(Halonen & Lehtovaara, 1995)		$1.68{:}1\text{-}5.7{:}1^d$
(Berrutto *et al.,* 1997)	$25\text{-}90^d$	$2{:}1\text{-}3{:}1^d$
(Loe *et al.,* 2000)	$>40^d$	
(Veitch & Newsham, 2000)	39.2^d	$1.7{:}1^d$
(Newsham, Marchand, & Veitch, 2002)	46.2^e, 62.7^c, $46.8\ (L_{walls/desktop})^d$	$1.21{:}1^e$, $1.15{:}1\ (L_{desktop}:L_{walls/desktop})^d$
(IESNA, 2004)	$71.6\text{-}193.4^{d,1}$	$3{:}1^d$
(Newsham, Arsenault, Veitch, Tosco, & Duval, 2005)	$30\text{-}40^e$	
(CIBSE, 2005)	$14.3\text{-}89.1^{d,1}$	$3{:}1^d$
(CEN, 2011)	$11.1\text{-}14.3^c$, $11.9\text{-}19.1^{a,b,1}$	
a: facing wall b: side wall c: ceiling d: 40° horizontal band e: partition wall 1: standard recommendations		

Need for Research

The effect of background luminance and luminance to task ratios has been explored in a number of studies. Newer results are fairly consistent, stating a recommended minimum luminance of the background of 30-50 cd/m^2 for offices. However, a reliable control of photometrics was not always ensured by the experimental setup. Similar to research on task area illuminance (s. section 2.1, p. 13), many results have been derived from adjustment tasks that are not necessarily valid (Fotios *et al.,* 2011). A possible interaction between surrounding area illuminance and luminance of the background has not been explored conclusively. The use of solid-state lighting installations potentially allows for a better control of photometric parameters in the space. Thus, a more accurate determination of how luminance values and ratios affect visual appearance in office spaces is needed. Literature review and a pre-study to this work (Prella, 2013) suggest the possibility of reducing the illuminance in surrounding areas without compromising visual appearance, if background luminances are increased to a level higher than standard recommendations. Conclusively observed, a redistribution of lighting from the surrounding areas to vertical surfaces has the potential to increase lighting quality without altering the lighting energy budget of an office space.

Research Questions:

- How are lightness and attractiveness of a space affected by different background luminances independent from all other lighting parameters?

- Can a decreased surrounding area illuminance be compensated by increased background luminances?

- Can a mathematical dependency be found between the rating of visual lightness and background luminance?

Background Luminance Distribution

Spatial distribution of light has been suggested to influence 'lightness' (e.g. Goodman, Gibbs, & Cook, 2006) and 'visual interest' (e.g. Loe *et al.,* 1994) of a space. Research indicates that especially variations in luminance distributions in the field of view can affect brightness perception and appearance of a space. Luminance ratios between or within different surfaces are defined as the "ratio of the maximum luminance to the minimum luminance that is either: present in a specific scene, artwork, photograph, photomechanical, or other reproduction; or is capable of being created using a particular output device and medium" (CIE, 2011, p.95). Jay (1971) stated that low illumination gradients and corners without contrasting brightness are likely to cause gloom. Collins *et al.* (Collins 1990) found out that luminance distribution in a space is an important factor influencing satisfaction and brightness perception. In an investigation by Tiller and Veitch (1995), participants matched the brightness of different rooms with relatively uniform and non-uniform luminance distributions by adjusting the illuminance on the work-plane to a degree where the rooms appeared equally bright. It was found that a non-uniform distribution led to lower adjusted illuminances. Thus, a room with non-uniform luminances appeared equally bright with lower work-plane illuminance. The Illumination Engineering Society (2011) recommends accent lighting to affect and enhance brightness perception but does not specify to what extent.

Boyce (1979) found a slightly higher appraisal of background lighting using spotlights, which was judged as more relaxed and interesting by participants of the experiment. In an experiment by Bean and Hopkins (1980), an increase of wall illuminance by factor three only marginally changed the number of participants satisfied with the lighting if illuminance distribution was uniform. The same changes created by spotlights resulting in a non-uniform distribution increased the number of satisfied observers by 50%. Since walls were painted dark it is likely that participants in the experiment did not significantly notice the resulting small changes in wall luminance achieved by the uniform lighting. The spotlighting, on the other hand, created accented highlights of 1150 lux resulting in a noticeable change of luminance in this area. The adequacy of the usage of illuminance as an important criterion affecting attractiveness of the space can therefore be questioned.

Loe *et al.* (1994) found responses to a semantic differential measuring 'visual interest', an appraisal-dimension often but not necessarily connected to visual attractiveness (cf. Kaplan, 1988), to highly correlate with the logarithm of minimum to maximum luminance ratio in a 40° horizontal band. A study by the German Institute of Applied Lighting Technology (DIAL, 2003) investigated user acceptance under different lighting conditions. Accent lighting on walls resulted in a higher attractiveness rating and was, together with indirect lighting, found to enhance brightness perception. This is supported by the Illumination Engineering Society (2011) where accent lighting is recommended to affect visual attraction.

Cuttle (2013) defined an illumination hierarchy (IH) depending on the significance of different areas of a space and the activity most likely performed in these areas. The concept involves the structuring of a space and the highlighting of objects. 'Hierarchy', in this case, is defined as the ratio of the illuminance of an object and its surroundings. Research findings are summarized in Table 2-5.

Table 2-5: Influence of luminance distribution

Investigation	Effects of background luminance distribution
(Bean & Hopkins, 1980)	Spot-lighting on walls has a stronger effect on acceptance of a space than uniform wall lighting
(Tiller & Veitch, 1995)	Non-uniform distributions appear brighter than uniform
(Loe *et al.,* 1994)	A minimum maximum to minimum luminance ratio of 13:1 in a 40° horizontal band for 'visual interest'
(Moore *et al.,* 2003)	Skews are rated positive, smaller areas with brighter surfaces are rated darker
(DIAL, 2003)	Accent lighting leads to higher attractiveness
(IES, 2011)	Accent lighting affects brightness perception and visual attraction
(Cuttle, 2013)	Object luminance and surrounding luminance define hierarchy of a space

Need for Research

The effect of different distributions of background luminance has not been researched extensively. Results by Tiller and Veitch (1995) and Loe *et al.* (1994) suggest, that non-uniform distributions can enhance visual lightness and visual interest. Extensive research in which the illuminance distribution in the visual field has been systematically varied does not yet exist. Cuttle's concept of illumination hierarchy is one approach to describe accentuation of objects. Surface illuminances together with reflectance determine the luminance of that surface. However, illuminances alone are not an appropriate measure for the accentuation of an object if reflectances of the object and its surroundings are not known. Additionally, in lighting design practice a room is usually structured by highlighting different areas depending on their importance for the space and their usage. Specific objects, as described by Cuttle (2013), are not necessarily the only target of this structuring.

Current solid-state lighting technology enables high contrast distributions that could have a negative effect on room appearance, but could also be used to enhance the visual quality of a space. To achieve the latter, it is necessary to evaluate, which distributions and contrasts enhance or deteriorate aspects of perceived lighting quality.

Research Questions:

- Do different luminance distributions across the visual field influence visual lightness and/or visual attractiveness?

- Which surfaces or areas of the visual field contribute most to the sensation of visual lightness and/or visual attractiveness, and are therefore more effective than others?

3 Individual Differences

As described in section 1.1 on page 6, lighting appraisal and visual appearance of a scene do not only depend on the lighting conditions in the space but also on the occupant himself. Individual differences between observers or users experiencing a scene are discussed in this section.

3.1 Age and Gender

Literature concerning age differences and gender in lighting judgement and preferences is inconsistent to a certain degree. Knez and Kers (2000) found that gender and age interactions have a significant effect on mood preservation when presented with different lighting scenes. In the same study, younger adults (mean age around 23 years) assessed the room as brighter than older adults (mean age around 65 years), regardless of color temperature and lamp type. Performance of cognitive tasks was generally better for younger adults. However, it is not clear if this is a result of changes in lighting or just an effect of age, where younger people are generally better at performing certain tasks. A decrease in visual acuity and general vision related to the aging eye makes a preference for higher lighting levels probable. Veitch (2001) assumed that the general preference for higher illuminance and luminance may often mask age effects. A study by Juslén, Wouters, and Tenner (2005) showed no significant correlation between the participants' age and their preferred illuminances. Boyce (1973) did not find changes in illuminance preferences or environmental assessment due to the participants' age. Only examining the older adult group (46-60 years) separately showed minor differences in satisfaction with the lighting. Balder (1957) did not find gender effects in office lighting preferences.

Although possible effects of gender and age on lighting appraisal may exist, they are not within the scope of this work.

3.2 Chronotype and Time

White light exposure has shown significant psychobiological effects on both subjective and objective measures of alertness, vitality and well-being (e.g. Bellia, Pedace, & Barbato, 2013; Maierova, Borisuit, Scartezzini, & Münch, 2012; Smolders, de Kort, & Cluitmans, 2012; Tsai *et al.,* 2009). Research also indicates a time of day dependency, where alertness levels and performance as well as subjective estimates of mood are higher in the morning than in the evening due to fatigue. This was, however, more dependent upon the amount of time awake than on the absolute time of day (e.g. Valdez, Reilly, & Waterhouse, 2008). Higher doses of lighting were intuitively linked to alertness and arousal (Cajochen, 2007).

Maierova *et al.* stated that a better understanding of circadian lighting effects depending on a person's chronotype could "contribute to develop high quality indoor lighting environments which also consider physiological and behavioural needs" (Maierova *et al.* 2012, p.1). Their survey included the effects of different lighting conditions on well-being and alertness. One hour after habitual wake time, 18 participants (11 morning types, 7 evening types) were exposed to three lighting conditions ('Dim' with <5 lux at corneal level, 'Bright' with 1000 lux at corneal level and 'self-selected') for a time of 16 hours. Participants felt significantly more alert when exposed to the 'bright' and 'self-selected' conditions regardless of the participants' chronotype. Considering the chronotype/time-of-day interaction, morning-types felt significantly more alert during the first half of the study under the 'bright' condition and less well in the second half of the exposure time under the 'self-selected' condition.

Smolders *et al.* (2012) tested two light settings (1000 lux and 200 lux at eye level) on their influence on subjective alertness and vitality. As expected, participants felt more alert and energetic when exposed to brighter light. These findings are in accordance with previous research (e.g. Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006).

Regarding positive and negative affect, Kantermann *et al.* (2012) conducted a study where participants were exposed to bright light (4420 lux at eye level) and dim light (230 lux at eye level) for 160 minutes. At the end of the experimental session they performed a bicycle ergo-meter test. Work performance was higher under the bright light condition for all participants. The experiments always took place at the same time-of-day. However, the participants' chronotypes indicated a different individual 'internal time' depending on the time passed since the mid-sleep time. It was found that the differences in performance for the two lighting conditions were larger when participants were tested at a later point in time relative to their mid-sleep. This indicates an effect of internal time on work performance and sensitivity to light exposure. Internal time can also be determined using the interaction of a subject's chronotype and the external time-of-day. The latter method is used in this work.

Research by Gabel *et al.* (2013) indicated a significant improvement in mood and well-being for participants under sleep restriction when being exposed to a dawn simulating polychromatic light, which gradually increased from 0 lux to 250 lux compared to control groups that were exposed to monochromatic light or dim white light.

Need for Research

While multiple studies on psychobiological effects of lighting have been conducted, no studies can be found regarding the influence of biological lighting effects on subjective preferences. The experiment by Maierova *et al.* (2012) suggested a chronotype/time interaction on alertness and well-being for different lighting conditions. Due to the small sample size of 18, these studies can only be an indicator that biological effects of lighting can influence subjective estimates. Additionally, most studies investigated very large differences in illuminances at eye level. Thus, it has not been investigated extensively if biological effects of lighting have a direct impact on the appraisal of a lit scene within the typical luminance and illuminance range found at workplaces under artificial lighting conditions.

This work can serve as a pilot study on possible connections between biological effects and the subjective appraisal of a lit scene.

Research Questions:

- Does a person's chronotype influence visual lightness and/or visual attractiveness ratings?
- Does the time-of-day influence visual lightness and/or visual attractiveness ratings?
- Does the interaction of time-of-day and chronotype (internal time) influence visual lightness and/or visual attractiveness ratings?

4 Measurement of Visual Appearance

Flynn, Spencer, Martyniuk, and Hendrick stated that "the experience of lighted space is, to some extent, a measurable experience" (1975, pp.45–46). In a number of studies the impact of different photometric criteria on different aspects of perceived lighting quality has been investigated. The following sections give a brief overview over the test laboratories and questionnaires used in previous research.

4.1 Lighting Laboratories

Many different experimental setups have been used in the past to investigate the influence of different lighting conditions on subjective responses to a lit scene. Most frequently, mock-ups of offices and spaces for similar occupations are used. While open-plan offices are the most common type of office spaces in North America and some parts of Europe, other parts of Europe use cell or group offices in great numbers. Viewing conditions in both office types differ significantly. In a cell office, occupants usually have a mostly unobstructed view on two or more of the room's enclosing walls. Cubicles with partition walls used in open-plan offices completely change distances and visual angles in relation to lit surfaces throughout the space. Moreover, room boundaries other than the ceiling are often obstructed from the occupants' view. One must consider these differences when comparing experimental results.

One of the most important factors describing the quality of an investigation is the definition and control of independent variables. To attribute changes in subjective responses to a certain criteria it is important to keep all other criteria constant that might influence the outcome of the survey. The following study may serve as an example: An experiment (Pellegrino, 1999) led to the conclusion that direct lighting was preferred over direct/indirect and indirect lighting, in contradiction to most other research (e.g. Houser *et al.,* 2002; Veitch *et al.,* 2010a). However, task luminance, wall luminances and luminance ratios of task to remote areas changed significantly between the three settings used in the study.

For example, the luminance of the desktop where participants were seated changed from 105 cd/m^2 for the indirect system to 160 cd/m^2 for the direct system. Thus, it cannot be stated that direct lighting was the only influencing variable since the luminance of the desktop affected judgements. Interdependent variables, such as an increase of wall luminance due to an increase of task area luminance, exist in many laboratories. Table 4-1 gives an overview on different experimental setups and their respective control of independent variables. Variables are marked as 'not independent' if a variation of one photometric quantity resulted in a change of another independent variable and was not considered in the investigation. Photometrics that were evidently changed in the study but not considered or measured in the investigation were marked as 'not considered in survey'.

Table 4-1: Overview on different test laboratories and control of independent variables

		Control of independent variables		
Investigation	**Test Lab**	**Wall Luminance**	**Ceiling Luminance**	**Work plane Illuminance**
(Saunders, 1969)	experimental room 7.3 m x 5.5 m	no^{B}	no^{B}	yes
(Collins & Plant, 1971)	open plan office 1:12 Scale model,	no^{A,B}	yes	no^{A}
(Tregenza *et al.,* 1974)	experimental office	no^{A,B}	no^{B}	yes
(van Ooyen *et al.,* 1987)	3 identical cell offices 3.6 m x 5.4 m	yes	yes	yes (±10%)
(Loe *et al.,* 1994)	conference room 6 m x 4.2 m	no^{A}	no^{A}	no^{A}
(Pellegrino, 1999)	48 m^2 office with different light settings	no^{A}	no^{A}	no^{B}
(Loe *et al.,* 2000)	room, four light settings 6 m x 4.2 m,	no^{A}	no^{B}	no^{B}
(Houser *et al.,* 2002)	experimental room 12.7 m x 7.2 m	no^{A}	no^{A}	yes
A: not independent B: not considered in survey				

It becomes clear that most lighting laboratories do not have full control over independent variables, especially over luminances on different surfaces. For lighting systems using fluorescent lamps with hardly controllable optical properties, this leads to valid results. Solid-state lighting technology, however, has the capability of providing a more exact and decided light distribution with accurate distinction between different room surfaces. This begs question: are the results derived from previously conducted studies also valid for prospective LED lighting solutions?

4.2 Questionnaires to Determine Lighting Quality

Overall approaches to predicting subjectively perceived lighting quality such as the 'Comfort, Satisfaction and Performance (CSP)' index by Bean and Bell (1992) and Bean and McFadder (1998) tend to work quite well in certain environments, but fail to correlate with human responses in others (Chung & Burnett, 2000). A number of different questionnaires have been used in lighting research to evaluate different aspects of subjectively perceived lighting quality.

Probably the most frequently used questionnaire design in lighting research are sets of semantic differential scales. As mentioned in section 1, most of these questionnaires are similar with small variations in items and composition. One of the first studies using a set of semantic differentials for lighting quality and room appearance measures was presented by Flynn *et al.* (1979). Their 30 item questionnaire has been used as a basis for many other questionnaires using bipolar scales (e.g. Loe *et al.,* 1994; Pellegrino, 1999). The 'Room Appearance Judgement' questionnaire by Veitch and Newsham (1998) contained a set of 27 semantic differentials that were partially derived from the works by Flynn *et al.* and Loe *et al.* mentioned above. The questionnaire contents have evolved over time, but differences between the various questionnaires are small.

Many questionnaires are very long and some contain items that cannot be applied to all presented scenes, or are difficult to understand. Thus, a short version was used in (Veitch *et al.* 2010b), who revised the items used in (Boyce *et al.,* 2003; Newsham *et al.,* 2003; Veitch & Newsham, 1998). When used in principal component analyses in different studies, the obtained 8 items consistently loaded on two factors that are identical to the 'visual lightness' and 'visual attractiveness' as described in 1.2.1 and 1.2.2. In this work, a translation of this shorter version is used (s. section 5.1 for a detailed description).

5 Experiment I

The first experiment was conducted to investigate research hypotheses on the influence of surrounding area illuminance, desktop luminance and walls/ceiling luminance on visual appearance. The participants' chronotypes and the time of observation were determined to explore possible effects. From preliminary testing and literature research it can be assumed that changes in surrounding area illuminance have an effect on room appearance regarding visual lightness of a space. This experiment was designed to test the following hypotheses:

- Surrounding area illuminance has an effect on visual lightness, but not on visual attractiveness

However, current research also suggests a greater effect due to changes in background luminance. Both, visual lightness and visual attractiveness are affected.

- Background luminance has an effect on both visual lightness and visual attractiveness

- Wall and ceiling luminances have a greater impact on visual lightness and visual attractiveness than surrounding area illuminance

If these hypotheses are confirmed in this experiment, it can be concluded that changing the luminance of the background has a stronger impact on room appearance and can lead to more energy efficient lighting solutions.

The effect of an occupant's chronotype on lightness and attractiveness rating of a lit scene has not been explored extensively. However, some recent research indicates the judgement of a lit scene is dependent upon a subject's chronotype. Since further research indicates a change in alertness and well-being at different times of day depending on the observer's chronotype, an interaction between chronotype and point of time of the experimental procedure is assumed.

- The interaction between chronotype and time-point of observation has an effect on judgements of visual lightness and visual attractiveness

This experiment may serve as a pilot study exploring the impact of the biological effects of lighting on subjective preferences of a lit scene.

5.1 Research Design

Experiment I was a 4 x 3 x 2 x 5 x 3 mixed within-between design (Figure 5-1) with 2 repeated-measures variables (4 levels of wall/ceiling luminance and 3 levels of surrounding area illuminance) and 3 between-groups variables (2 levels of desktop luminance, 5 times of day, and 3 chronotypes).

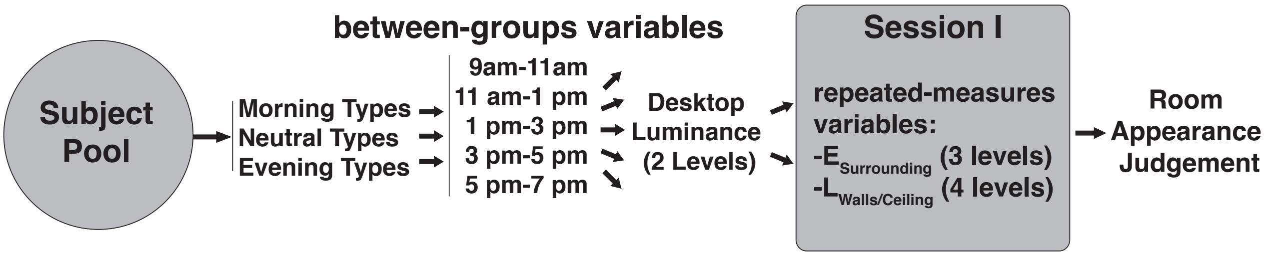

Figure 5-1: Experimental design

All groups of participants observed all 12 possible combinations of surrounding area illuminances and luminances of the walls and ceiling, thus acting as their own control group. For the between-groups variable 'desktop luminance' half of the sample was presented with the first level, the other half with the second level respectively.

Independent Variables

Table 5-1 shows the range of independent repeated-measures variables. The levels of surrounding area illuminance were chosen to cover the range from 100 lux (as suggested in (Inoue, 2010) for around 80% allowance) to 300 lux (as suggested in (Tabuchi *et al.,* 1995) for the 'energy efficient evaluation grade'). Conveniently, a level of 300 lux is also recommended for office surrounding areas in EN 12464-1 (2011) whereas 100 lux is the recommendation for circulation areas. The three steps represent levels with perceptual differences. The levels of the walls and ceiling luminance start with 11 cd/m^2 derived from EN 12464-1 (2011) to represent the lowest recommendation found in research or standardization (s. chapter 2.2, p.24). The highest level, 75 cd/m^2, exceeds most preferred or recommended levels (e.g. Collins & Plant, 1971; van Ooyen *et al.,* 1987; Veitch & Newsham, 2000). It can be assumed that the improvements achieved by even higher luminances greater than 100 cd/m^2 are marginal (Loe *et al.,* 1994).

Table 5-1: Repeated-measures variables in experiment I

Repeated measures variable	Range
surrounding area illuminance	100 lux, 200 lux, 300 lux
walls/ceiling luminance	11 cd/m^2, 30 cd/m^2, 50 cd/m^2, 75 cd/m^2

The first between-groups variable was the participant chronotype derived from the Morningness-Eveningness questionnaire (MEQ) first introduced by Horne and Östberg (1976). A German translation (D-MEQ) was used (Griefahn, Künemund, Bröde, & Mehnert, 2001). Griefahn *et al.* (2001) showed that the results of the German and English questionnaires given to 436 participants correlated significantly (r=-0.91, p<0.0001) and resulted in assignments to the different types almost equal to the original version. The evaluation of the MEQ distinguishes between five different types: definite morning an evening types, moderate morning and evening types and neutral types. Definite types only account for a very small percentage of the population, so the necessary sample size to include a sufficient amount of more extreme chronotypes would be very large. Thus, a 'simple chronotype' is introduced, where definite and moderate types are pooled together. Since a time*chronotype interaction was hypothesized, the second between-groups variable was the time of observation. The times from 9 am to 7 pm represent a normal office working day. The two levels of desktop luminance roughly represent the preferred desktop luminance of about 60 cd/m^2 derived from (Veitch & Newsham, 2000) and a brighter desktop with a reflectance of 60% resulting in a luminance of 95 cd/m^2. An overview of between-groups variables is presented in Table 5-2.

Table 5-2: Between-groups variables in experiment I

Between-groups variable	Range
simple chronotype	morning type, neutral type, evening type
time of day	9 am - 11 am, 11 am - 1 pm, 1 pm - 3 pm, 3 pm - 5 pm, 5 pm - 7 pm
desktop luminance	60 cd/m^2, 95 cd/m^2

Age, sex and knowledge in the field of research may affect the outcomes of the survey. These measures are not in the main focus of this work but were included in the questionnaire.

Dependent Variables

The desired outcome of the experiment is the appraisal of room appearance depending on different factors. Thus, responses to the request "Please tell us your opinion of the appearance of the space" compose the dependent variable. The questionnaire used in this work is a short version of the room appearance judgement first used by Veitch and Newsham (1998) containing semantic differential ratings derived from previous research by Flynn (1979) and Loe (1994). As described in 4.2 on page 33 a modified version of the 'room appearance judgement' questionnaire (Veitch & Newsham, 1998) was used to determine the participants' ratings of visual lightness and visual attractiveness. The short version in this work was also used in (Veitch *et al.,* 2010b) where questionnaires developed in past research were examined to identify consistency in factor loadings. A German and English native speaker first translated the items to German. The German items were then re-translated to English by another German and English native speaker to test for consistency. The English version is shown in Table 5-3, the German translation is shown in parantheses.

Table 5-3: Items of room appearance judgement questionnaire

Negative	Positive
unattractive (unattraktiv)	attractive (attraktiv)
ugly (häßlich)	beautiful (schön)
unpleasant (unangenehm)	pleasant (angenehm)
dislike (nicht mögen)	like (mögen)
sombre (bedrückend)	cheerful (fröhlich)
vague (undeutlich)	distinct (definiert)
dim (dunkel)	bright (hell)
gloomy (düster)	radiant (leuchtend)

There was a problem with the 'vague-distinct' item since the literal translation to German changes the meaning within the language context. One possible translation preserving the meaning is 'undeutlich-definiert', which literally translates to 'indistinct-defined'. The ratings of all eight items were used in a principal component analyis. Expected results were the two resulting components, 'visual lightness' and 'visual attractiveness' similar to the components 'illumination' and 'attractiveness' retrieved from the principal component analysis (PCA) in (Veitch *et al.* 2010b). The results of the PCA are presented in detail in Appendix A. The results obtained from this study are not critical in terms of health, security or accident prevention. Thus, a significance level of α=0.05 is chosen throughout all experiments if type I error accumulations can be avoided. This is the case in multivariate procedures and orthogonal contrasts. In some cases, due to the experimental design and the desired pre-planned comparisons an inflation of type I errors cannot be prevented. In these cases a more conservative significance level of α=0.01 is used.

Scaling of dependent variables

In 'CIE 175:2006: A Framework for the Measurement of Visual Appearance' the term 'soft metrology' is defined as "The measurement of parameters that, either singly or in combination, correlate with attributes of human response" (CIE, 2006, p.2). A measurement scale is generated when human perceptual or subjective responses are correlated with physical measurements (e.g. photometry). An example frequently used in lighting research is the semantic differential introduced by Osgood (1957). Human responses to a lit environment are measured on a bipolar scale, and are then in some way correlated to photometric measurements (e.g. Flynn *et al.,* 1975; Loe *et al.,* 2000). Semantic differential ratings are frequently used in psychological research to assess characteristics of a scene that cannot be measured by physiological techniques. The scales are constructed to rate the same scene or item using several bipolar rating dimensions (Dawis, 1987). Generally, two versions of bipolar semantic differential scales can be found in research. The main difference is the composition of the scale itself, where discrete points (e.g. 5- or 7-point-scales) or continuous scales are used. Albaum, Best, and Hawkins (1981) examined information obtained from 5-point and continuous scales of equal length. The response distribution, means and variances were equal for both types. However, due to the higher possibilities of discrimination continuous scales had an advantage over discrete scales when individual differences between participants were important. Similar conclusions were found by Funke and Reips (2012), where ratings on continuous scales were adjusted more thoroughly and thus, precision of the continuous ratings was higher. Another advantage of continuous scales is the implicit avoidance of a logarithmic contraction bias (Poulton, 1989) that only occurs when digits and step changes are used.

Research by Rea (1982) generally challenges the methodology of semantic differentials in accordance with (Osgood *et al.,* 1957). According to his research, participants use scales differently, and scales should therefore be calibrated in advance. Since no 'independent standard' exists for affective emotional measure calibration is not possible for scales such as beauty or attractiveness. Even increasing the sample size will not necessarily lead to more consistent results. Another issue with subjective scales is the participants' personal understanding of the bipolar adjectives. In a study by Tiller and Rea (1992) different participants interpreted the adjectives meanings differently. Thus, responses were inconsistent to some extent. If a subject is presented with the same pair of semantic differentials in different situations, the correlation between these pairs often changes due to 'concept-scale interaction' (cf. Bynner & Coxhead, 1979, p.369). This effect may also influence the factor structure if factor analysis is used. However, there are established methods to evaluate the validity and reliability of tools to measure abstract concepts (e.g. Ghiselli, Campbell, & Zedeck, 1981; Kerlinger & Lee, 2000). Additionally, using semantic differential ratings in principal component analysis and parametric tests is standard procedure in psychometric research (e.g. Jaen, Sandoval, Colombo, & Troscianko, 2005; Schutz, 1964; Veitch & Newsham, 2000; Völker, 2006). It is often argued that semantic differential scales have an arbitrary neutral zero-point and that intervals can be treated as equal. That is, interval levels can be assumed. Under this assumption, semantic differentials scales are used in this work to achieve maximum comparability with other research in the field.

5.2 Participants

The minimum sample size was calculated using power analysis in G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) with $\alpha=0.05$ to achieve a power of $1-\beta\geq0.95$. The estimate of effect sizes was derived from experiences with pre-tests (Prella, 2013). The between-groups variables 'chronotype' and 'time of day' are treated as exploratory. Since no previous research on the effect exists, the effect sizes necessary to determinate the minimum sample size cannot be estimated meaningfully. The mixed within-between design required a sample size of 60 individuals to detect medium size effects. The actual sample size of 68 was expected to provide more than adequate power and redundancy in case some data had to be discarded.

Participants were drawn from a pool of participants who previously participated in different experiments at the Technical University Berlin or were recruited from the Humboldt University Philosophy Department. None of the individuals knew about the aims or procedure of the experiment. The applied sample size was probably too small to measure both the described effects and age or gender effects. To avoid unwanted influence from age effects, the sample selection was designed to include an age homogeneous group. Especially older participants (>50 years) could not take part in the experiment. This approach is loosely corresponding to the two younger groups (16-30 years, 31-45 years) used by Boyce (1973).

The actual achieved age distribution included participants between the age of 21 years and 47 years (mean 26.28, median 26.0, standard deviation 3.73). Gender effects were minimized selecting roughly equal shares of male and female participants (44.1% male, 55.9% female). Observations were made at different times of the day representing normal office working hours from 9 am to 7 pm (Table 5-4). The participants' chronotype was not known in advance, so all participants were randomly assigned to the experimental conditions. Participants were roughly equally distributed across all time intervals obtaining groups of comparable size. Definite or extreme morning or evening types were not regarded separately but are included in a 'simple chronotype' only distinguishing between morning types, neutral types and evening types. This reduces the number of investigated groups and maintains an adequate sample size for each group. Intermediate or neutral chronotypes make up for about half of the population (Schur, 1994). Thus, the achieved neutral types ratio of 45.3% approximately represents the population. The different chronotypes were roughly equally distributed across the times of day (Table 5-5).

Table 5-4: Sample characteristics

Sex	38 female			30 male	
Age	21-47 years, mean=26.28 years, median=26 years, SD=3.733				
Time of day	9 am - 11 am:	11 am - 1 pm:	1 pm - 3 pm:	3 pm - 5 pm:	5 pm - 7 pm:
	17 (25.0%)	14 (20.6%)	9 (13.2%)	12 (17.6%)	16 (23.5%)
Chronotype	morning types		neutral types		evening types
	19 (27.9%)		29 (42.6%)		20 (29.4%)

Table 5-5: Chronotype distribution over time

	9 am - 11 am	11 am - 1 pm	1 pm - 3 pm	3 pm - 5 pm	5 pm - 7 pm
Morning types	6 (8.8%)	3 (4.4%)	2 (2.9%)	3 (4.4%)	5 (7.4%)
Neutral types	7(10.3%)	5 (7.4%)	4 (5.9%)	6 (8.8%)	7 (10.3%)
Evening types	4 (5.9%)	6 (8.8%)	3 (4.4%)	3 (4.4%)	4 (5.9%)

5.3 Setting and Materials

The experimental setting of this research aims to completely separate independent variables, and therefore enable results valid for future lighting applications. The minimum photometric requirements for the setup arise from the previous sections on independent variables and are shown in Table 5-6.

Table 5-6: Photometric requirements for the test laboratory

Desktop illuminance	constant 500 lux, progressive local dimming
Wall and ceiling luminance	$L_{average}$=11-200 cd/m^2, progressive local dimming
Surrounding area illuminance	E_{sur}=100-300 lux, progressive local dimming
Luminance distribution	rendering of gradients, uniform distributions, areas of strong contrasts
Diffuser	blurring of transition areas between points of high luminances and areas of different dimming statuses

Experimental Setup

The experiments took place in a 4 m x 5 m x 2.8 m (width x length x height) cell office mock-up at the Lighting Technology Department at the Technical University Berlin. Walls and ceiling consisted of diffuse acrylic glass back-lit by 18 cm x 18 cm LED panels (Figure 5-2) that could be dimmed separately to generate the desired room surface luminance distribution. Each panel held 36 mid-power LEDs with a correlated color temperature of 3000 K according to the manufacturer. Measurements of the LEDs including the diffusing acrylic with a 'specbos 1211' spectrometer by 'Jeti Technical Instruments' in different areas of the room resulted in a correlated color temperature of 3065 K ± 32 K.

Six projectors inside the ceiling illuminated the horizontal work plane. Synchronization by a media server enabled the projection of a single conjoint image from all six projectors. The main aim of the setup was the strict separation of independent variables. Projecting a darker image counterbalanced light from walls or ceiling encountering the work plane. Local dimming of the LED panels compensated light from the projectors spilled on the walls. Figure 5-3 shows the six projector positions and the area covered by each projector. The correlated color temperatur of 4551 K of the projectors was measured with a 'specbos 1211' spectrometer by 'Jeti Technical Instruments'.

Generally, two methods of adjusting desktop luminances have been used in research: changing the illuminance on the desktop as used by Veitch and Newsham (2000) and Balder (1957) and changing the reflectance as used by van Ooyen *et al.* (1987). In this work, since a constant task area illuminance of 500 lux is desired, the material of the desktop is changed to achieve the desired luminances.

The setup was programmed using an e:cue lighting control engine by Traxon Technologies. Different scenes can be recorded and saved on a computer. The scenes can then be triggered using a tablet computer program specifically developed for lighting experiments. The application holds the used questionnaire and controls the timing of the experiment using a programmed sequence.

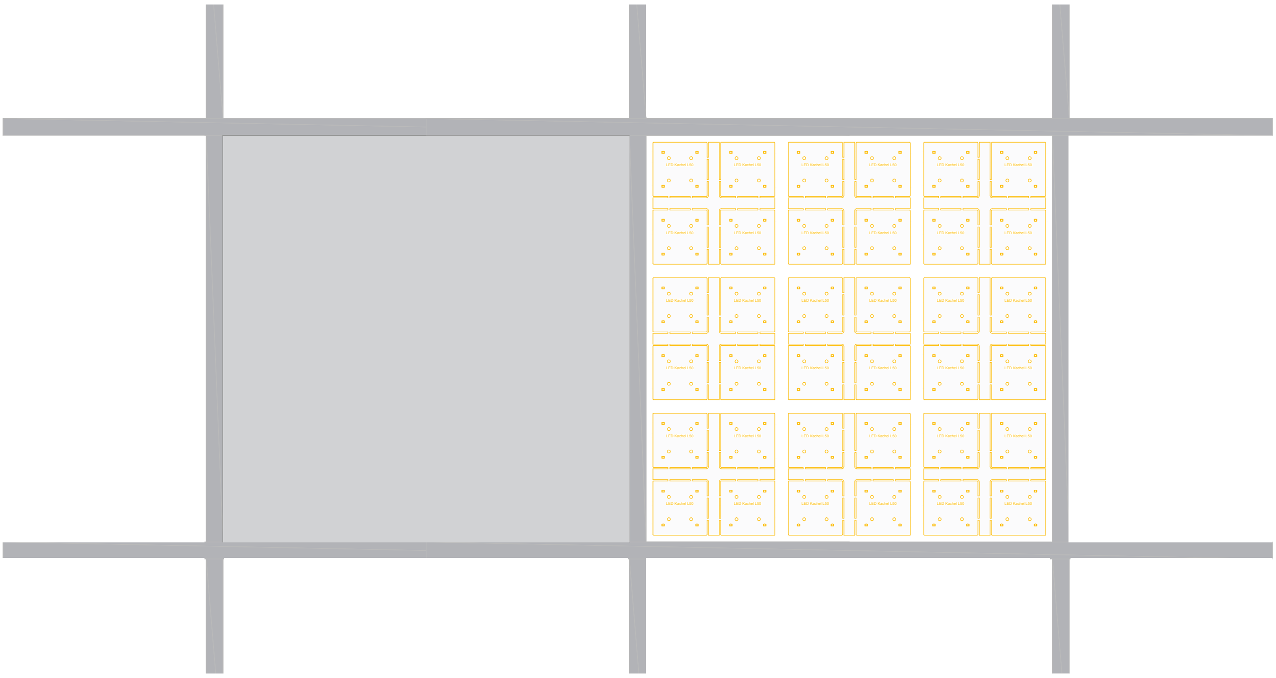

Figure 5-2: Ceiling element with acrylic (left) and LED-panels (right)

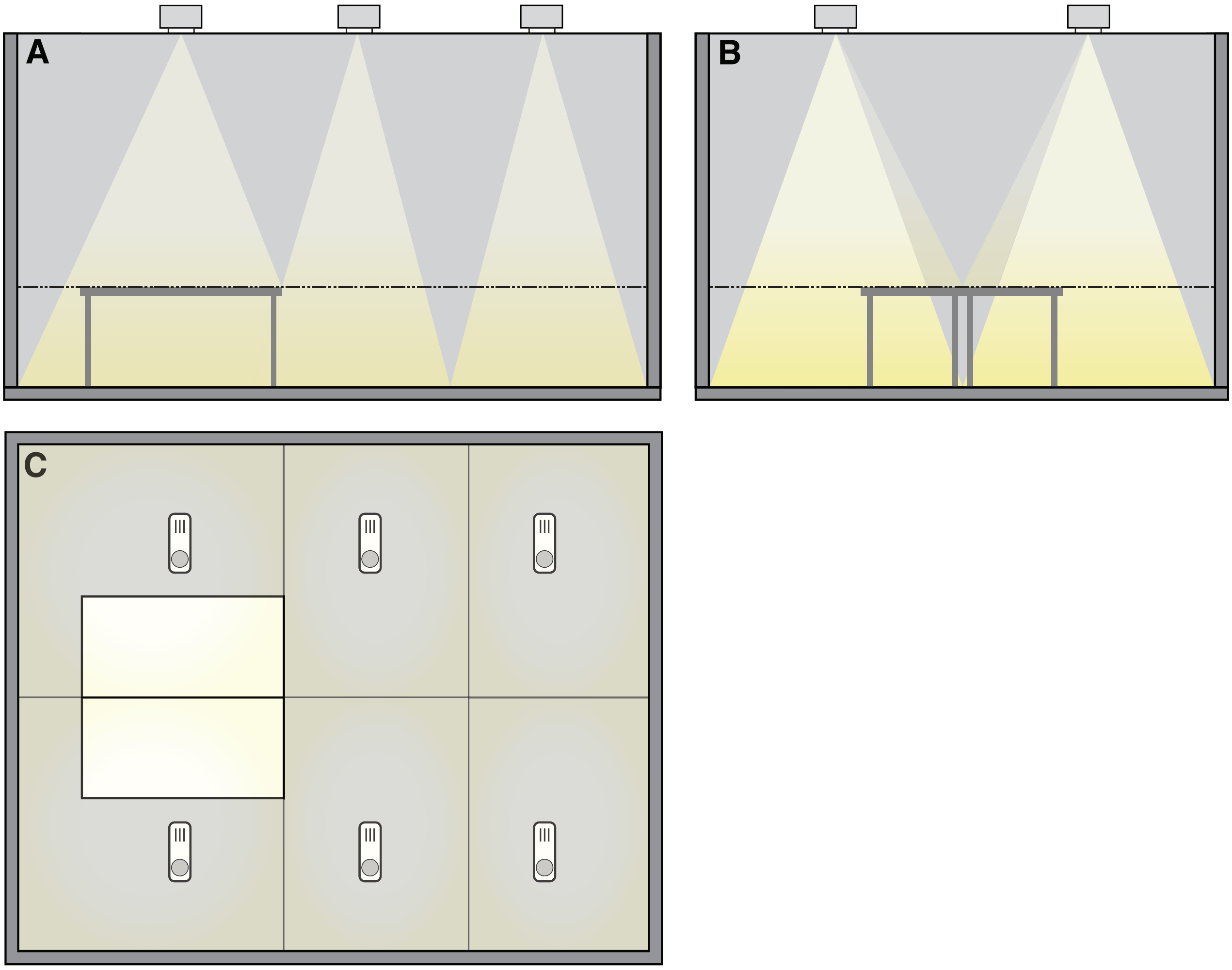

Figure 5-3: Projector positions and coverage. The dashed line marks the work plane. (A: Longitudinal Elevation, B: Cross Section, C: Ceiling Plan)

Illuminance Measurements

Horizontal illuminances were measured using a measuring grid specifically developed for the measurement of work-plane illuminances (Figure 5-4). The grid consists of 32 LMT and PRC Krochmann photometer heads (DIN 5032-7 error class A (DIN, 1985)). The photometers are arranged in 4 rows and 8 columns at 25 cm a pitch. The dimensions of the physical grid are 1.75 m x 0.75 m; the measurement reach of the photometers extends the effective measurement plane dimensions to 2 m x 1 m. According to EN 12464-1 (2011), horizontal illuminance measurements in a 5 m x 4 m surrounding area require a measurement grid size of 0.6 m; a 1.6 m x 1.6 m task area requires 0.27 m. The values were measured using an integration time of 200 ms. The unit measuring photo-currents and scanning the photometer heads was designed by Czibula & Grundmann GmbH. Table 5-7 shows the measured task and surrounding area illuminances for the scenes with desired mean surrounding area illuminances of 100 lux, 200 lux and 300 lux. All measurements were taken at a work plane height of 0.75 m.

Table 5-7: Illuminance Measurements

Planned surrounding area illuminance E_{Sur}	Range	Mean	Standard Deviation
E_{Sur}=100 lux	86.1 lux - 115.5 lux	101.9 lux	12.9
E_{Sur}=200 lux	181 lux - 208.7 lux	195.8 lux	13.0
E_{Sur}=300 lux	270.1 lux - 286.4 lux	274.5 lux	8.0
Planned task area illuminance	470.3 lux - 528.5 lux	500.9 lux	20.2

Note that the surrounding area illuminances for the 300 lux scenes do not quite reach the desired value. However, all measurements fell within 10% of the required mean illuminance, and were therefore considered sufficient. Illuminance on the work plane was mainly provided by projections with beams converging at floor level as described in the previous section about the experimental setup. Thus, there were areas of lower illuminances between the beams at work plane height. These 'gaps' can be seen in the measurements charts in Appendix C. Since participants were seated at the desk at all times, the gaps could not be experienced or seen during the experiment. The illumination on the floor appeared uniform. Illuminance at eye level was measured using an LMT luxmeter at a height of 1.2 m at the subject position. The photometer head was aligned with the participants' axis of vision. The results are shown in (Figure 5-5). More detailed results of illuminance measurements are available in Appendix C, measurement uncertainties are discussed in section 7.5 on page 90.

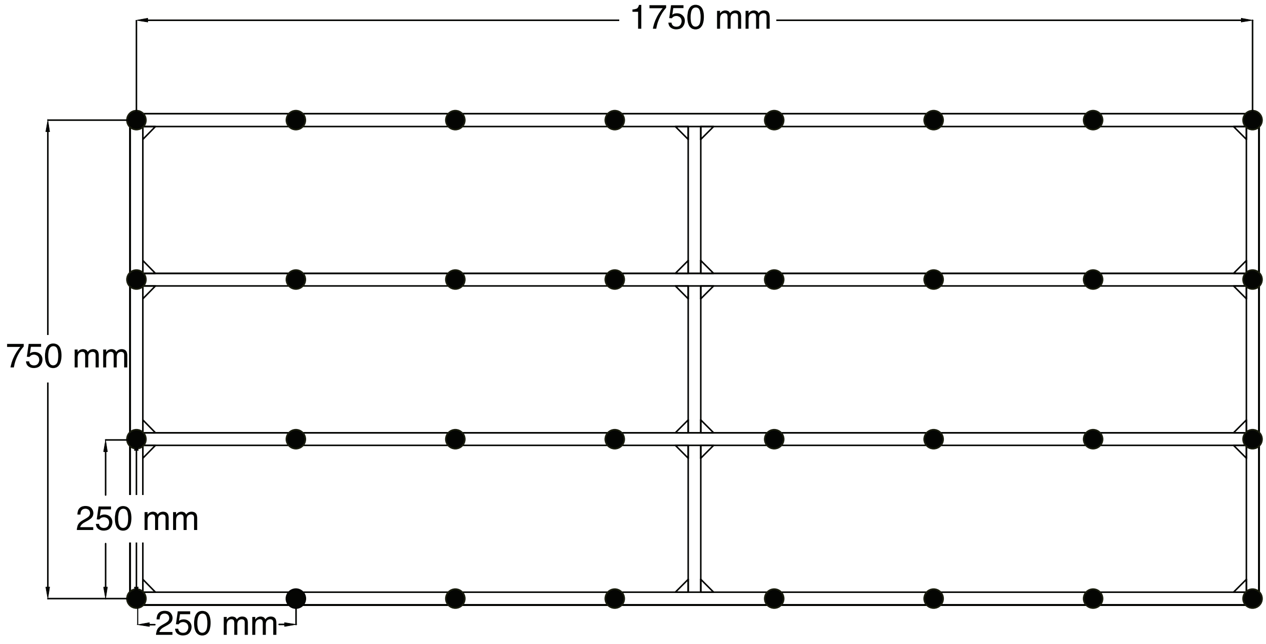

Figure 5-4: Measuring grid for horizontal illuminances

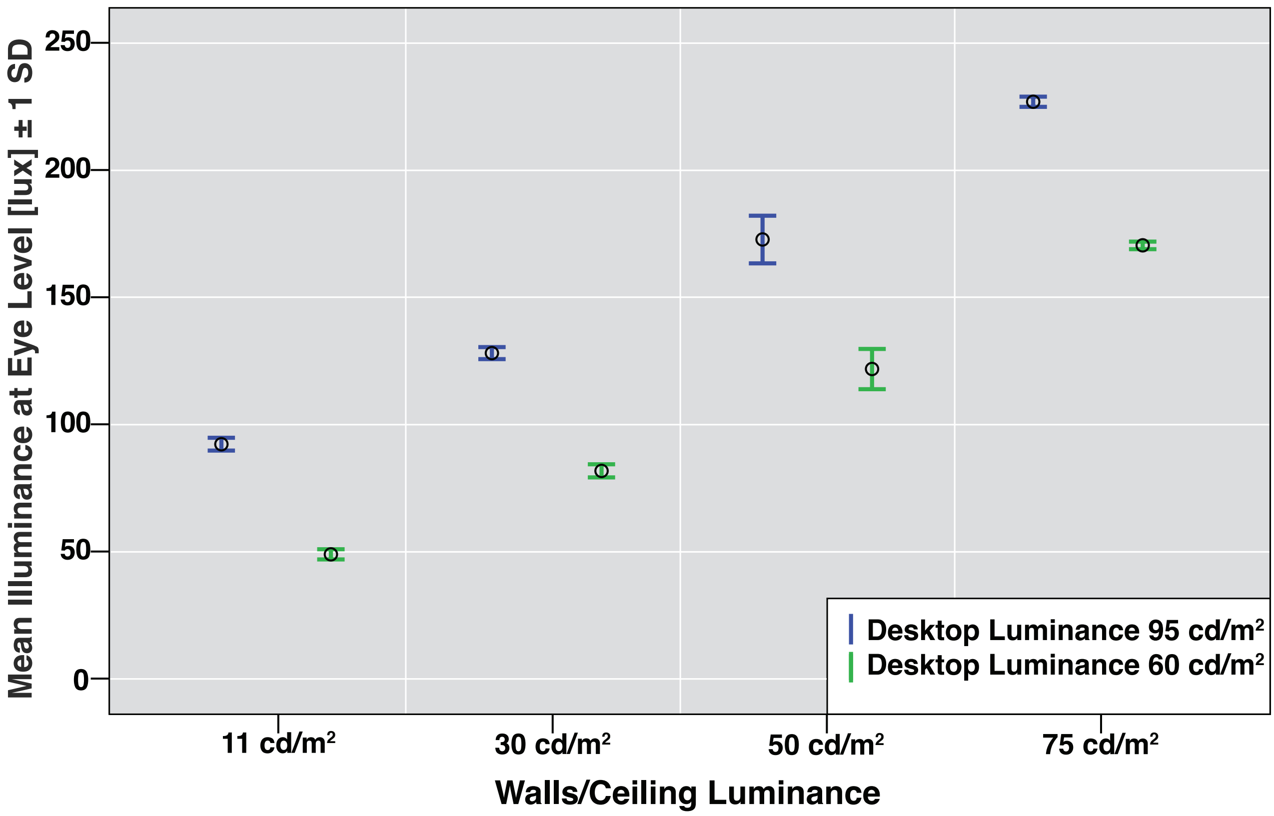

Figure 5-5: Illuminance at eye level for different walls/ceiling and desktop luminance combinations

Luminance Measurements

Luminances were measured using a Technoteam LMK 98 with a 4.5 mm fish-eye lens. The camera was mounted at the observer's position at eye height of 1.2 m, aligned along the axis of vision. The fish-eye lens covered approximately 180° horizontal and 180° vertical opening angle covering the visual field of the observer. Luminances were measured on different surfaces and areas throughout the visual field:

- whole visual field ($L_{\text{Visual Field}}$)
- facing wall, back wall and ceiling ($L_{\text{Walls/Ceiling}}$, does not include wall with windows)
- desktop (L_{Desktop})
- 40° horizontal band ($L_{40°}$)
- 60° horizontal band ($L_{60°}$)

Figure 5-6 (a) shows the measuring position and the opening angles of the two horizontal bands; Figure 5-6 (b) shows the areas covered by the measurement of walls/ceiling luminance and the luminance of the desktop. Table 5-8 shows the results of the luminance measurements.

Table 5-8: Luminance Measurements averaged across all desktop luminance and surrounding area illuminance conditions

$L_{\text{walls/ceiling}}$	Mean $L_{40°}$	SD $L_{40°}$	Mean $L_{60°}$	SD $L_{60°}$	Mean $L_{\text{Visual Field}}$	SD $L_{\text{Visual Field}}$
11 cd/m²	22.3 cd/m²	4.1	28.0 cd/m²	6.1	27.3 cd/m²	7.8
30 cd/m²	34.2 cd/m²	4.7	38.8 cd/m²	6.4	37.7 cd/m²	8.1
50 cd/m²	48.7 cd/m²	5.1	52.5 cd/m²	7.1	51.3 cd/m²	9.2
75 cd/m²	65.2 cd/m²	5.6	67.4 cd/m²	7.9	66.4 cd/m²	10.1

Figure 5-7 shows measurement results for selected areas and different wall and ceiling luminances. The upper band of the chart contains the measured luminances for the brighter desktop; luminances for the darker desktop are shown in the lower band. The error bars indicate one standard deviation. As desired, luminances in the visual field only depended slightly on changes in surrounding area illuminance ($\Delta L_{\text{Visual Field}}$ ~4% between E_{sur}=100 lux and E_{sur}=300 lux). More detailed results of luminance measurements can be found in Appendix C. Uncertainties of the measurement of photometric quantities is discussed in section 7.5 on page 90.

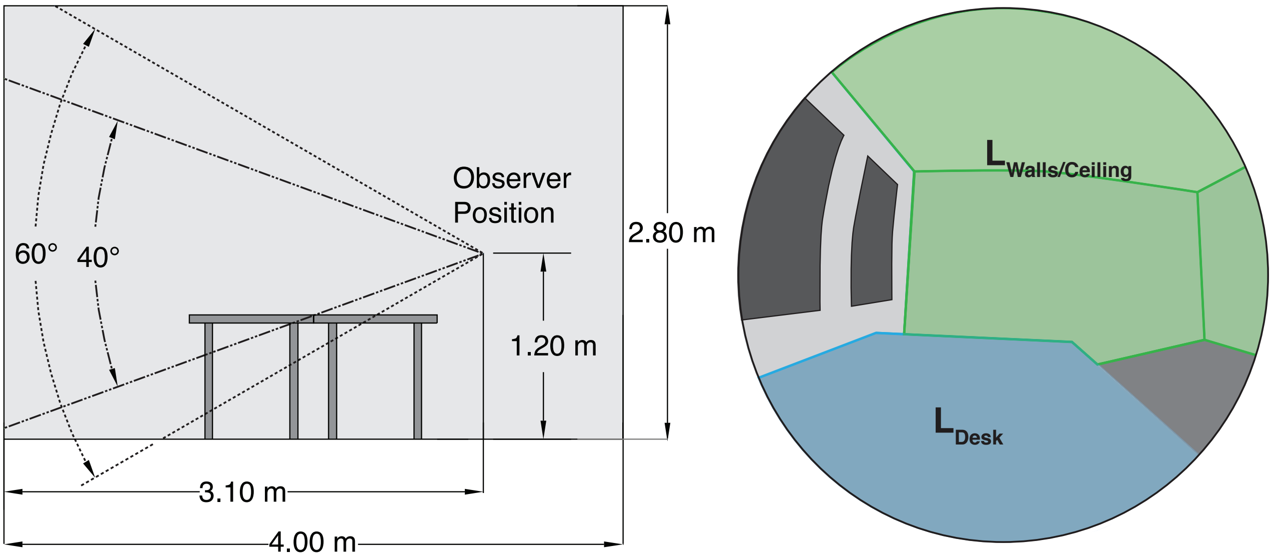

Figure 5-6: (a) Opening angles of 40° and 60° horizontal band
(b) areas of luminance measurements

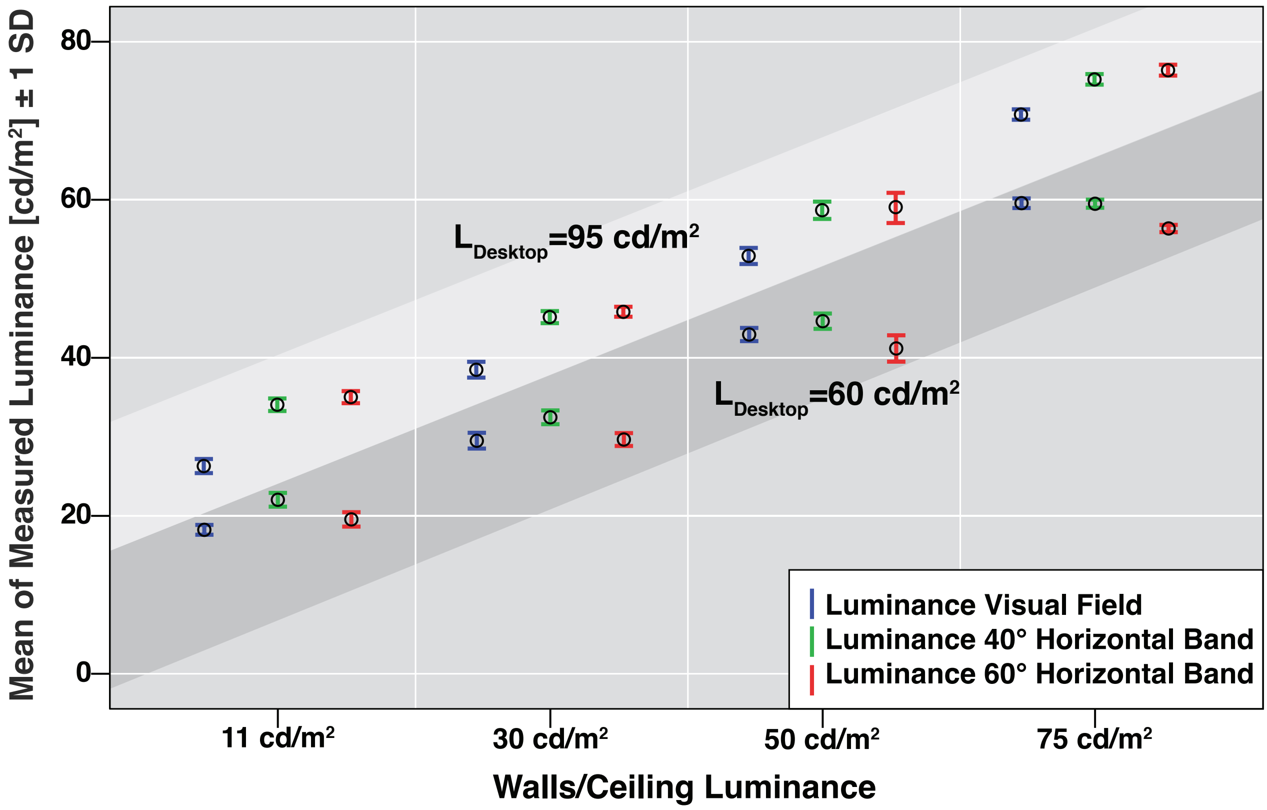

Figure 5-7: Measured luminances in different areas of the visual field for different walls/ceiling and desktop luminance

5.4 Experimental Procedure and Bias Control

Experiments including subjective responses to stimuli are unavoidably afflicted with various biases influencing the participants' judgement. Some confounding variables can be ruled out by the use of general countermeasures. In the experimental sessions in this work, a great effort was made to achieve nearly identical testing conditions for all participants. The experimental setup and procedure were held consistent throughout the experiment to avoid unwanted between subject factors. All participants were randomly assigned to experimental times throughout the day in order to evenly distribute or counterbalance possible daytime-effects. The time flow of each session stayed the same. All scenes were presented for the same time period controlled by the questionnaire software.

About one hour before the first participant of the day started with the experiment, the lighting setup was activated to achieve thermal equilibrium for all LED-based components and a stabilized light output for the projector lamps.

At the beginning of each session, the participants entered the laboratory and were immediately led into the experimental setup. Walking through the projector beams may cause discomfort glare and provide unwanted information about the installation. Thus, a diffuse entrance scene was presented to ensure that the participants did not see the projector beams when entering the setup. The beams were also not visible from the subject's final position during the experiment.

All participants filled in the Morningness-Eveningness-Questionnaire described in section 5.1 on page 38 to determine their chronotype. To prevent a possible research bias or experimenter-expectancy effect, the participants read all further introductions and explanations about the course of the experiment on a tablet computer positioned on the table in front of them.

In the beginning of the experiment, participants filled in a set of demographic questions on sex, age and pre-knowledge about lighting.

Biases related to the experimental procedure were also considered. The 'decision tree' from E. C. Poulton's 'Bias in Quantifying Judgements' (1989) was used to avoid or to at least quantify as many of these biases as possible (Figure 5-8).

To set an anchor stimulus and to define the range of the experiment the first two scenes (Anchor Scene 'high' and 'low')in the sequence showed the brightest ($L_{\text{Walls/Ceiling}}$=75 cd/m^2, E_{Sur}=300 lux) and darkest ($L_{\text{Walls/Ceiling}}$=11 cd/m^2, E_{Sur}=100 lux) overall conditions. A known range of stimuli and alternating orientations of scale labels prevents a stimulus contraction bias. A presentation of an anchor response-to-stimulus range before the actual start of the experiment minimizes response contraction bias. The two anchor scenes were presented in randomized order to avoid a possible sequential contraction bias for the first scene. Since the data of these scenes was not used in the evaluation, it also gave the participants some time to get used to the procedure and the questionnaire on the tablet computer. Figure 5-9 shows the overall sequence of both experimental sessions.

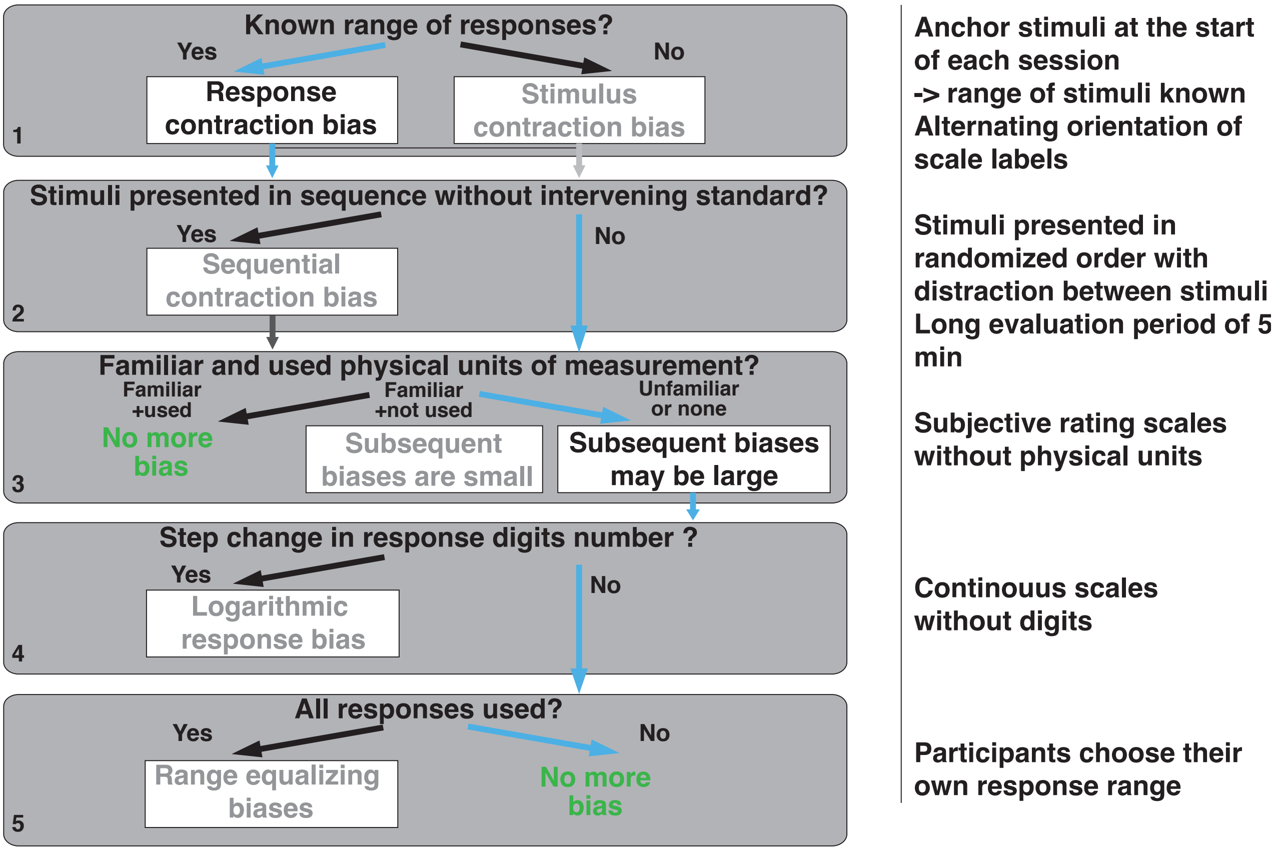

Figure 5-8: Bias decision tree, (cf. Poulton, 1989). The blue arrows indicate the course followed in this work.

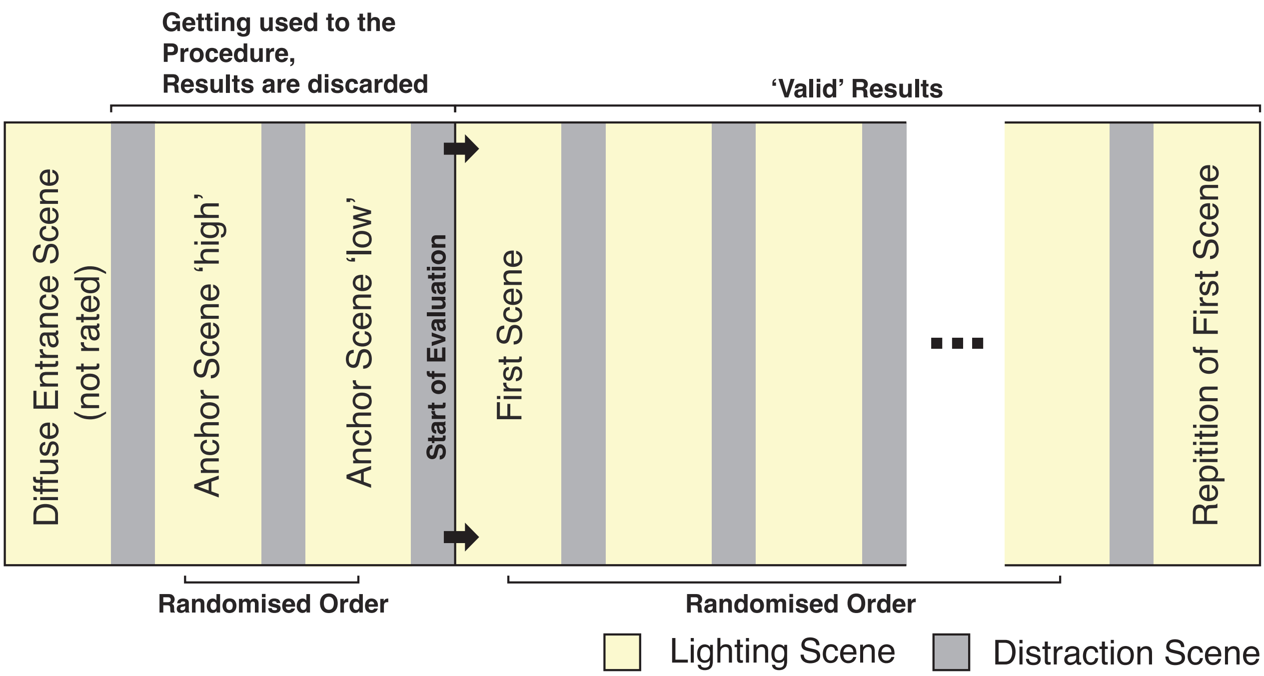

Figure 5-9: Sequence of experimental session I and II

After the familiarization phase, the actual experiment started with a randomly assigned first scene. The same scene was repeated at the end of each session to explore possible learning effects and the participants' consistency in their responses. In between, all other scenes of the experimental design were presented exactly once. Because a comparison with the previously observed scene cannot be ruled out with certainty, the order of scenes was randomized to avoid a possible order bias. By randomizing the order of scenes, the error caused by an order bias, although obviously still present, is randomly distributed across all judgements. Additionally, after each rated scene, a short distraction scene was presented for 30 seconds to avoid a sequential contraction bias (Poulton 1989). Each distraction scene was identical, and presented lower wall and ceiling luminances than all other scenes. Thus, if a sequential contraction bias is still present, one can assume that it is unidirectional.

Usually, two different images or judgements form the appearance of a scene. The 'impact image' in Hutchings total appearance concept (1995) is commonly referred to as first impression. It is a mental concept that can develop instantly (cf. Gregory, 1971; Schierz, 2004). After some time, the appearance of a scene is completed by the 'sensory image', which contains affective and intellectual components as well as basic stimulus responses (cf. CIE, 2006). The latter image lasts longer, and contributes more to scene appraisal with an increasing duration of stay. Hence, the sensory image is a better indicator for office lighting appraisal, as office workers spend most of their working hours on-site. How long the impact image lasts exactly is unknown. In this work, participants observed each scene for five minutes to avoid judgements solely based on first impressions (Figure 5-10).

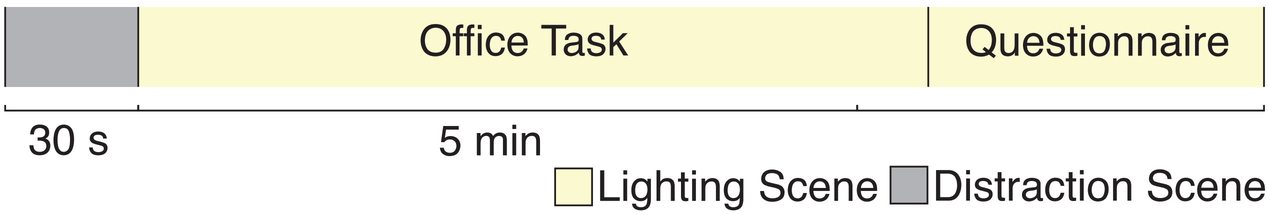

Figure 5-10: Time-sequence of a presented scene

Increased exposure to a scene prior to actual judgement further helps to prevent a comparison of consecutive scenes, and thereby a sequential contraction bias. In an actual office, the appraisal of the space only consists of first impressions and long term evaluation, since comparisons between offices are typically not possible. The time-sequence design used here is an attempt to allow participants to judge each scene independently.

During the five minute presentation of each lighting scene the participants were asked to perform simple horizontal reading and writing tasks, including reading a daily newspaper, working in puzzle books and completing a d2-test of attention. The projectors illuminating the task area caused harsh shadows on the desktop. However, this was the case for all presented scenes and thus a constant distraction. Participants were free to choose, which task to perform and when. Performance or quantities regarding the task were not in the scope of this work, and therefore not included in the evaluation. After the five-minute period, the tablet computer presented the questionnaire with the room appearance scales. These scales are discussed in greater detail in section 5.1, pp. 40-41. Regarding bias control, a logarithmic contraction can be ruled out since the semantic differential scales did not show any digits. Range equalizing biases are reduced by withholding fixed stimulus-response pairs, and thus leaving the range of responses entirely to the observer. Completing the questionnaire required about one minute. After completion of all questions, the software automatically switched to the distraction scene, and eventually to the next lighting scene.

5.5 Results

In this work notations from the publication manual of the American Psychological Association, 6th edition (2012) are used for all statistical reports.

Initially, the gathered set of data was inspected regarding consistency of responses and possible outliers to be able to achieve meaningful results. First scenes and repeated scenes were compared using a scatter plot (s. Appendix A). The answers are roughly located around the reference line of $y=x$, indicating a good consistency between equal scenes. Therefore, the arithmetic mean of responses to the first and repeated scenes was used for the following statistical procedure.

Outliers were explored with boxplots (Appendix A). There were 33 outliers representing about 0.63% of the cases. It was decided to keep all data.

The principal component analysis (Appendix A, pp. 116-119) resulted in the expected components 'visual lightness' and 'visual attractiveness' also found by Veitch *et al.* (2010b) as a measure for the visual appearance of the space.

Scaling was discussed in section 5.1, p.41 in greater detail. All Scales are assumed to be continuous and provide interval level. The assumption of normality was discussed for the principal component analysis in Appendix A; multivariate normality was assumed.

Sample sizes are relatively large. Thus, a multivariate analysis of variance is robust against a violation of the assumption of homogeneity of variances and covariances (Field, 2009). The conducted PCA used the orthogonal Varimax rotation in which the two components are geometrically interpreted in a two-dimensional space. Since the axes of the resulting coordinate system are orthogonal and assumed to contain normally distributed observations, the independence of observations can be assumed.

Statistics and Data Analysis

A multivariate analysis of variance (MANOVA) was conducted for the 4 x 3 x 2 x 5 x 3 mixed within-between design (walls/ceiling luminance (4 levels) x surrounding area illuminance (3 levels) x desktop luminance (2 levels) x time of day (5 levels) x simple chronotype (3 levels)) to test for an overall difference across outcomes. A detailed description of null hypotheses and alternative hypotheses for the main test and the pre-planned comparisons can be found in Appendix B. Only significant main effects and two-way interactions are explored, univariate tests are only interpreted for significant main tests.

There was a significant main effect of walls/ceiling luminance $L_{\text{walls/ceiling}}$ on room appearance, Wilks' $\Lambda=0.19$, $F(6,33)=23.43$, $p<0.001$. The estimated marginal means (EMM) are shown in Table 5-9.

Table 5-9: Estimated marginal means of walls/ceiling luminance

Measure	$L_{\text{walls/ceiling}}$	EMM	SE
visual lightness	11 cd/m²	2.30	0.13
	30 cd/m²	3.37	0.17
	50 cd/m²	4.30	0.15
	75 cd/m²	4.67	0.14
visual attractiveness	11 cd/m²	2.13	0.13
	30 cd/m²	3.56	0.17
	50 cd/m²	4.59	0.14
	75 cd/m²	5.02	0.14

For the pre-planned comparisons, Cohen's *d* was calculated to determine the effect size using equation (13) provided in (Rosnow & Rosenthal, 2003, p.224). According to Cohen, d=0.2 defines a small effect, d=0.5 a medium effect and d=0.8 a large effect (cf. Cohen, 1988, pp. 284-287).

Repeated contrasts revealed that increasing walls/ceiling luminance from 11 cd/m^2 to 30 cd/m^2 ($F(1,38)=40.64$, $p<0.001$, Cohen's d= 1.03), from 30 cd/m^2 to 50 cd/m^2 ($F(1,38)=34.04$, $p<0.001$, Cohen's d=0.95) and from 50 cd/m^2 to 75 cd/m^2 ($F(1,38)=22.12$, $p<0.001$, Cohen's d=0.76) significantly increased the perception of visual lightness. Repeated contrasts also revealed that increasing walls/ceiling luminance from 11 cd/m^2 to 30 cd/m^2 ($F(1,38)=61.98$, $p<0.001$, Cohen's d=1.28), from 30 cd/m^2 to 50 cd/m^2 ($F(1,38)=38.94.55$, $p<0.001$, Cohen's d=1.00) and from 50 cd/m^2 to 75 cd/m^2 ($F(1,38)=19.73$, $p<0.001$, Cohen's d=0.72) significantly increased the perception of visual attractiveness.

There was a significant main effect of surrounding area illuminance E_{sur} on room appearance, Wilks' Λ=0.72, $F(4,35)=3.37$, p=0.02. The estimated marginal means (EMM) and standard errors of the mean (SE) are shown in Table 5-10.

Table 5-10: Estimated marginal means of surrounding area illuminance

Measure	E_{sur}	EMM	SE
visual lightness	100 lux	3.49	0.11
	200 lux	3.64	0.12
	300 lux	3.85	0.11
visual attractiveness	100 lux	3.73	0.10
	200 lux	3.81	0.10
	300 lux	3.92	0.11

Planned orthogonal Helmert contrasts revealed that an increase of surrounding area illuminance from 100 lux to a higher level (200 lux or 300 lux) significantly enhanced the appraisal of visual lightness, $F(1,38)=9.52$, p=0.004, Cohen's d=0.5. Visual lightness also increased significantly when surrounding area illuminance changed from 200 lux to 300 lux, $F(1,38)=4.84$, Cohen's d=0.36. Planned comparisons on the effect of surrounding area illuminance on visual attractiveness were all non-significant (Cohen's d=0.28 for 100 lux vs. higher illuminances, and Cohen's d=0.22 for 200 lux vs. 300 lux) .

There was no significant interaction effect between surrounding area illuminance and walls/ceiling luminance on room appearance.

Figure 5-11 and Figure 5-12 show the results of experiment I. As expected from the pre-planned comparisons, visual lightness is enhanced by increasing luminances and surrounding area illuminances. Changes in luminance have a much greater impact on visual lightness than do changes in illuminance. The statistically significant contrast for visual lightness between the trials with 100 lux surrounding area illuminance and the trials with higher illuminance in surrounding areas can be observed in the graph. However, the changes in the participants' ratings were relatively small ($|\Delta_{Median}|=0.2$) as compared to the differences in ratings related to changes in wall/ceiling luminance. Also in accordance with the pre-planned comparisons, changes in surrounding area illuminance do not have a noticeable impact on visual attractiveness.

The graphs also clearly indicate an increase in the perception of visual lightness and visual attractiveness with increasing luminance of walls and ceiling. For both factors, the improvement of visual appearance due to an increase of walls and ceiling luminance from 11 cd/m^2 to 30 cd/m^2 at the 100 lux level exceeds possible impairments resulting from a decreased surrounding area illuminance from 300 lux to 100 lux.

The effect of different wall and ceiling luminances does not visibly change at different surrounding area illuminances. This was statistically confirmed by the non-significant luminance-illuminance interaction.

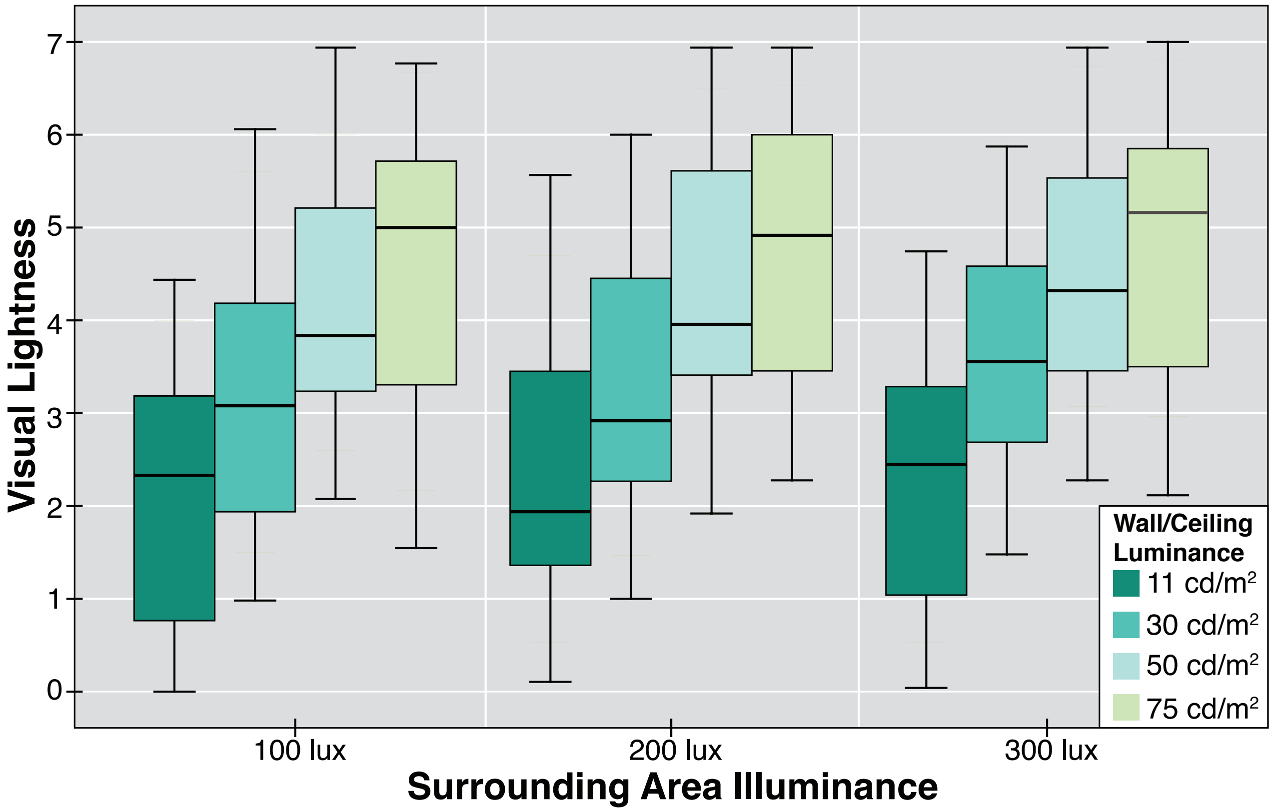

Figure 5-11: Boxplot of the effect of E_{sur} and $L_{walls/ceiling}$ on visual lightness

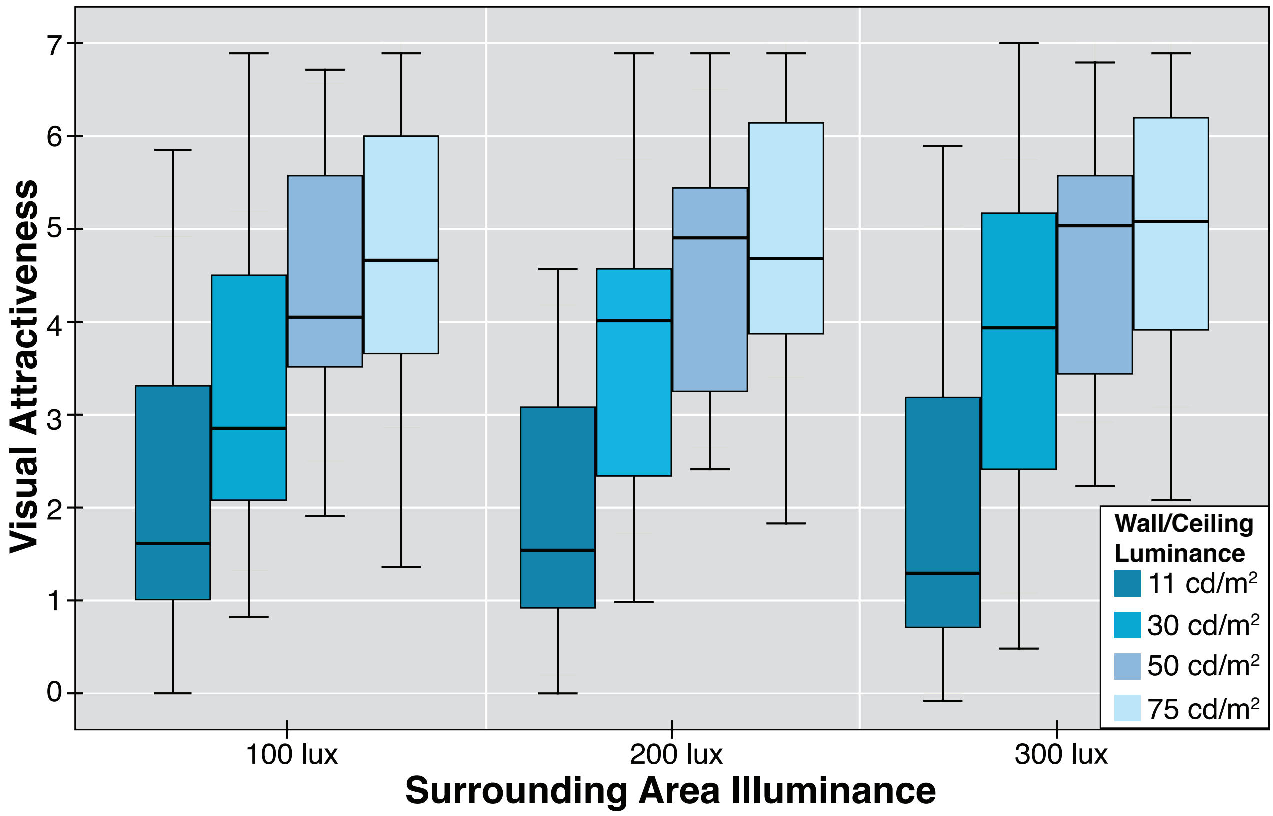

Figure 5-12: Boxplot of the effect of E_{sur} and $L_{walls/ceiling}$ on visual attractiveness

There was no significant main effect of desktop luminance on room appearance, $p>0.05$.

There was a significant interaction effect between desktop luminance and surrounding area illuminance on room appearance, Wilks' $\Lambda=0.59$, $F(4,35)=6.15$, $p=0.001$. The estimated marginal means (EMM) and standard errors of the mean (SE) are shown in Table 5-11.

Table 5-11: Estimated marginal means of the interaction between desktop luminance and surrounding area illuminance

Measure	$L_{Desktop}$	E_{sur}	EMM	SE
visual lightness	60 cd/m²	100 lux	3.32	0.16
		200 lux	3.67	0.17
		300 lux	3.96	0.15
	95 cd/m²	100 lux	3.66	0.16
		200 lux	3.62	0.17
		300 lux	3.76	0.15
visual attractiveness	60 cd/m²	100 lux	3.73	0.14
		200 lux	3.83	0.15
		300 lux	3.81	0.16
	95 cd/m²	100 lux	3.73	0.14
		200 lux	3.80	0.15
		300 lux	4.05	0.16

The interaction was explored using plots of estimated marginal means (Figure 5-13 and Figure 5-14). The dashed lines do not suggest a trend, but simply connect observations belonging to the same desktop luminance level.

Deviations in the visual lightness graph as a function of desktop luminance exist but are very small. Visual lightness was affected in a way that at 100 lux surrounding area illuminance the brighter desktop was rated slightly better ($|\Delta_{Mean}|=0.34$ rating units). At a surrounding area illuminance of 200 lux, scenes with both desktop luminances were almost rated equally. At 300 lux surrounding area illuminance the scene with a desktop luminance of 60 cd/m² was rated slightly higher by $|\Delta_{Mean}|=0.20$ rating units. Calculation of effect size from EMM indicated a medium size effect with Cohen's *d (*60 cd/m² vs. 95 cd/m², 100 lux vs. 300 lux)=0.42.

For visual attractiveness the brighter desktop was nearly equal for surrounding area illuminances of 100 lux and 200 lux. For a surrounding area illuminance of 300 lux the higher desktop luminance appeared slightly more attractive by about $|\Delta_{Mean}|=0.22$ rating units. The effect size was small with Cohen's *d (*60 cd/m² vs. 95 cd/m², 100 lux vs. 300 lux)=0.14.

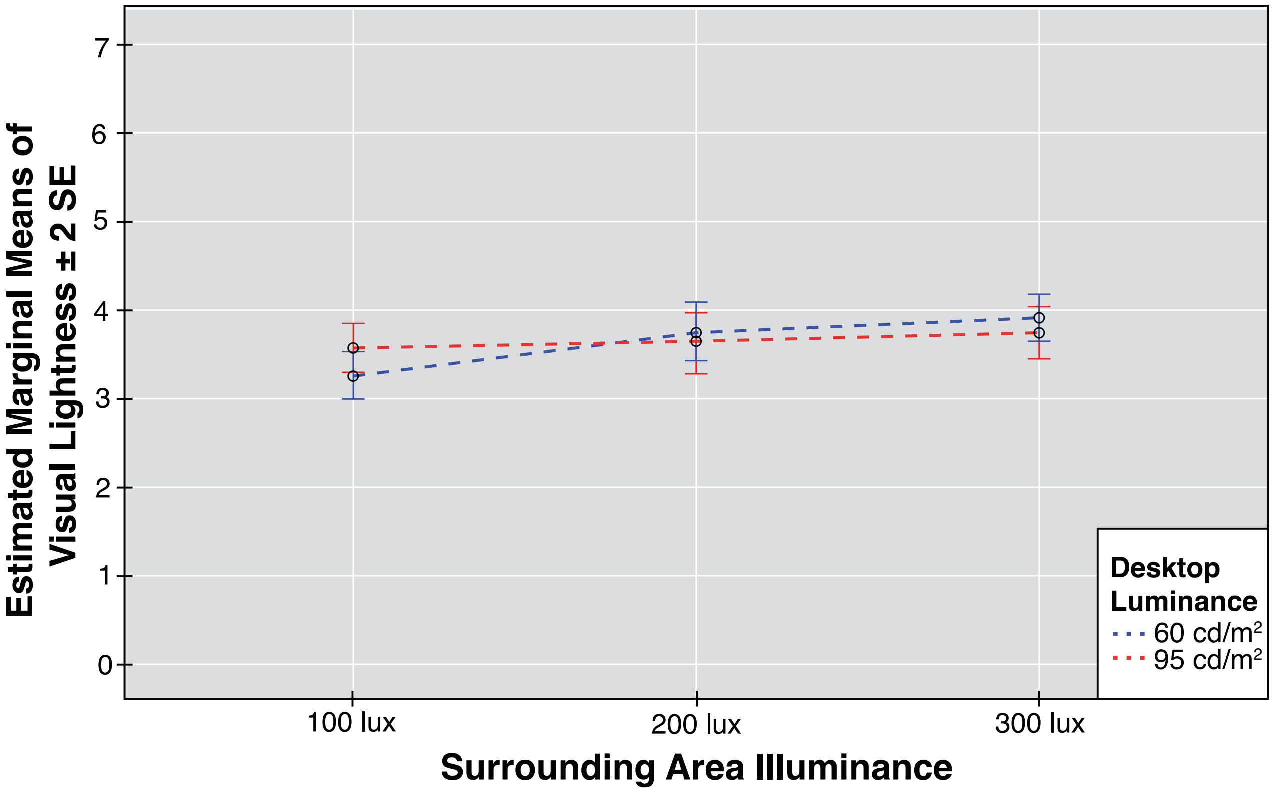

Figure 5-13: Estimated marginal means of visual lightness for the interaction between desktop luminance and surrounding area illuminance

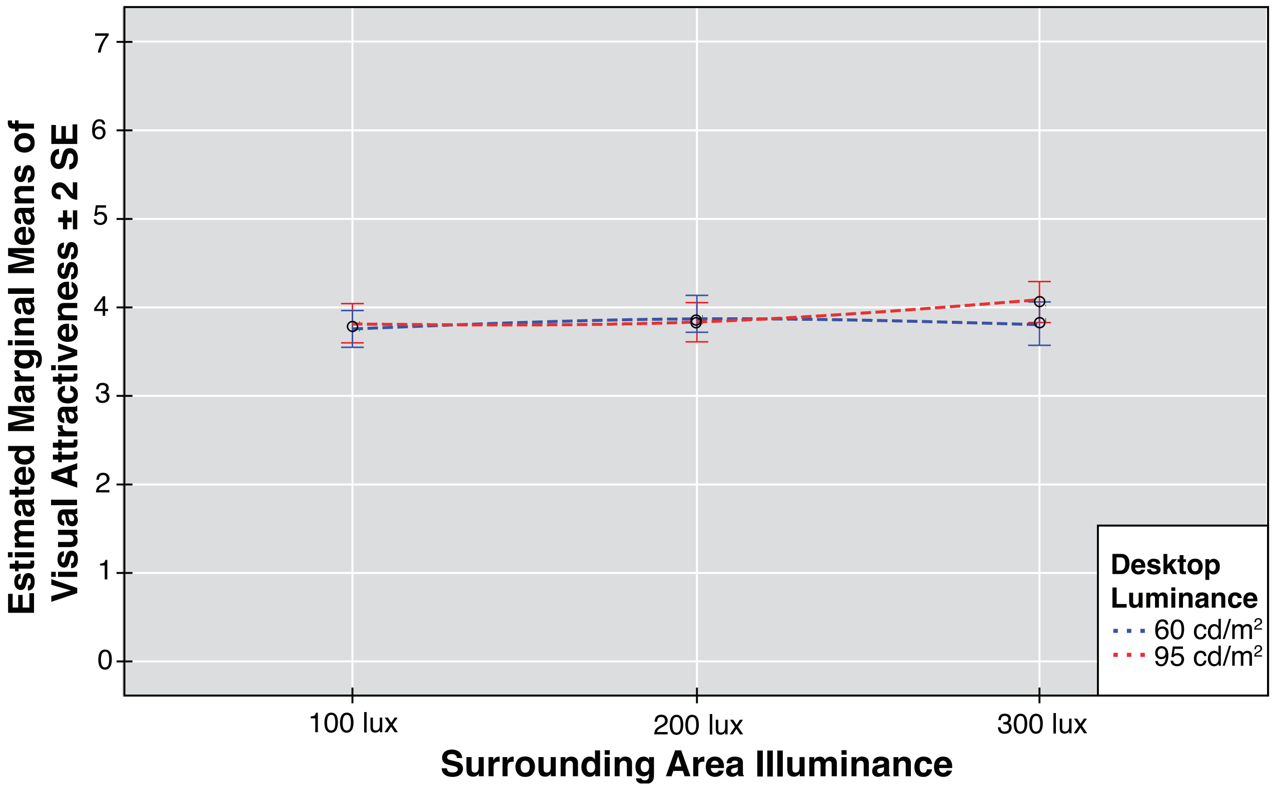

Figure 5-14: Estimated marginal means of visual attractiveness for the interaction between desktop luminance and surrounding area illuminance

There was also a significant interaction effect between desktop luminance and wall/ceiling luminance on room appearance, Wilks' Λ=0.66, $F(6,33)$=2.78, p=0.027. The estimated marginal means (EMM) and standard errors of the mean (SE) are shown in Table 5-12.

Table 5-12: Estimated marginal means of the interaction between desktop luminance and walls/ceiling luminance

Measure	$L_{Desktop}$	E_{sur}	EMM	SE
visual lightness	60 cd/m²	11 cd/m²	2.00	0.18
		30 cd/m²	3.31	0.23
		50 cd/m²	4.49	0.20
		75 cd/m²	4.79	0.19
	95 cd/m²	11 cd/m²	2.61	0.19
		30 cd/m²	3.42	0.24
		50 cd/m²	4.11	0.21
		75 cd/m²	4.56	0.20
visual attractiveness	60 cd/m²	11 cd/m²	1.68	0.20
		30 cd/m²	3.36	0.23
		50 cd/m²	4.76	0.19
		75 cd/m²	5.37	0.20
	95 cd/m²	11 cd/m²	2.57	0.20
		30 cd/m²	3.76	0.24
		50 cd/m²	4.43	0.20
		75 cd/m²	4.67	0.20

The interaction was explored using estimated marginal means (Figure 5-15 and Figure 5-16). Again, the dashed lines do not suggest a trend but connect observations belonging to the same desktop luminance level.

Both charts show a similar course where the brighter desktop is rated higher for lower background luminances ($|\Delta_{Mean}|$=0.61 rating units for visual lightness, $|\Delta_{Mean}|$=0.89 rating units for visual attractiveness). At a walls/ceiling luminances of 30 cd/m², the ratings of the two desktops are about equal, for higher walls/ceiling luminances, the darker desktop is rated higher ($|\Delta_{Mean}|$=0.23 rating units for visual lightness, $|\Delta_{Mean}|$=0.7 rating units for visual attractiveness). Effect sizes were calculated from EMM. Cohen's d (60 cd/m² vs. 95 cd/m², 11 cd/m² vs. 75 cd/m²)=0.54 for visual lightness indicated a medium effect while Cohen's d (60 cd/m² vs. 95 cd/m², 11 cd/m² vs. 75 cd/m²)=0.96 for visual attractiveness showed a large effect.

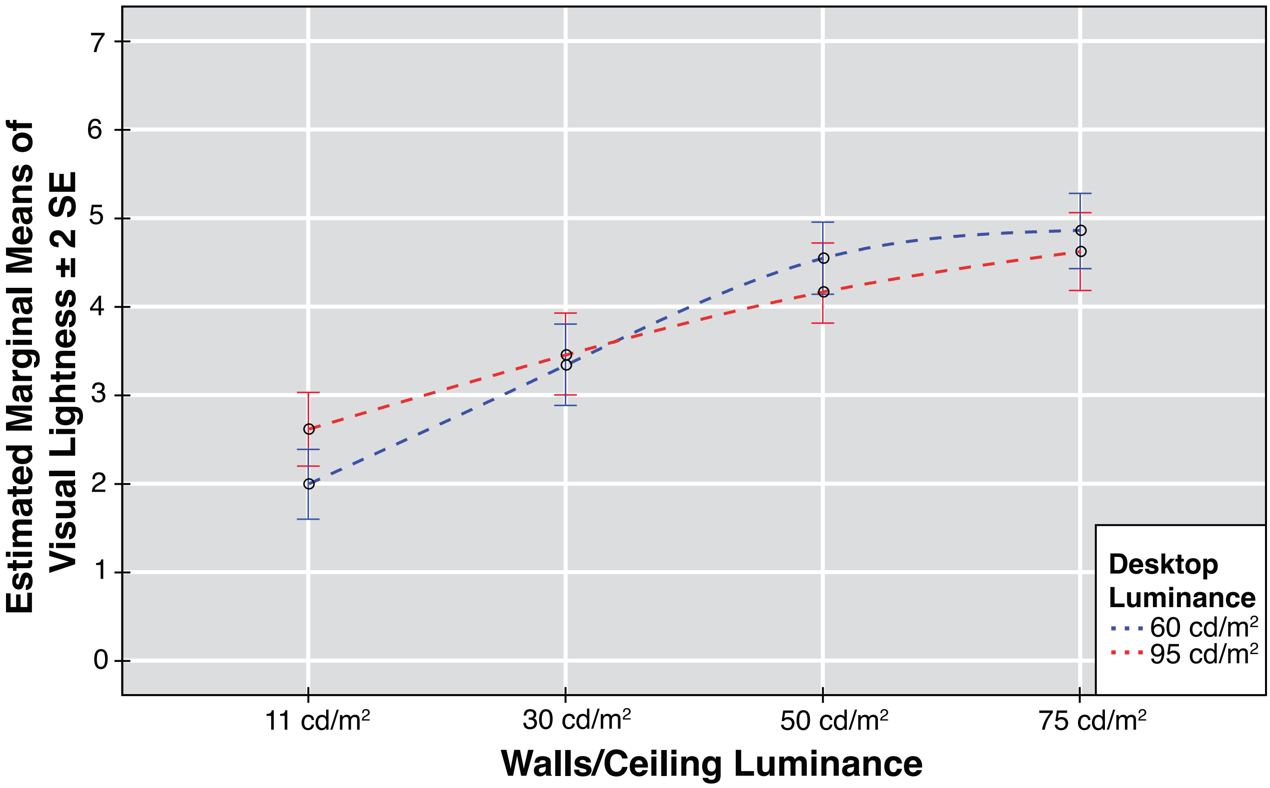

Figure 5-15: Estimated marginal means of visual lightness for the interaction between walls/ceiling luminance*desktop luminance interaction

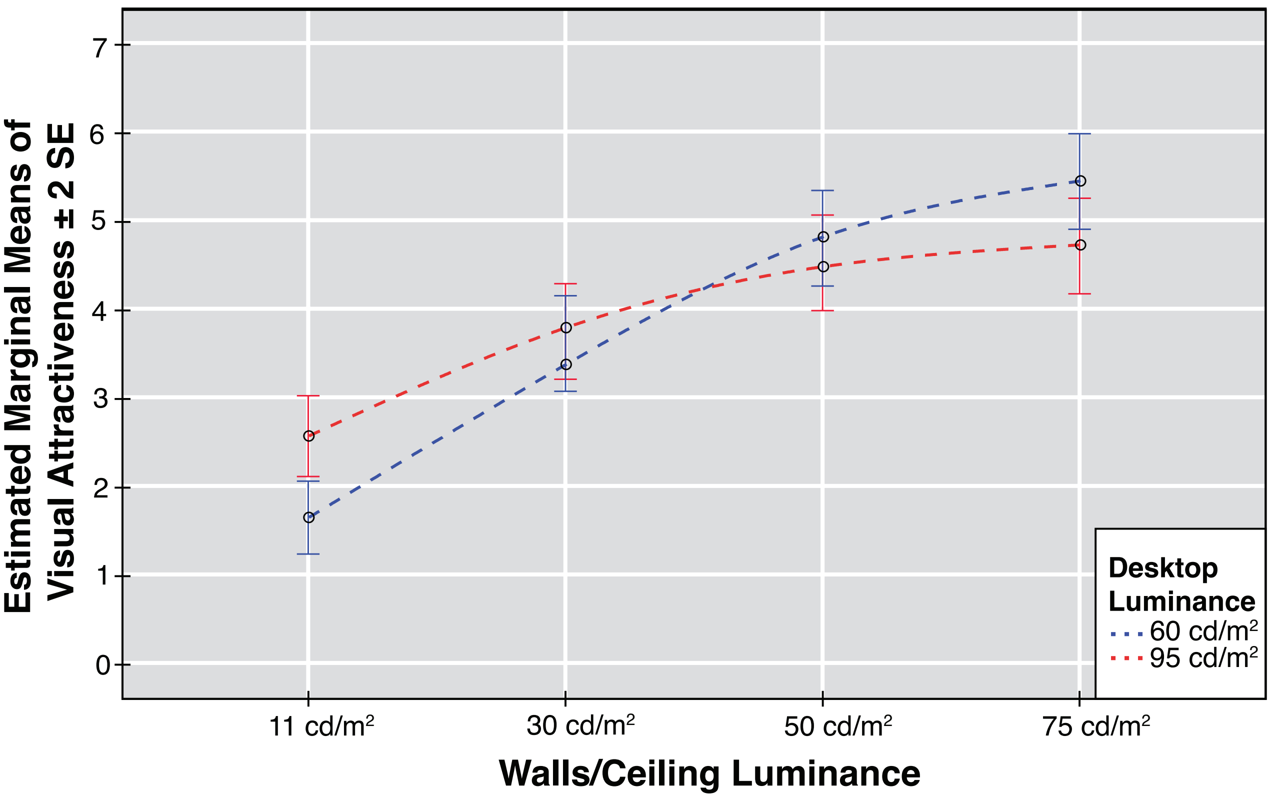

Figure 5-16: Estimated marginal means of visual attractiveness for the walls/ceiling luminance*desktop luminance interaction

There was no significant main effect of the observers' chronotype or the time of day on room appearance, $p>0.05$.

However, there was a significant interaction effect between a person's chronotype and the time of presentation, Wilks' $\Lambda=0.51$, $F(16,74)=1.87$, $p=0.037$. Effect sizes were calculated from descriptive statistics using equation (8.2.1) provided in (Cohen, 1988, p.275) resulting in Cohen's *f*. For a better comparability with other effect sizes used in this work, Cohen's *f* was then converted to Cohen's *d* using equation (8.2.10) from the same book (Cohen, 1988, p.278). Effect sizes for the univariate main effects were large with Cohen's $d=1.16$ for visual lightness and Cohen's $d=1.24$ for visual attractiveness. Descriptive statistics are presented in Table 5-13 showing means and standard deviations (SD).

Table 5-13: Descriptives of the interaction between chronotype and time of day

Simple chronotype	Time of day	Mean visual lightness	SD visual lightness	Mean visual attractiveness	SD visual attractiveness
morning types	9am-11am	4.22	1.26	4.22	1.26
	11am-1pm	3.70	1.61	3.70	1.61
	1pm-3pm	3.36	1.17	3.85	1.30
	3pm-5pm	3.19	0.93	3.42	0.83
	5pm-7pm	2.94	1.19	2.31	1.37
neutral types	9am-11am	3.65	1.57	3.88	1.78
	11am-1pm	4.40	1.09	4.32	1.01
	1pm-3pm	4.06	1.15	4.35	1.32
	3pm-5pm	3.96	1.10	4.22	1.02
	5pm-7pm	3.82	1.22	3.73	1.31
evening types	9am-11am	2.76	0.98	3.33	0.73
	11am-1pm	3.59	1.54	3.57	1.42
	1pm-3pm	3.33	1.63	3.47	1.58
	3pm-5pm	3.91	1.29	4.05	1.27
	5pm-7pm	3.61	0.97	4.50	1.06

The effects of the interaction are illustrated with boxplots (s. Figure 5-17 and Figure 5-18). Effect sizes for comparisons between two groups with $df=1$ are calculated from descriptive statistics using equation (4) from (Rosnow & Rosenthal, 2003, p.223).

Morning types rated visual lightness the highest in the morning between 9 am and 11 am; visual lightness ratings decreased over time to the lowest ratings in the evening between 5 pm and 7 pm, Cohen's *d* (morning types: 9am-11am vs. 5pm-7pm)=1.04. Neutral types showed no visible differences in ratings over time. Evening types' ratings were lowest in the morning and increased in the evening, Cohen's *d* (evening types: 9am-11am vs. 5pm-7pm)=0.87.

Similar trends were observed visual attractiveness ratings. For morning types, ratings in the morning from 9 am to 11 am were significantly higher than in the evening from 5 pm to 7 pm, Cohen's *d* (morning types: 9am-11am vs. 5pm-7pm)=1.46. Also for visual attractiveness, neutral types showed no interpretable difference in ratings over time. Evening types, analogous to visual lightness, rated visual attractiveness lower in the morning than in the evening, Cohen's *d* (evening types: 9am-11am vs. 5pm-7pm)=1.28.

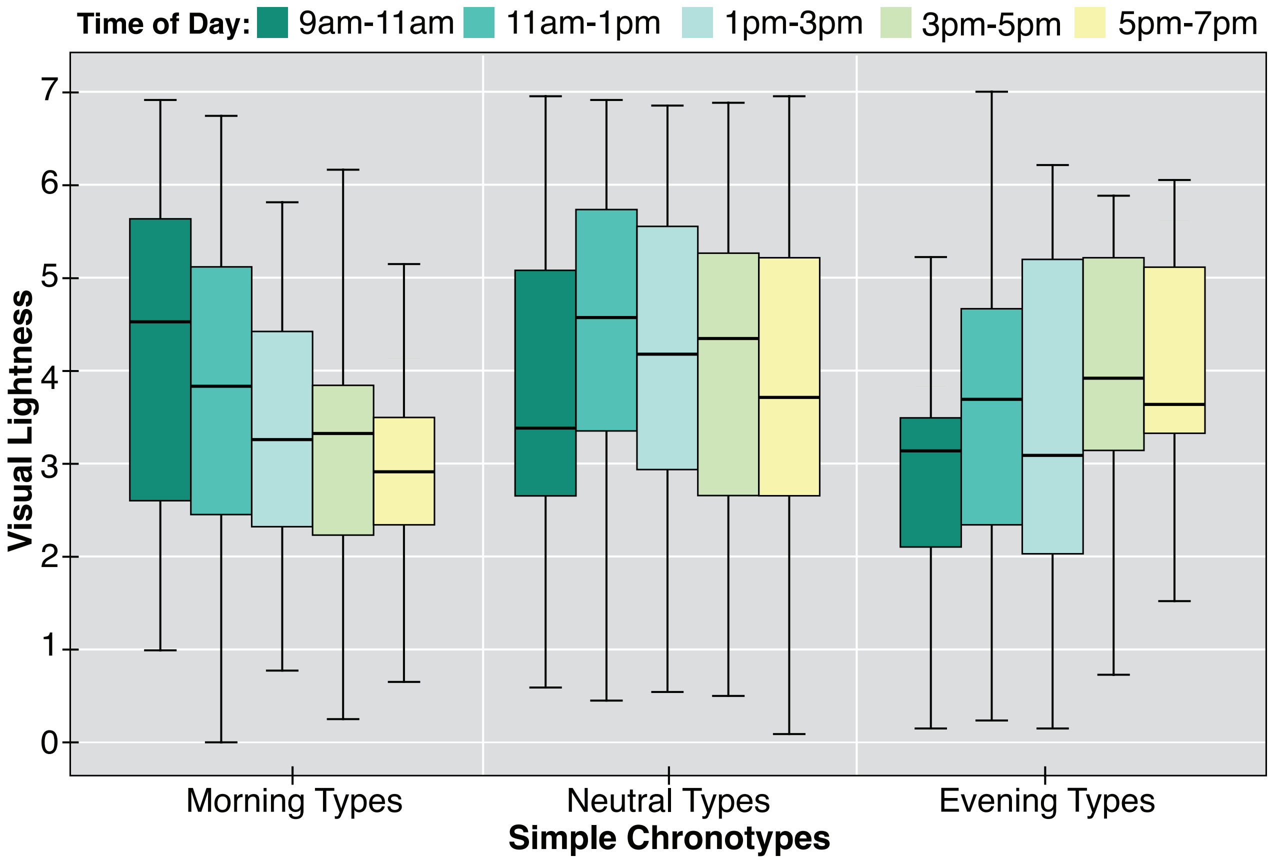

Figure 5-17: Chronotypes and time of day interaction effects on visual lightness

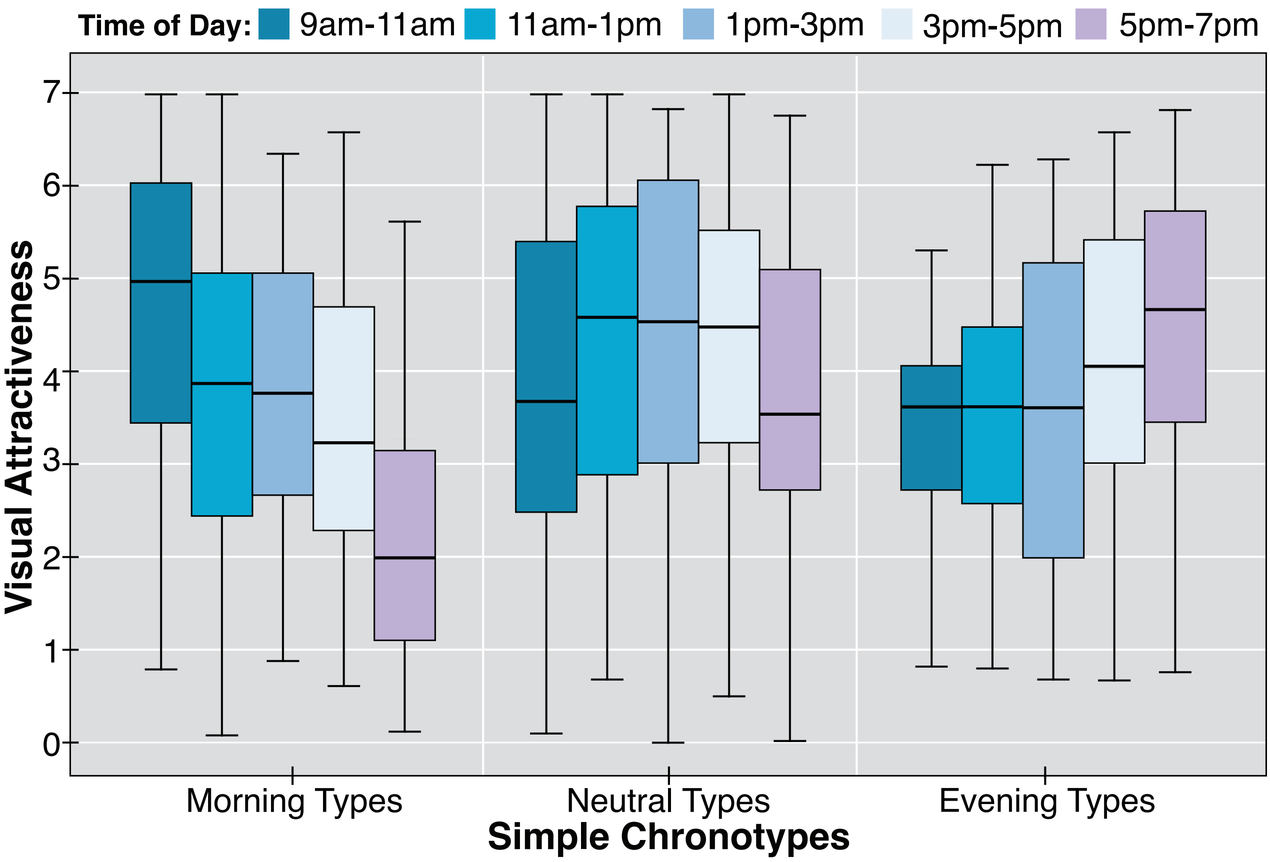

Figure 5-18: Chronotypes and time of day interaction effects on visual attractiveness

Correlations between Human Responses and Photometric Criteria

As could be expected from the geometry of the setting and from photometric dependencies, the measured photometric values of $L_{40°}$, $L_{60°}$, $L_{\text{Visual Field}}$ and $E_{\text{Eye Level}}$ were highly correlated (Table 5-14). The correlation coefficients with desktop luminance were still significant but smaller.

Table 5-14: Pearson correlations of photometrics

	$L_{40°}$	$L_{60°}$	$L_{\text{Visual Field}}$	L_{Desktop}	$E_{\text{Eye Level}}$
$L_{40°}$	1	0.99	0.97	0.46	0.98
$L_{60°}$	0.99	1	0.99	0.58	0.99
$L_{\text{Visual Field}}$	0.97	0.99	1	0.66	0.99
L_{Desktop}	0.46	0.58	0.66	1	0.61
$E_{\text{Eye Level}}$	0.98	0.99	0.99	0.61	1

In the presented scenes some surfaces, such as the desktop, were held at a constant luminance independent from the uniform wall and ceiling luminance. Thus, minimum to maximum luminance ratios in the visual field correlate to other photometrics (Table 5-15). Correlations between luminance ratios and component scores in this case are not a reliable indicator and do not contribute additional information.

Table 5-15: Pearson correlations of average luminances with luminance ratios

	$L_{\text{Min }40°}/L_{\text{Max }40°}$	$L_{\text{Min }60°}/L_{\text{Max }60°}$	$L_{\text{Min Visual Field}}/L_{\text{Max Visual Field}}$
$L_{\text{Visual Field}}$	-0.74	-0.77	-0.86
$L_{40°}$	-0.78	-0.82	-0.88
$L_{60°}$	-0.76	-0.80	-0.88
$L_{\text{Walls/Ceiling}}$	-0.76	-0.79	-0.84

Since in this experiment participants were nested within different groups and photometrics were nested within participants, a hierarchical linear model was used to estimate the two component scores for each level of measured photometric values. These parameter estimates were then correlated to the different levels of photometrics (Table 5-16) to determine the best fitted model and, thus, the best predictor for room appearance judgement scores.

Table 5-16: Correlations of the different hierarchical models with photometrics

Photometric value	Correlation with parameter estimates of visual lightness	Correlation with parameter estimates of visual attractiveness
$L_{40°}$	0.86	0.87
$L_{60°}$	0.81	0.81
$L_{\text{Visual Field}}$	0.76	0.76
L_{Desktop}	0.15	0.11
$E_{\text{Eye Level}}$	0.79	0.79

Current research (e.g. Berrutto *et al.,* 1997; Loe *et al.,* 1994; Veitch & Newsham, 2000) compared experimental outcomes with measured luminances in a 40° horizontal band ($L_{40°}$). This was supported by the hierarchical linear model, where the best fit was also found for the average luminance in this band. Thus, correlations between the two visual component scores and the luminance measurements for the 40° horizontal band from the present setup were investigated.

As expected, there was a significant effect of luminance in the 40° horizontal band on visual lightness, $F(23, 558.9)=25.92$, $p<0.001$, and on visual attractiveness, $F(23, 555.4)=33.91$, $p<0.001$. Table 5-17 shows the estimated marginal means (EMM) and standard error (SE) from the model.

Table 5-17: Estimated marginal means from hierarchical linear model

Luminance in 40° band ($L_{40°}$)	EMM visual lightness	SE visual lightness	EMM visual attractiveness	SE visual attractiveness
17.58 cd/m^2	1.78	0.22	2.03	0.24
18.27 cd/m^2	2.29	0.22	1.66	0.24
18.82 cd/m^2	2.13	0.22	1.44	0.24
25.44 cd/m^2	2.64	0.22	2.53	0.24
26.24 cd/m^2	2.56	0.22	2.56	0.24
27.22 cd/m^2	2.45	0.22	2.55	0.24
28.41 cd/m^2	3.10	0.22	3.36	0.24
29.74 cd/m^2	3.28	0.22	3.50	0.24
30.36 cd/m^2	3.80	0.22	3.50	0.24
38.37 cd/m^2	3.16	0.22	3.51	0.24
38.77 cd/m^2	3.44	0.22	3.87	0.24
39.32 cd/m^2	3.56	0.22	4.03	0.24
42.82 cd/m^2	4.32	0.22	4.57	0.24
43.81 cd/m^2	4.72	0.22	4.89	0.24
44.37 cd/m^2	4.85	0.22	4.90	0.24
52.68 cd/m^2	4.22	0.22	4.43	0.24
53.92 cd/m^2	4.12	0.22	4.27	0.24
54.65 cd/m^2	4.16	0.22	4.59	0.24
58.95 cd/m^2	4.65	0.22	5.20	0.24
59.58 cd/m^2	4.95	0.22	5.41	0.24
60.18 cd/m^2	5.12	0.22	5.38	0.24
70.12 cd/m^2	4.54	0.22	4.56	0.24
70.79 cd/m^2	4.58	0.22	4.57	0.24
71.44 cd/m^2	4.44	0.22	4.58	0.24

To find a mathematical term to estimate the ratings of visual lightness and visual attractiveness from the luminance $L_{40°}$ a curve estimation model was fitted to the parameter estimates from the hierarchical linear model. The two basic approaches, as described in section 1.2 on page 9, were used to determine the best fit.

1. Logarithmic

$$C = a \cdot \ln(L_{40°}) + b \quad \textbf{(5-2)}$$

2. Power function

$$C = a \cdot L_{40°}^{b} \quad \textbf{(5-3)}$$

with component score *C* and constants *a*,*b*.

Table 5-18: Results of curve estimation regression model

	Estimated function for visual lightness	R^2
logarithmic	visual lightness $= 2.08 \cdot \ln(L_{40°}) - 3.93$	0.83
power	visual lightness $= 0.35 \cdot L_{40°}^{0.63}$	0.84

	Estimated function for visual attractiveness	R^2
logarithmic	visual attractiveness $= 2.46 \cdot \ln(L_{40°}) - 5.18$	0.82
power	visual attractiveness $= 0.22 \cdot L_{40°}^{0.77}$	0.84

The logarithmic and power regressions show high coefficients of determination with R^2>0.8 for both the visual lightness and visual attractiveness score data. Thus, dependencies upon $L_{40°}$ can be assumed. It was decided to use the power function regression in both cases because of the slightly higher coefficients.

Whether or not a subjective scale has a defined midpoint is discussed controversial. However, a midpoint representing the reversal point from one adjective to another has been frequently used in research (e.g. Loe *et al.,* 1994; van Ooyen *et al.,* 1987; Völker, 2006) and is therefore used here to achieve comparable results. For visual lightness, the midpoint of the scale (3.5 in this case) can be regarded as the point where appraisal changes from generally light to generally dim; the 40° horizontal band luminance corresponding to this midpoint can be calculated using the power function from Table 5-18. The same procedure can be used on the visual attractiveness scale, where the midpoint represents the change from generally attractive to generally unattractive.

Figure 5-19 and Figure 5-20 show the estimated component scores for each level of $L_{40°}$ and the corresponding power functions derived from the curve estimation. The dashed lines mark the midpoints or reversal points of the scale and the associated luminance value. The charts indicate that the visual lightness scale midpoint correspond to a 40° horizontal band luminance of about $L_{40°}$=38.2 cd/m^2; the visual attractiveness scale midpoint corresponds to $L_{40°}$=37.4 cd/m^2.

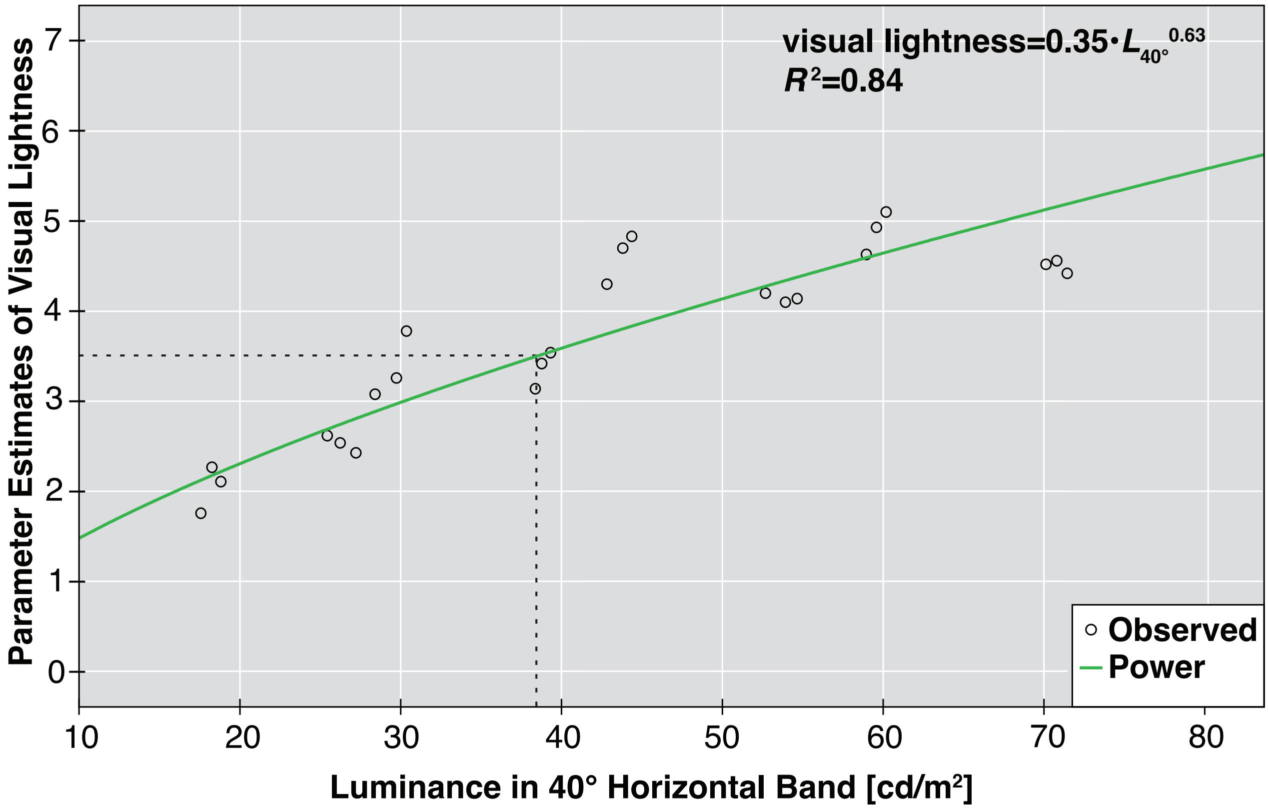

Figure 5-19: Parameter estimates of visual lightness and fitted power function

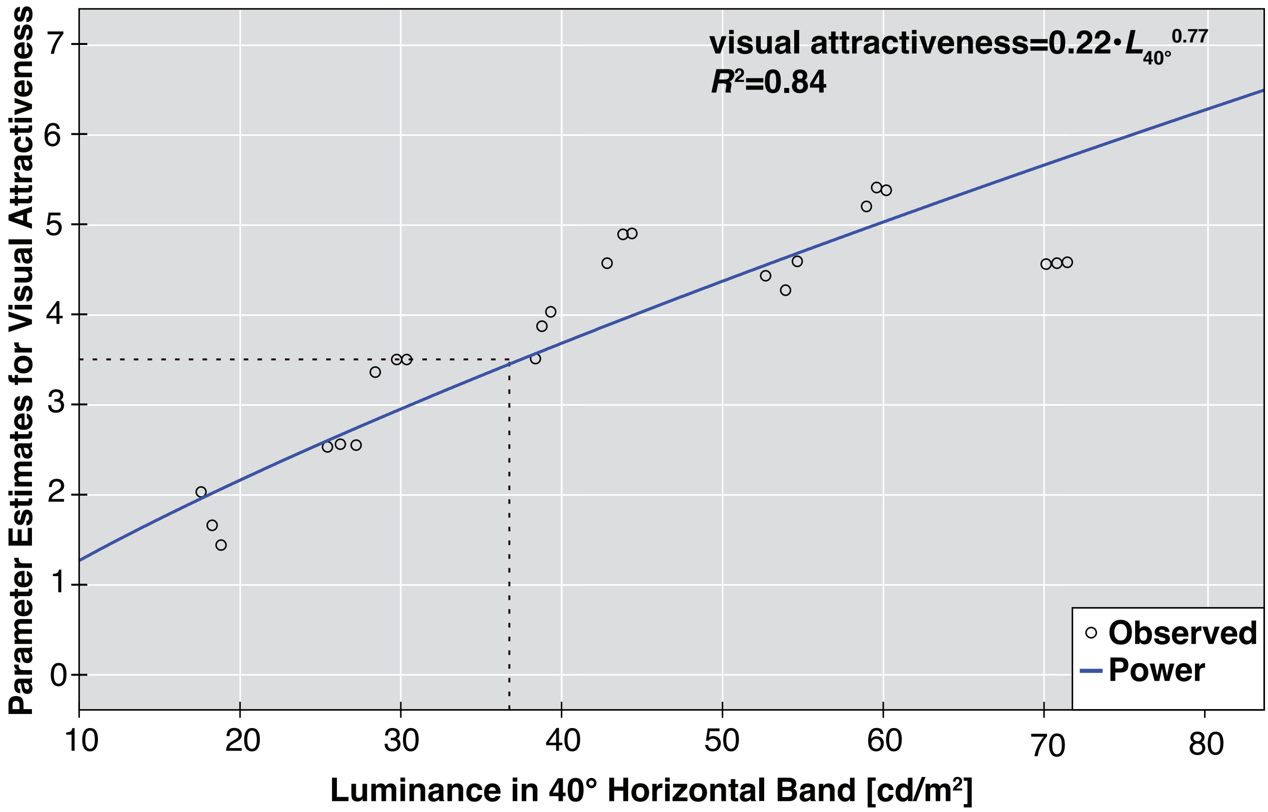

Figure 5-20: Parameter estimates of visual attractiveness and fitted power function

Since the interaction effect between chronotype and the time of day on the participants' appraisal of the scene was significant, hierarchical linear modelling was then used to investigate possible differences in correlations between the luminance in the 40° band ($L_{40°}$) and participants' ratings. The parameter estimates were used in a curve estimation regression to fit a power function to the data.

Figure 5-21 and Figure 5-22 show the parameter estimates of the responses of evening types to different luminances in a 40° horizontal band. In the charts, judgements are subdivided according to the time of presentation. The fitted power functions for visual lightness showed high coefficients of determination (R^2=0.69 (9am - 11am), R^2=0.68 (5pm - 7pm)). Again, the midpoint of the visual lightness scale is assumed to be the point where judgements change from generally dim to generally bright. The power functions indicate that evening types who participated in the morning required a 40° band luminance of about 56.5 cd/m^2 to judge the room as generally bright, while evening types tested in the evening only required about 33.0 cd/m^2 for the room to appear generally bright.

Similar results were observed for visual attractiveness, where evening types in the morning required about 47.0 cd/m^2 to judge the room as generally attractive as compared to 28.7 cd/m^2 in the evening (R^2=0.57 (9am - 11am), R^2=0.58 (5pm - 7pm)).

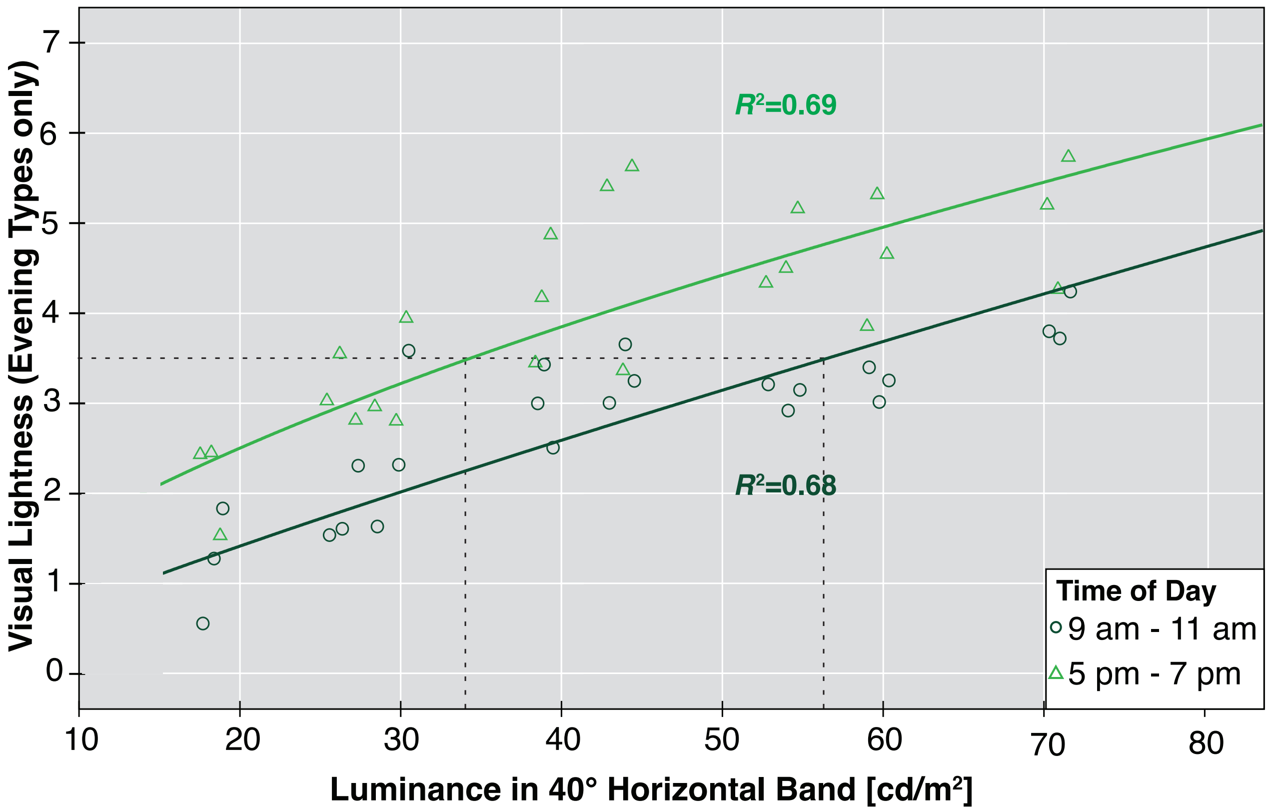

Figure 5-21: Power function curve fit of evening type-ratings of visual lightness in the morning and evening

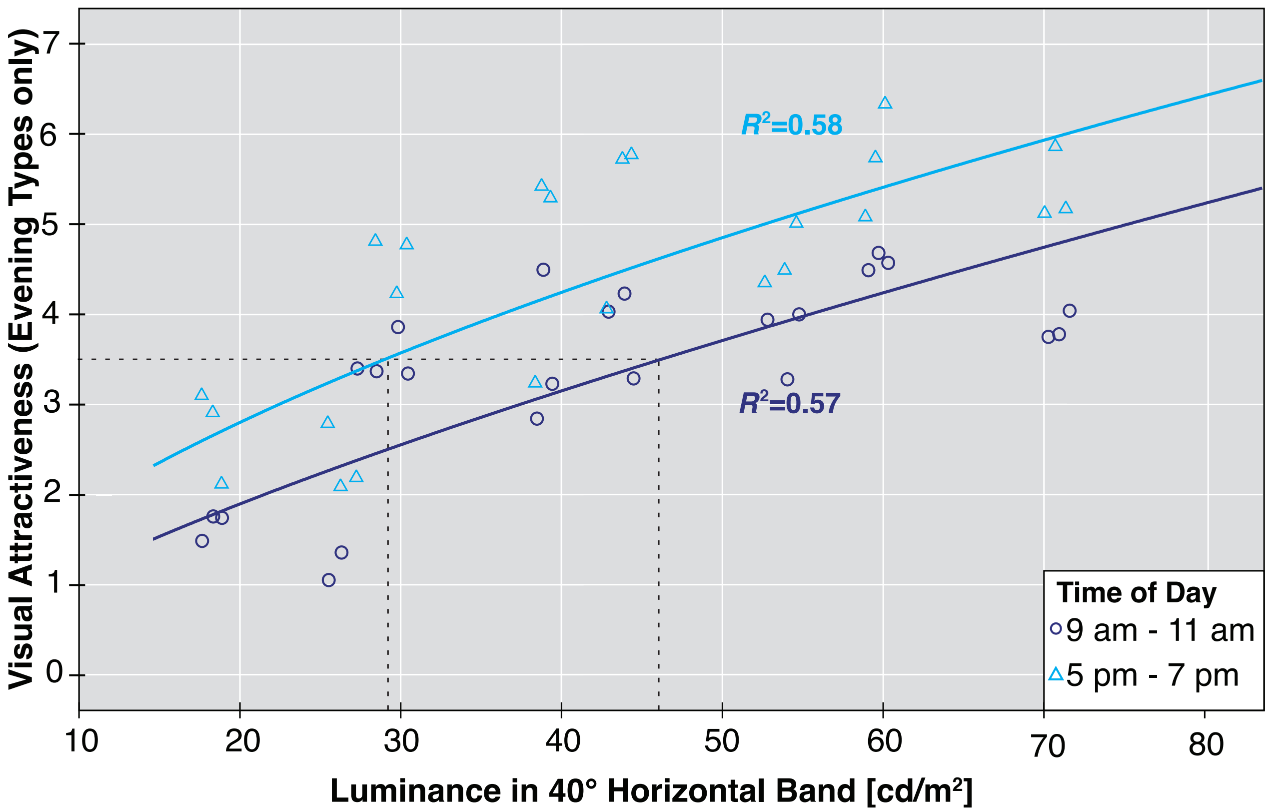

Figure 5-22: Power function curve fit of evening type-ratings of visual attractiveness in the morning and evening

Figure 5-23 and Figure 5-24 provide the visual lightness (R^2=0.80 (9am - 11am), R^2=0.64 (5pm - 7pm)) and visual attractiveness (R^2=0.64 (9am - 11am), R^2=0.60 (5pm - 7pm)) responses for morning types. Morning types tested in the morning judged a room as generally bright when the 40° horizontal band luminance exceeded 34.5 cd/m^2; those tested in the evening required about 52.0 cd/m^2 to achieve the same result. For the experimental setup to be generally attractive, a 40° band luminance of 36.0 cd/m^2 was sufficient in the morning, while a luminance of 50.0 cd/m^2 was required in the evening.

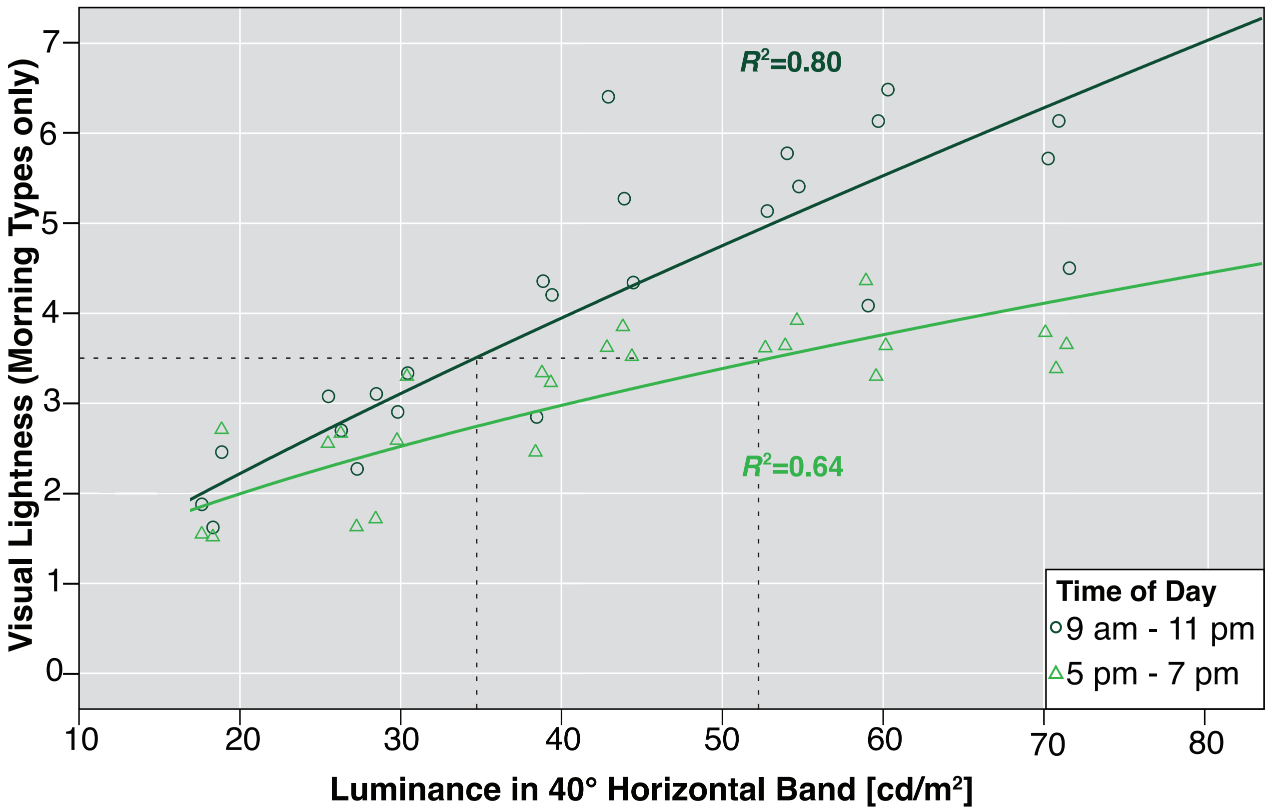

Figure 5-23: Power function curve fit of morning type-ratings of visual lightness in the morning and evening

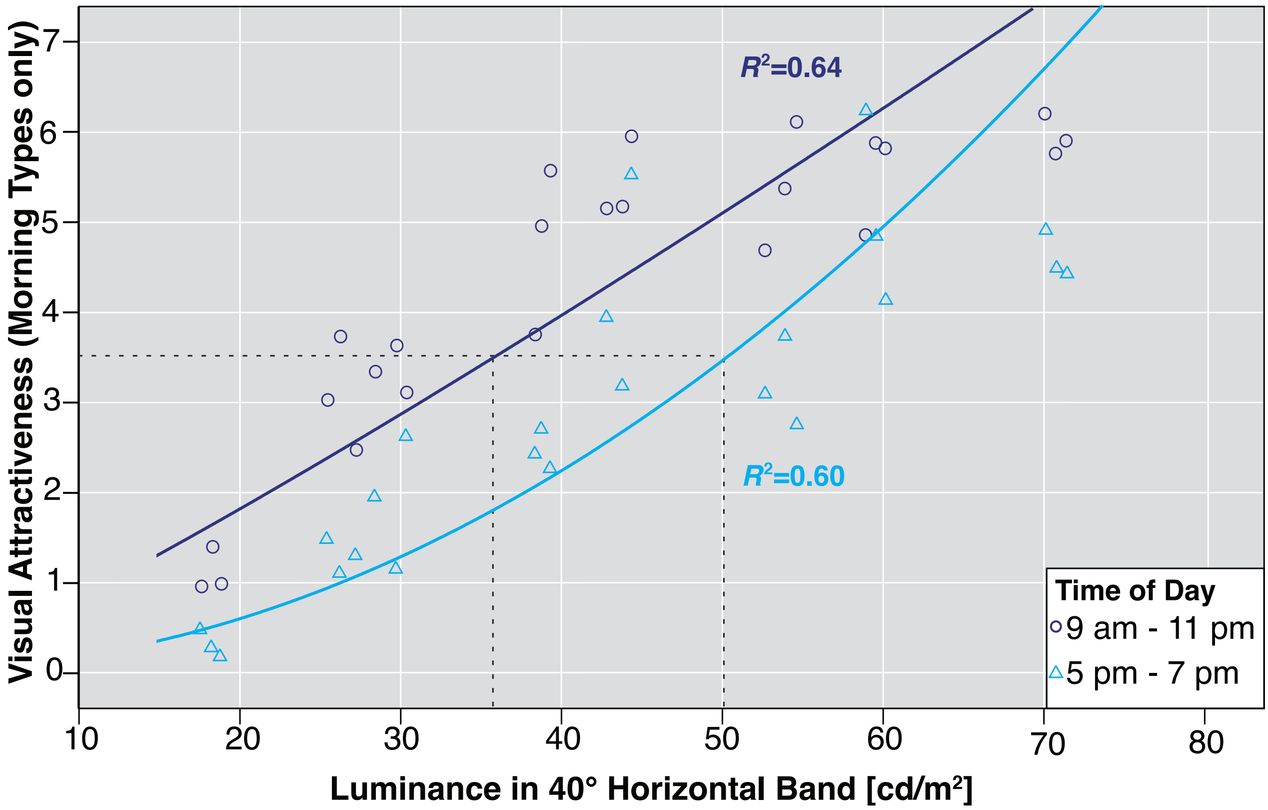

Figure 5-24: Power function curve fit of morning type-ratings of visual attractiveness in the morning and evening

5.6 Discussion

The discussion is structured by means of the hypotheses tested in this experiment. An overall discussion of both experiments conducted in this work, suggestions for practical application, and the meaning for office lighting energy efficiency can be found in section 8.

Surrounding area illuminance has an effect on visual lightness, but not on visual attractiveness

Surrounding area illuminance as defined in section 2.1 on page 13 had an effect on visual lightness and thus, perceived brightness of the space. Planned comparisons showed that increasing the illuminance in this area from 100 lux to a higher value led to statistically significant differences in ratings. Graphical examination only indicated small changes in the visual lightness perception of about 0.3 rating units, while the size of the effect was classified as medium. Changes were more pronounced when wall and ceiling luminances were low. However, this interaction effect was not statistically significant. Pre-planned comparisons of a change in illuminance from 200 lux to 300 lux resulted in a statistically significant effect for visual lightness with a small to medium effect size. Visual attractiveness was not significantly affected by changes in surrounding area illuminance. The results indicate that participants indeed noticed changes of surrounding area illuminance and adjusted their judgement of visual lightness. These small changes, however, did not impact on the affective domain.

This outcome is in line with research by Flynn (1977), Loe (1991) and Houser (2002), where the brightness of the floor only had a low correlation with the overall brightness of a space. The study by Tabuchi (1995) is supported, where a task to ambient illuminance ratio of 3:1 was accepted at a task area illuminance of 500 lux, even though a ratio of 1:1 was preferred. Outcomes by McKennan and Parry (1984) and Inoue (2010) are partially supported since the results of this work suggest possible non-uniform illumination of work planes. The deviation from results by Bean and Hopkins (1980), which suggested a preference for a completely uniform work plane illuminance, result from differences in the experimental designs. In their experimental space, walls were painted a dark cream unusual for office spaces. As a consequence, luminances of the side walls were low, focusing the observer's appraisal mainly on the work plane where small differences in illuminance and luminance could be noticed.

Lighting standards like EN 12464-1 (2011) give minimum recommendations for task to surrounding area illuminance ratios that are in the order of 1.7:1. A typical task area illuminance of 500 lux results in a surrounding area illuminance recommendation of 300 lux. The results of this experiment indicate that a decrease to 100 lux only marginally affects the way an office is experienced. The thereby 'saved' luminous flux can be used to enhance the appearance of the space in a more effective way.

Background luminance has an effect on both visual lightness and visual attractiveness

The results of experiment I showed significant multivariate effects of wall and ceiling luminance on room appearance judgements. This is in accordance with most previous research. A high correlation of subjective judgements of visual lightness and attractiveness was found with the luminance in a 40° horizontal band that is cited in many other studies (e.g. Loe, 1994).

A hierarchical linear model and a subsequent curve fitting procedure indicated a lightness-luminance relationship for uniform luminances characterized by a power function. The power function regression of the relationship between visual lightness and luminance in the 40° horizontal band was computed to

$0.35 \cdot L^{0.63}$ with a high coefficent of determination. This function is in very close agreement with Marsden's investigation, where a luminance brightness relationship of $\alpha \cdot L^{0.6}$ (α being a constant depending on the used scale) was proposed when the brightness of a number of surfaces was seen simultaneously. Thus, it can be assumed that for uniformly lit room surfaces, the visual lightness factor in this work can also be used as an indicator for apparent brightness. Note that in the research referred to here, methods to obtain appropriate, accepted or preferred luminances vary, and therefore cannot be compared to this work without reserve. It cannot be stated whether the results of this work represent preferences or satisfactory levels of luminances. However, the midpoint of a bipolar scale has often been regarded as a reversal point where overall impression changes from one attribute to the other. The results of the experiments in this work show that the room was considered generally bright with a luminance of >38.2 cd/m^2, and generally attractive with a luminance of >37.4 cd/m^2. The results are in good accordance with results by van Ooyen *et al.* (1987), Loe *et al.* (1994), (2000), Veitch and Newsham (2000) and Newsham *et al.* (2005).

The results are considerably lower than the luminances derived from older papers by authors such as Balder (1957), (95-135 cd/m^2), and Collins and Plant (1971), (71 cd/m^2). The reason for these differences can be found in the method of measurement. In both investigations questionnaires with the categories 'too dark'-'just right'-'too bright' were used. The value of 71.9 cd/m^2 by Collins and Plant was determined by 92% of the participants rating only scenes with lower luminances as 'too dark'. Only 8% of the participants rated the 71.9 cd/m^2-scene as 'too bright'. The luminances resulting from Bader's study were determined by the maximum of 'just right' ratings representing the maximum luminance that was not rated as 'too bright'. Thus, both results cannot be compared directly to the outcomes of this study since they describe different levels of appraisal.

Wall and ceiling luminances have a greater impact on visual lightness and visual attractiveness than surrounding area illuminance

Effect sizes and graphical evaluation showed that the impact on visual lightness and visual attractiveness of a small increase in wall and ceiling luminance, from 11 cd/m^2 to 30 cd/m^2 (Cohen's d=1.03 (visual lightness) and 1.28 (visual attractiveness)) outweighed the effect of decreasing surrounding area illuminance from 300 lux to 100 lux (Cohen's d=0.5 (visual lightness) and 0.28 (visual attractiveness)). Compared to European minimum recommendations (E_{sur}=300 lux, $L_{walls/ceiling}$=11 cd/m^2, (cf. CEN, 2011)) an installation with E_{sur}=100 lux and $L_{walls/ceiling}$=30 cd/m^2 leads to a significant improvement of room appearance.

Desktop luminance affects visual lightness and visual attractiveness

The two different desktop luminances examined in this work did not show a main effect on room appearance. However, there was an interaction effect of desktop luminance with surrounding lighting conditions. For the interaction with surrounding area illuminance, these effects, although statistically significant, were small (Cohen's d= 0.42 (visual lightness) and 0.14 (visual attractiveness)) and could not be conclusively elaborated. A similar interaction with walls and ceiling luminance was more pronounced (Cohen's d=0.54 (visual lightness) and 0.96 (visual attractiveness)). Participants rated a scene with a darker desktop as lighter and more attractive if average wall and ceiling luminance was 50 cd/m^2 or more. For wall and ceiling luminances of 30 cd/m^2 and below the lightness and attractiveness appraisals for scenes with a brighter desktop were higher. To some degree, these findings are in accordance with van Ooyen *et al.* where a "light desktop in dark surroundings gives a feeling of relaxation" and "a darker desktop in a bright room has a stimulating effect" (van Ooyen *et al.,* 1987, p.155). Relaxation and stimulation are not included in the questionnaire of this work. Still, the visual attractiveness factor is a similar measure leading to comparable results.

The interaction between chronotype and time-point of observation has an effect on judgements of visual lightness and visual attractiveness

The between group factors 'chronotype' and 'time of day' alone did not show a significant main effect on room appearance judgement. The reason for this becomes clear when one investigates the interaction between these two factors. Since evening types rated the space brighter and more attractive in the evening and morning types rated vice-versa by a close to equal difference in ratings, the main effects were averaged out across all times of day and chronotypes. The significant interaction effect between chronotype and time of day describes, how much time has passed since the subject's individual mid-sleep time and, thus, can be regarded as 'internal time' as described by Kantermann *et al.* (2012). In general, evening types rated the experimental space as brighter and more attractive in the evening; morning types rated the space as brighter and more attractive in the morning. Effect sizes were in the medium range for both components. The outcomes of this work indicate that biological needs for lighting are reflected in subjective judgements of a space even though participants were not aware of their chronotype or resulting biological effects of lighting. The results are not directly comparable to previous studies since no similar research on the effects of internal time on lighting appraisal exist. However, knowledge about biological effects of lighting and their influence on affect and appraisal of a space should find its way into lighting design practice.

Since the results of this work are limited to the described 'reversal points' of the used scales, no statements can be claimed regarding lighting preferences depending on the observer's internal time. Subsequent studies should further investigate the observed interaction effect with an even greater sample size to achieve more robust results for each subgroup. An adjustment experiment can aim for a better understanding of lighting preferences depending on biological differences between occupants to provide a basis for highly personalized office lighting.

6 Experiment II

The second experiment was conducted to investigate the influence of luminance distribution on walls and ceiling on the visual appearance of cell offices. Current research suggests that the impact of surface luminances on room appearance is not equal for all areas of the visual field in relation to the observer's position. The following hypotheses are tested:

- The distribution of background luminance affects the appraisal of visual lightness and visual attractiveness

- The effectiveness of a lit region to enhance visual lightness and visual attractiveness depends on the region's luminance, size, luminance distribution and position within the observer's visual field

These hypotheses, if confirmed, can support improved metrics of lighting quality in cell offices, including required luminance levels and luminance distributions within the field of view. These metrics will be able to contribute to the holistic quality evaluation of a lighting solution.

In experiment I, no main effect of the luminance of the desktop on visual appearance could be found. To confirm previous results, the following hypothesis was tested again:

- Desktop luminance affects visual lightness and visual attractiveness

In experiment I an interaction effect between a person's chronotype and the time of observation was hypothesized and statistically confirmed in the experiment. Chronotypes and time of observation are recorded in this experiment to validate the results of experiment I and to account for possible confounding variables.

Thus, the following hypothesis is tested again:

- The interaction between chronotype and time-point of observation has an effect on judgements of visual lightness and visual attractiveness

6.1 Research Design

Experiment II was a 2 x 6 x 5 x 3 mixed factorial design with 2 repeated-measures variables (2 levels of desktop luminances and 6 different luminance distributions), and 2 between-groups variables: 5 times of day, and 3 chronotypes (Figure 6-1).

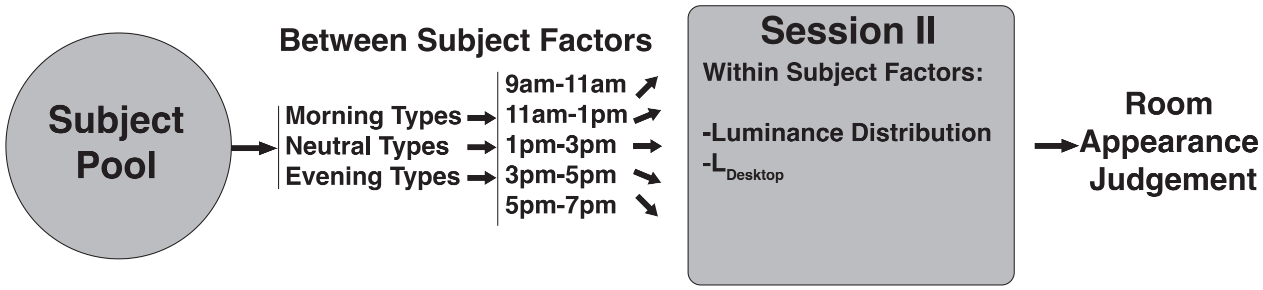

Figure 6-1: Experimental design

All groups of participants observed all 12 possible combinations of desktop luminance and luminance distribution, thus acting as their own control group.

Independent Variables

Table 6-1 shows the range of independent repeated-measures variables. The levels of desktop luminance were the same as in Experiment I. The distributions were chosen to include a rather wide range from completely uniform wall washing to distributions with areas of sharp luminance contrasts and non-uniform luminances as used in (Tiller & Veitch, 1995). Although luminance distributions differed, the average luminance in the 40° horizontal band was held at a constant 40 cd/m^2 (50 cd/m^2 for scenes with higher desktop reflectance) for all scenes, representing a level often found to be preferred (e.g. van Ooyen *et al.,* 1987; Veitch & Newsham, 2000). E_{sur} was kept at 100 lux for all scenes.

Table 6-1: Repeated-measures variables in experiment II

Within subject factors	Range
Desktop luminance	60 cd/m^2, 95 cd/m^2
Walls/ceiling luminance distribution	Uniform
	Vertical Gradient
	Step Subject
	Step Room depth
	Gradient Subject
	Gradient Room Depth

Non-uniform distributions are presented in two different ways, keeping the facing wall and ceiling darker with higher luminances in the back of the room, and vice-versa (Figure 6-2).

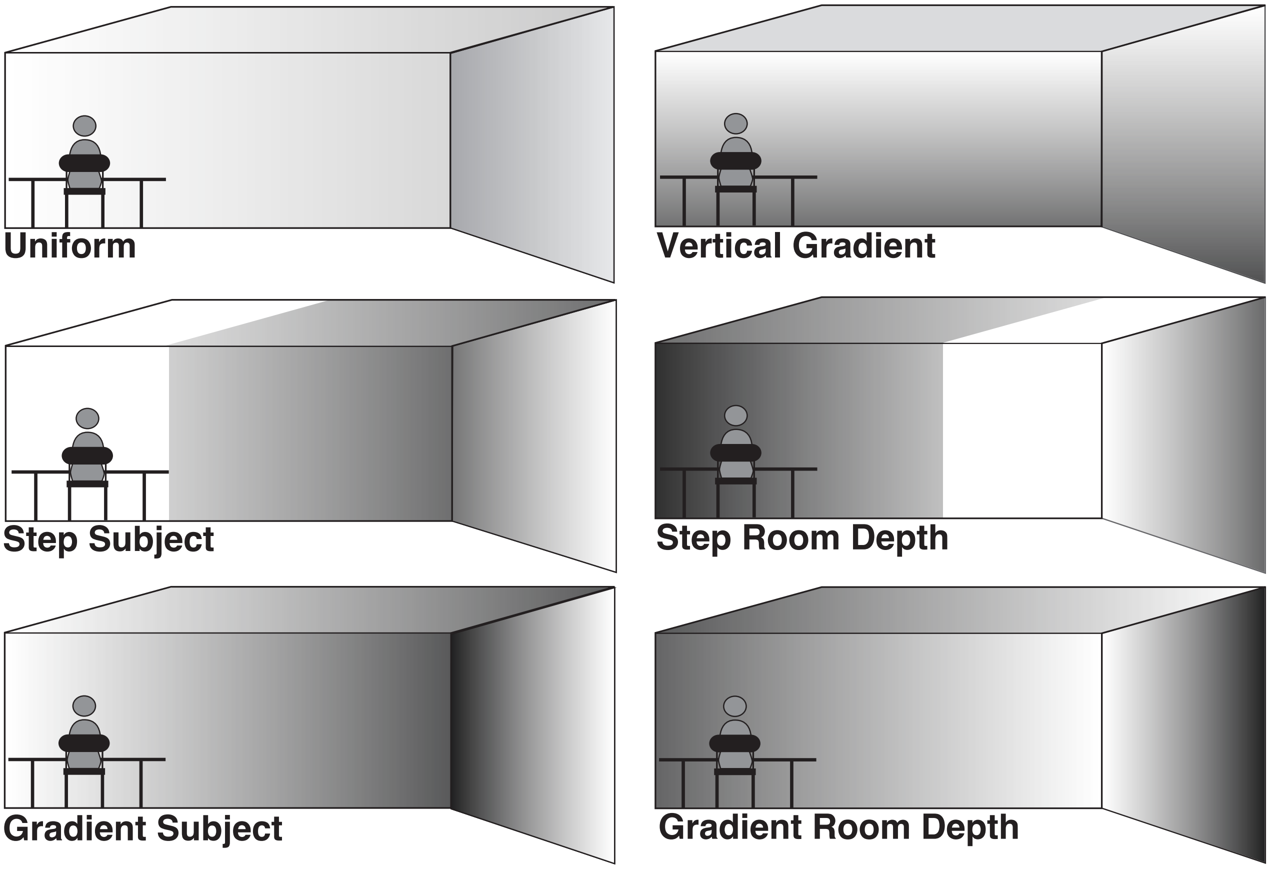

Figure 6-2:The six presented luminance distributions

The scenes represent a realistic cell office environment with one window wall and a back wall. Thus, the luminance distributions of these two walls are different in level and distribution. The back wall of the room was illuminated in a way that a smooth luminance gradient to the facing wall was realized. The window wall was not illuminated separately but by light from the facing wall. This setup made it possible to avoid harsh contrasts around the visible room corners.

Dependent Variables

Dependent variable was the same room appearance questionnaire as in experiment I with the two components visual lightness and visual attractiveness (s. Appendix A). The significance level of α=0.05 was kept.

6.2 Participants

The minimum sample size was calculated using power analysis in G*Power 3.1 (Faul *et al.,* 2007) with α=0.05 to achieve a power of 1-β≥0.95. The estimate of effect sizes was derived from experiences with pre-tests (Prella 2013). Again, the between-groups variables 'chronotype' and 'time of day' are treated as exploratory. The mixed factorial design required a minimum sample size of 30 to detect medium to large size effects (estimated partial η^2~0.1). A sample of 34 individuals was used. As in experiment I, participants were drawn from a pool of participants who previously participated in different experiments at the Technical University Berlin, or were recruited from the Humboldt University Philosophy Department. None of the individuals knew about the aims or procedure of the experiment. The applied sample size was probably too small to measure both the described effects and age or gender effects. To avoid unwanted influence from age effects, the sample selection was designed to include an age homogeneous group. Especially older participants (>50 years) were excluded. This approach is also loosely corresponding to the two younger groups (16-30 years, 31-45 years) used by Boyce (1973). The actual achieved age distribution included participants between the age of 20 years and 42 years (mean 26.79, median 25.0, standard deviation 5.24). Gender effects were minimized selecting roughly equal shares of male and female participants (52.9% male, 47.1% female). Observations were again made at different times of the day representing normal office working hours from 9 am to 7 pm. The participants' chronotype was not known in advance, so all participants were randomly assigned to the experimental conditions. There were more participants taking part in the study in the morning or evening than during the day. Thus, group sizes varied between times of day. Since a significant difference was expected between experimental sessions in the morning and evening the distribution was regarded sufficient. Analogous to experiment I, definite or extreme morning or evening types were not regarded separately but are included in a 'simple chronotype' only distinguishing between morning types, neutral types and evening types. This reduces the number of investigated groups and maintains an adequate sample size for each group. Descriptive statistics of the sample are given in Table 6-2 and Table 6-3.

Table 6-2: Sample characteristics

Sex	16 female			18 male	
Age	20-42 years, mean=26.79 years, median=25 years, SD=5.24				
Time of day	9 am - 11 am:	11 am - 1 pm:	1 pm - 3 pm:	3 pm - 5 pm:	5 pm - 7 pm:
	8 (23.5%)	5 (14.7%)	6 (17.6%)	6 (17.6%)	9 (26.5%)
Chronotype	morning types		neutral types		evening types
	10 (29.4%)		14 (41.2%)		10 (29.4%)

Table 6-3: Chronotype distribution over time

	9 am - 11 am	**11 am - 1 pm**	**1 pm - 3 pm**	**3 pm - 5 pm**	**5 pm - 7 pm**
Morning types	3 (8.8%)	1 (2.9%)	1 (2.9%)	3 (8.8%)	3 (8.8%)
Neutral types	3(10.3%)	3 (8.8%)	2 (5.9%)	1 (2.9%)	5 (14.7%)
Evening types	2 (5.9%)	1 (2.9%)	3 (8.8%)	2 (5.9%)	3 (5.9%)

Intermediate or neutral chronotypes make up for about half of the population (Schur, 1994). Thus, the achieved neutral types ratio of 41.2% slightly under-represents neutral types in the population. The different chronotypes were roughly equally distributed across the times of day.

6.3 Setting and Materials

The second experiment took place in the setup introduced in experiment I. Setting, materials and photometric measurement techniques did not change compared to experiment I and are explicitly described in section 5.3 on page 40.

Table 6-4: Luminance measurements for distribution scenes

	Minimum	Maximum	Mean	Std. Deviation
$L_{40°}$	41.70 cd/m^2	53.16 cd/m^2	47.50 cd/m^2	4.97
$L_{60°}$	43.40 cd/m^2	59.17 cd/m^2	51.24 cd/m^2	7.01
$E_{Eye\ Level}$	109.50 lux	186.00 lux	146.67 lux	27.80
E_{sur}	87.00 lux	115.00 lux	104.5 lux	11.26

More detailed results of photometric measurements can be found in Appendix C on pages 152 and 153.

6.4 Experimental Procedure

Essentially, the experimental procedure was kept unchanged compared to experiment I. Thus, a detailed description of the experimental procedure and measures taken to minimize different types of bias can be found in section 5.4 on page 46. The only differences were the presented anchor scenes at the beginning of the experimental session. In experiment II, the first two scenes showed the distributions 'uniform' and 'step room depth', representing the most and least uniform distributions in the experiment.

6.5 Results

As in the first experiment, the gathered set of data was inspected regarding consistency of responses and possible outliers, to be able to achieve meaningful results. First scenes and repeated scenes were compared using a scatter plot (s. Appendix A). The answers again were roughly located around the reference line of y=x, indicating a good consistency between equal scenes. Therefore, the arithmetic mean of responses to the first and repeated scenes was used for the following procedure. Outliers were explored with boxplots (s. Appendix A). For Experiment II, there were a total of 24 outliers, representing 0.7% of the cases. Outliers were not discarded. Assumptions for parametric tests were discussed in 5.5 on page 49, a multivariate analysis of variance was conducted.

Statistics and Data Analysis

A multivariate analysis of variance (MANOVA) was conducted for the 2 x 6 x 5 x 3 mixed factorial design (Desktop luminance (2 levels) x luminance distribution (6 levels) x time of day (5 levels) x simple chronotype (3 levels)) to test for an overall difference across outcomes. A detailed description of null hypotheses and alternative hypotheses for the main test and the pre-planned comparisons can be found in Appendix B. Only significant main effects and two-way interactions are explored and interpreted, univariate tests are only interpreted if the multivariate test reached significance.

There was a significant main effect of luminance distribution on room appearance, Wilks' Λ=0.16, $F(10,10)=5.36$, $p=0.007$. Estimated marginal means and standard errors are shown in Table 6-5.

Table 6-5: Estimated marginal means of luminance distribution

Measure	Distribution	EMM	SE
Visual Lightness	Step subject	3.01	0.11
	Gradient subject	3.10	0.15
	Vertical gradient	3.91	0.16
	Step room depth	4.17	0.14
	Gradient room depth	4.34	0.18
	Uniform	4.52	0.19
Visual Attractiveness	Step subject	3.41	0.15
	Gradient subject	3.23	0.10
	Vertical gradient	3.78	0.16
	Step room depth	4.05	0.12
	Gradient room depth	4.34	0.13
	Uniform	4.47	0.18

Simple contrasts were used to compare all luminance distribution to the uniform distribution. Simple contrasts are non-orthogonal. Thus, a significance level of 0.01 was chosen to avoid increased type I errors. Effect sizes were calculated for the comparisons with df=1 according to (Rosnow & Rosenthal, 2003, p.224). Contrasts revealed that visual lightness for the 'step subject' distribution was rated significantly lower than uniform, $F(1,19)=21.75$, $p<0.001$, Cohen's d=1.1. Visual lightness for the 'gradient subject' distribution was rated lower than uniform, $F(1,19)=33.68$, $p<0.001$, Cohen's d=1.3. Visual Lightness ratings for the 'vertical gradient' were lower than for the uniform distribution, $F(1,19)=18.07$, $p<0.001$, Cohen's d=0.97. For visual attractiveness, the 'step subject' distribution ($F(1,19)=47.66$, $p<0.001$, Cohen's d=1.6), the 'gradient subject' distribution ($F(1,19)=44.30$, $p<0.001$, Cohen's d=1.5) and the 'vertical gradient' ($F(1,19)=8.14$, $p=0.01$, Cohen's d=0.7) were rated significantly lower than the uniform luminance distribution. The results of experiment II can be seen in Figure 6-3 and Figure 6-4. For the visual lightness component, the ratings of the distributions 'gradient room Depth' and 'step room depth' do not appreciably differ from the uniform distribution. Ratings for the 'vertical gradient' are slightly lower. The distribution 'step subject' is rated significantly lower than 'uniform' (Δ_{Median}=1.1). 'Gradient subject' has the lowest rating (Δ_{Median}=1.2) compared to the 'uniform' distribution. Visual attractiveness ratings showed a trend similar to visual lightness. The scenes with significantly lower ratings were rated lower by Δ_{Median}=1.6 representing a slightly greater difference.

There was no significant main effect of desktop luminance or interaction effect between desktop luminance and luminance distribution on visual appearance, $p>0.05$.

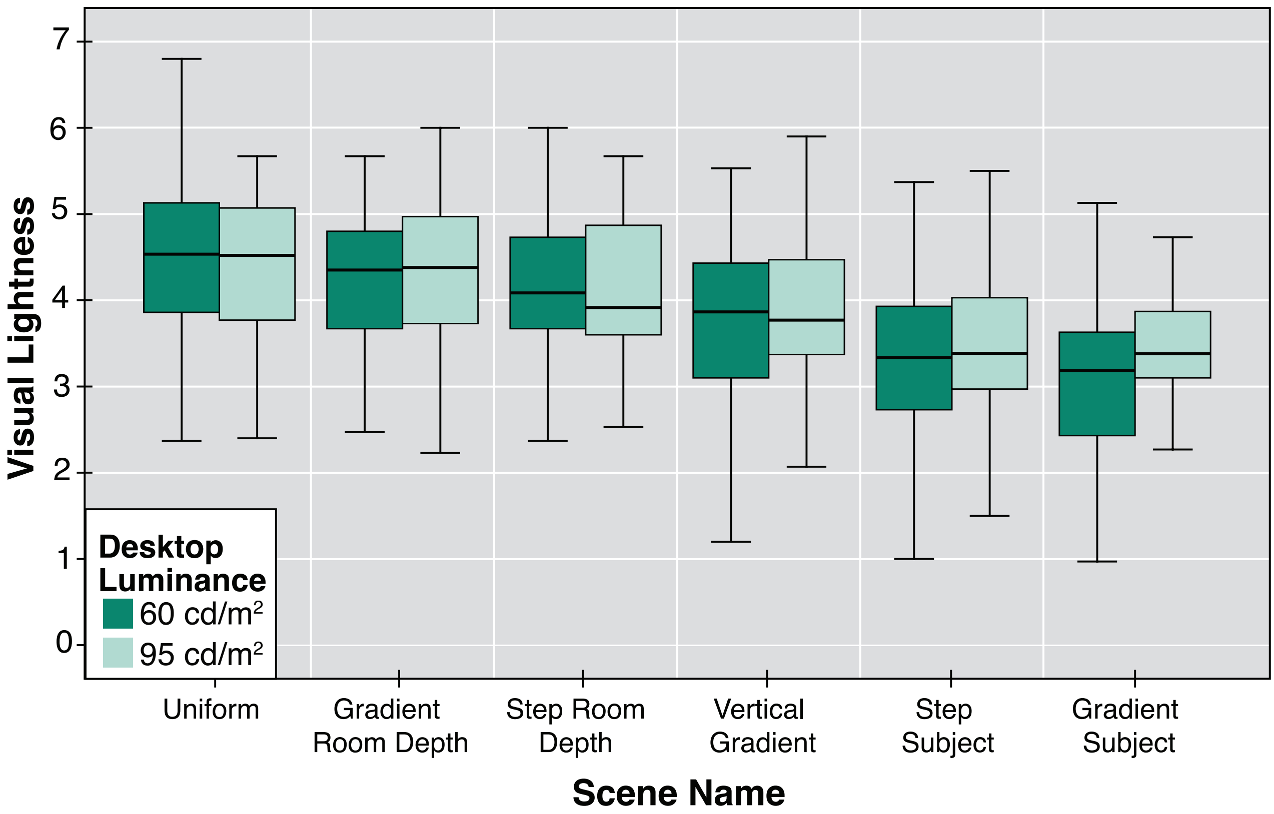

Figure 6-3: Boxplot of visual lightness responses

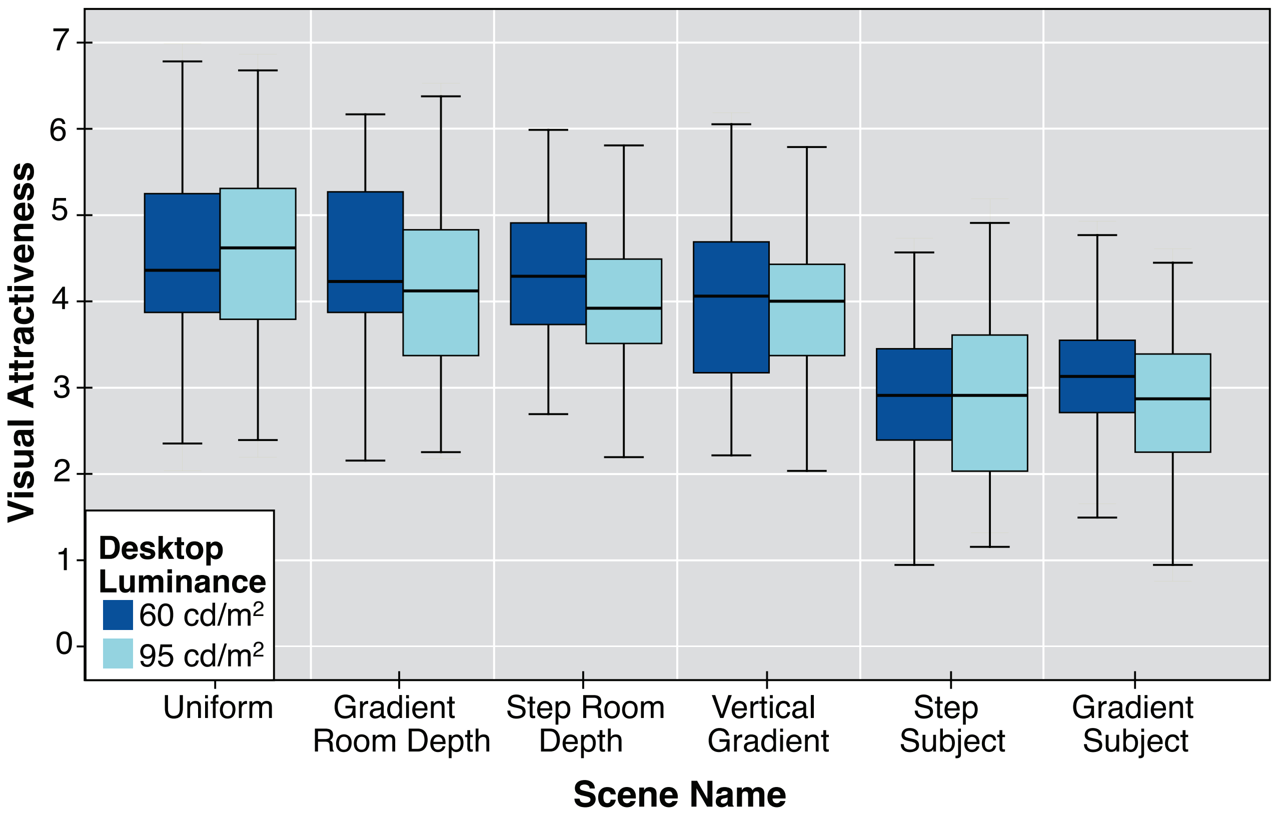

Figure 6-4: Boxplot of visual attractiveness responses

Main effects and interaction of the participants' chronotype and the time of day were non-significant, $p>0.05$. It is standard practice not to further interpret an effect if the multivariate test is not statistically significant. However, the results of experiment I indicate an interaction effect between chronotype and time of day that might be existent but non-significant due to the insufficient sample size. For this reason the effects are interpreted graphically using boxplots (Figure 6-5 and Figure 6-6).

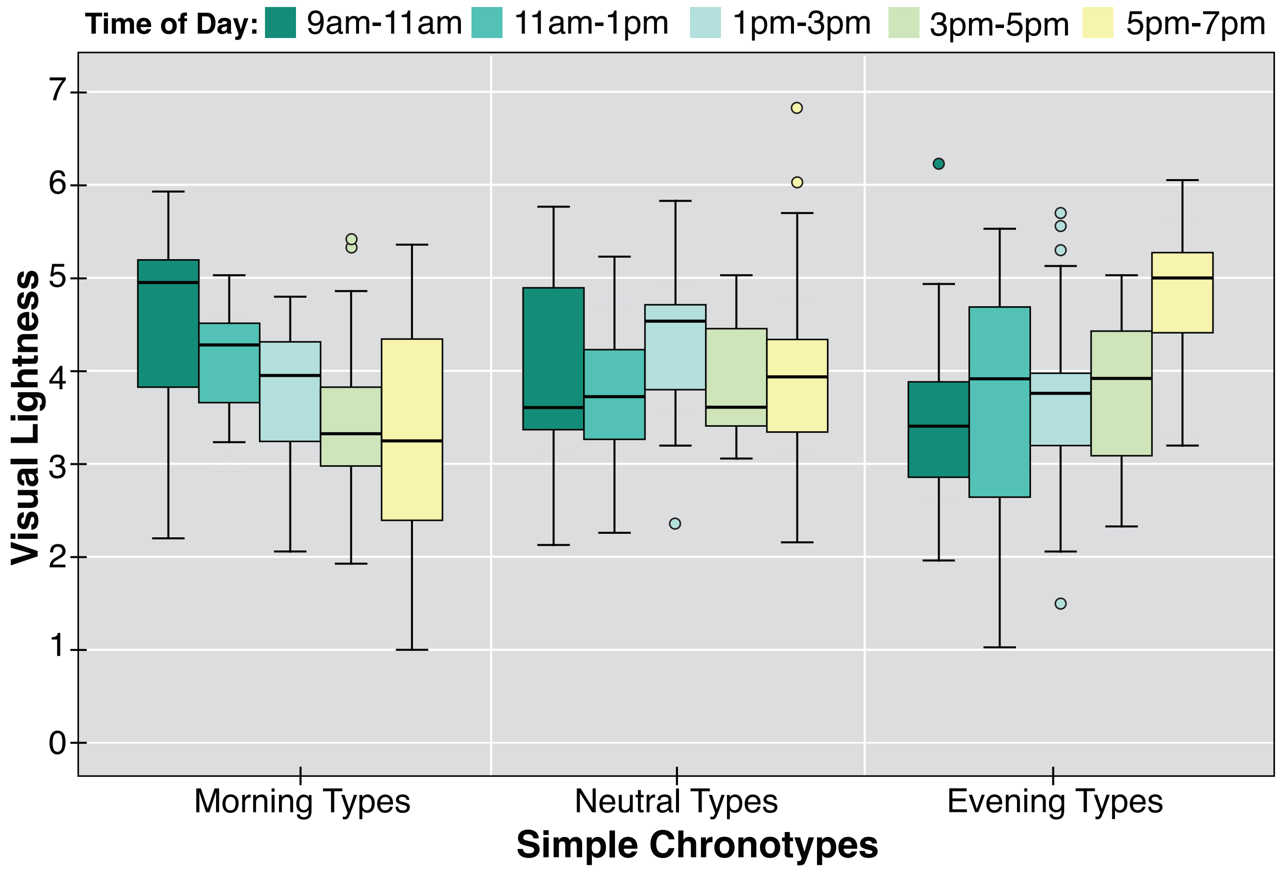

Figure 6-5: Boxplots of chronotypes and time of day influencing visual lightness

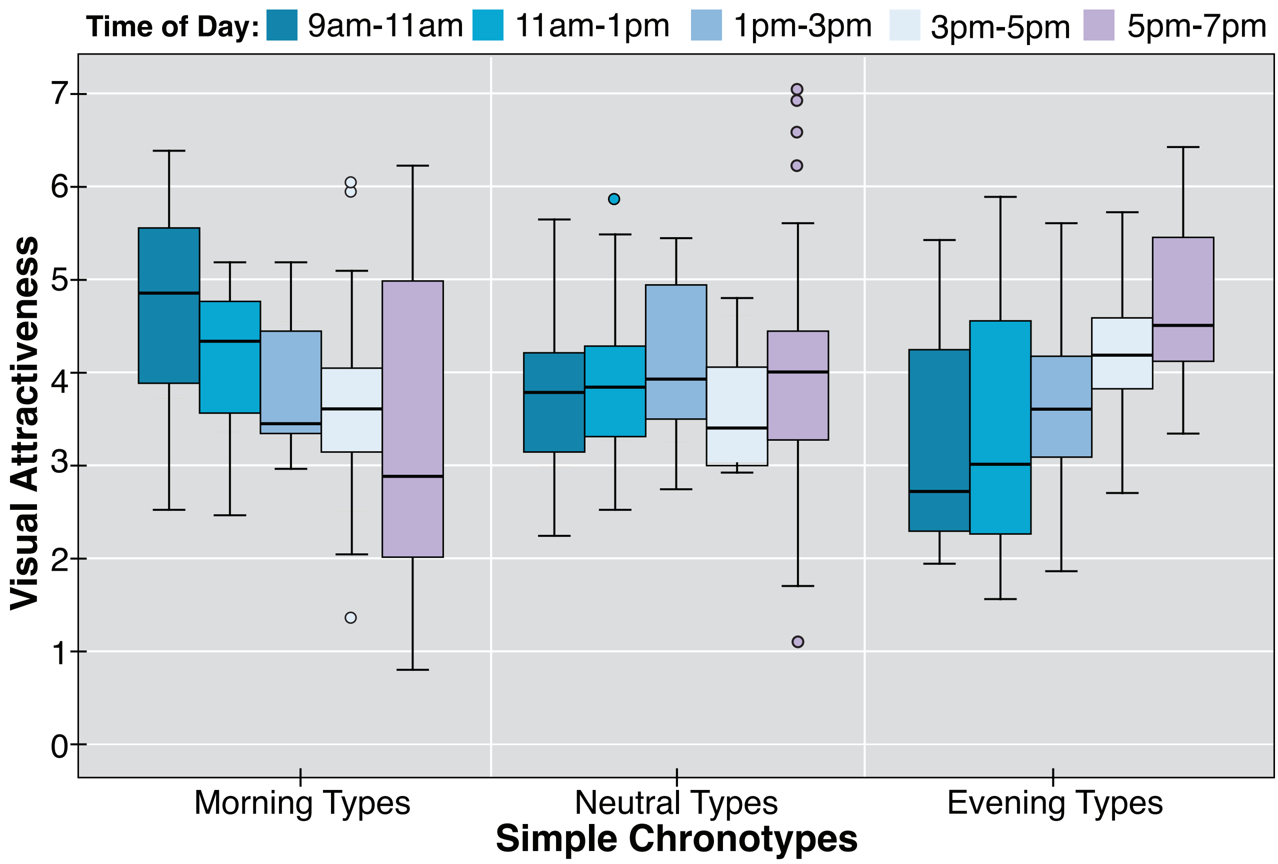

Figure 6-6: Boxplots of chronotypes and time of day influencing visual attractiveness

Correlations with Luminance Ratios

In experiment I, correlations of subject responses with absolute photometric criteria were examined. Further important characteristics of a lighting installation are the luminance variations within different areas of the visual field (Loe *et al.,* 1994). Uniformity and contrast are assumed to affect both brightness perception and visual attractiveness; the effect of these measures on the two components is presented here. Correlations between luminance ratios and response scores are more meaningful in experiment II, where luminances in the 40° horizontal band are held at 40 cd/m^2 within the limits of measurement uncertainty. Correlations between absolute luminances and luminance variations are shown in Table 6-6.

Table 6-6: Pearson correlations of average luminances with luminance ratios in experiment II

	$L_{Max\ 40°}/L_{Min\ 40°}$	$L_{Max\ 60°}/L_{Min\ 60°}$	$L_{Max\ Visual\ Field}/L_{Min\ Visual\ Field}$
$L_{Visual\ Field}$	0.03	0.03	-0.74
$L_{40°}$	-.0.10	-0.10	-0.77
$L_{60°}$	-0.13	-0.13	-0.79

Correlations of absolute luminances $L_{40°}$ and $L_{60°}$ with maximum to minimum ratios $L_{Max\ 40°}$ / $L_{Min\ 40°}$ and $L_{Max\ 60°}$/ $L_{Min\ 60°}$ were very small and not statistically significant. Regarding the whole visual field correlations between absolute luminance and minimum to maximum ratio were high. The reason for this is the area of overall minimum luminance that does not change across scenes and which lies within the visual field but not within the 40° or 60° horizontal bands. Changes of walls and ceiling luminance distribution, where the area of maximum luminance is located, result in a change of the maximum to minimum luminance ratio.

As in experiment I, a hierarchical linear model was used to calculate parameter estimates for the two component scores depending on photometric parameters and their ratios (Table 6-7).

Table 6-7: Pearson correlation of subject responses and maximum to minimum luminance ratios in experiment II

Photometric value	Pearson correlation with parameter estimates of visual lightness	Pearson correlation with parameter estimates of visual attractiveness
$L_{40°}$	0.07	-0,12
$L_{60°}$	0.10	-0.09
$L_{Visual\ Field}$	-0.04	-0.24
$E_{Eye\ Level}$	-0.17	-0.35
$L_{Max\ 40°}/L_{Min\ 40°}$	-0.91	-0.89
$L_{Max\ 60°}/L_{Min\ 60°}$	-0.91	-0.87
$L_{Max\ Visual\ Field}/L_{Min\ Visual\ Field}$	-0.39	-0.30

Judgements of visual lightness and visual attractiveness did not correlate significantly with absolute luminances. The correlations for luminance ratios in both the 40° and 60° horizontal band were high and statistically significant for both components. Correlations are close to equal since the maximum to minimum ratios are nearly the same for both bands. For a better comparability with current research the 40° horizontal band is explored here.

As expected there was a significant effect of the maximum to minimum luminance ratio in the 40° horizontal band on visual lightness, $F(11,68.33)=9.86$, $p<0.001$, and on visual attractiveness, $F(11,63.35)=14.13$, $p<0.001$.

Table 6-8 shows the estimated marginal means derived from the hierarchical linear model with the maximum to minimum luminance ratio in the 40° horizontal band.

Table 6-8: Estimated marginal means derived from hierarchical linear model for $L_{Max\ 40°}/L_{Min\ 40°}$

$L_{Max\ 40°}/L_{Min\ 40°}$	EMM visual lightness	SE visual lightness	EMM visual attractiveness	SE visual attractiveness
42.76	4.13	0.14	3.98	0.15
45.02	4.12	0.15	4.32	0.16
45.36	4.28	0.15	4.23	0.18
45.84	4.28	0.13	4.45	0.17
53.95	4.41	0.14	4.60	0.17
60.16	4.49	0.17	4.43	0.18
66.14	3.90	0.16	3.95	0.15
72.95	3.76	0.17	4.02	0.17
90.47	3.44	0.10	3.02	0.15
100.70	3.44	0.17	3.04	0.16
103.68	3.10	0.16	3.27	0.15
111.18	3.34	0.17	3.08	0.15

Analogous to experiment I, a power function regression was used to determine a mathematical estimation between the component scores and photometric quantities (Table 6-9). Coefficients of determination were R^2=0.79 for visual lightness and R^2=0.76 for visual attractiveness.

Table 6-9: Power function estimates

Estimated power function	R^2
$\text{visual lightness} = 0.35 \cdot L_{40°}^{0.632}$	0.79
$\text{visual attractiveness} = 0.216 \cdot L_{40°}^{0.769}$	0.76

As can be seen in Figure 6-7 and Figure 6-8, under similar average luminances visual lightness and visual attractiveness ratings in this experiment did not correlate with the luminance itself but rather on overall (maximum to minimum) luminance uniformity in a 40° horizontal band. Assuming that the mid-point of the visual lightness scale is the point where judgements change from generally dim to generally bright, for participants to judge the room to appear generally bright, a maximum to minimum luminance ratio of about $L_{max}/L_{min} \leq 90.4$ is needed. On average, participants judged the room as generally attractive when $L_{max}/L_{min} \leq 82.1$.

For both components two of the parameter estimates (marked in red in Figure 6-7 and Figure 6-8) noticeably deviate from the power function graph. They are the responses to the 'uniform' scenes with the two different desktop luminances that are rated over-proportionally higher compared to the other distributions.

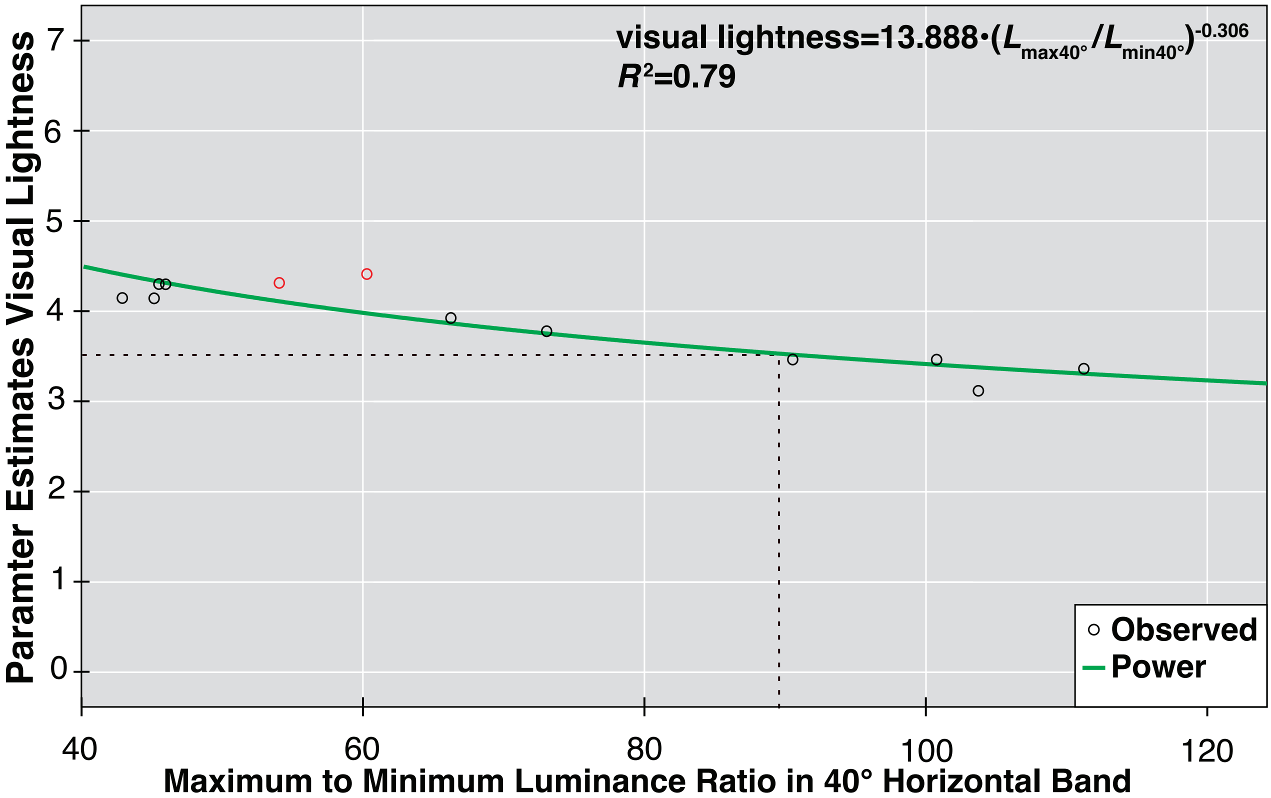

Figure 6-7: Parameter estimates of visual lightness and power function curve fit

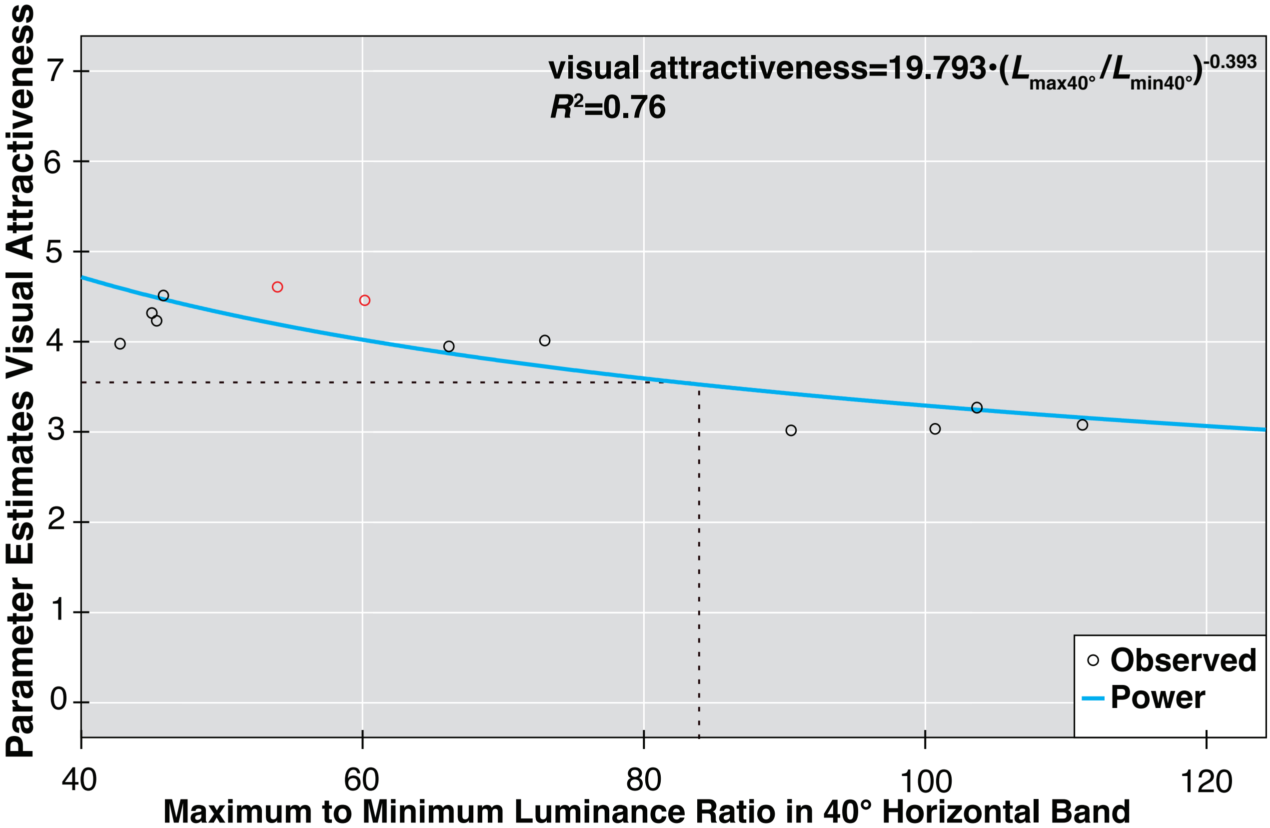

Figure 6-8: Parameter estimates of visual attractiveness and power function curve fit

6.6 Discussion

As for the first experiment, this brief discussion is structured by the experimental hypotheses. An overall discussion of outcomes and consequences of this work together with possible practical applications, and energy efficiency potentials is presented in section 8.

The distribution of background luminance affects the appraisal of visual lightness and visual attractiveness

In uniform lighting conditions as presented in the first experiment of this work, luminance seems to be an appropriate indicator to predict the occupants' impression of visual lightness and attractiveness of the space. In this experiment different luminance distributions were presented, changing the hierarchy and uniformity of the lighting. When non-uniform patterns were presented on walls and ceiling, absolute luminance alone could not determine visual appearance. Room appearance judgement varied between distributions, even though luminances in the visual field and the 40° horizontal band were kept constant within the measurement uncertainty. This supports the theory that brightness perception goes beyond a merely stimulus based concept. Since average luminances were kept constant and only uniformity and main focus changed, a stimulus-response system should have given the same brightness judgement for all presented scenes. This was not the case for the presented distributions. The employed hierarchical model implied that luminance uniformity (L_{max}/L_{min}) in a 40° horizontal band affected visual lightness judgements even for constant luminances. Similar results were observed in the visual attractiveness domain. A psychology-based concept of complexity, mystery and coherence by Kaplan (1987) may explain these outcomes. The naturally most coherent distribution was the 'uniform' scene, where the 40° horizontal band was evenly lit. The uniform light distribution enabled the space to "hang together" (Kaplan, 1987, p.9), hence, it was easy to understand. This distribution was judged as brighter and more attractive than all other presented scenes. The scenes 'Gradient Room Depth' and 'Step Room Depth' showed a non-uniform luminance distribution on walls and ceiling. However, in terms of coherence, all areas of the space were illuminated. The back of the room was connected to the working area by light. This is in accordance with findings by Jay (1971) where the perception of gloom improves, "if a table lamp is switched on in the darkest corner of the room" (Jay, 1971, p.141). The 'vertical gradient' represents a distribution well known by all participants. One can find vertical gradients with a luminance decrease from top to bottom in most lighting installations with ceiling mounted or pendant luminaires, especially when wall washing is included. The distributions 'gradient subject' and 'step subject' focus almost all the available light on the participant's position. These are scenes one finds in office spaces with windows during the day, when the occupant is seated close to the window with viewing direction parallel to the window plane. In the setting used in this work, however, the window wall and the windows were not illuminated separately; the luminance resulted not from the windows, but from the facing wall itself. Thus, bright windows are a missing component preventing the creation of a coherent scene. Additionally, the back of the room was kept dark for these scenes to a degree that this area of the space was visually 'cut off' from the desk area.

The effectiveness of a lit region to enhance visual lightness and visual attractiveness depends on the region's luminance, size, luminance distribution and position within the observer's visual field

Jay (1971) found that low gradients and corners without 'contrasting brightness' cause gloom perception; this result could not be verified in this study. On the contrary, the distribution with totally uniform luminances across walls and ceiling was perceived brighter and more attractive than non-uniform surfaces.

The differences in outcomes can be explained by the scope of the work. While Jay describes spaces with daylight and the resulting sharp gradients, this work only investigates artificial lighting. Gradients created by artificial light fixtures are usually lower in contrast than gradients created by daylight due to intensity and directionality of the light source (lamp compared to sun or overcast sky). A study by Perry, Campbell, and Rothwell (1987) suggests an increasing feeling of gloom when non-uniformities occur in the luminance distributions of a space. This work indicates similar results where more uniform distributions were judged as brighter than non-uniform.

The 'visual interest' scale used by Loe (1994) indicates that a room is perceived as more interesting as the ratio of maximum to minimum luminance in a 40° horizontal band increases. In this work, visual lightness and attractiveness of a scene, when disconnected from average luminances, increased with a decreasing maximum to minimum luminance ratio or increasing uniformity. At first glance, this appears to be a contradiction, since visual interest and attractiveness of a scene are parts of a similar affective domain. However, Kaplan's concepts of 'mystery' and 'coherence' (1987), may offer an explanation. Kaplan (1988) states that, although there are things that can be both interesting and attractive, this is not a necessary condition. Scenes or objects that attract interest are not necessarily attractive – and vice-versa. Attention to a part of the scene can be arrested involuntarily and thus, can be independent from pleasantness or attractiveness (James, 1984). This finding is also supported by Veitch and Newsham (2000), where the most preferred luminous conditions are not necessarily the most interesting scenes.

The results are somewhat dissenting from the results of Tiller and Veitch (1995), in which participants in a laboratory experiment matched the brightness of different scenes by adjusting the work-plane illuminance. In their investigation, a non-uniform luminance distribution over the field of view led to a lower adjusted work-plane illuminance compared to a room with relatively uniform luminance distribution. However, it is possible that in the investigation by Tiller and Veitch participants used the brighter areas of the room for their judgements while in this study the darker areas were used for visual lightness ratings. Thus, non-uniform luminance distributions may appear brighter when adjusting equivalent brightness and can still appear gloomy when rated independently (cf. Tiller & Veitch, 1995, p.147).

The findings of this study may also serve as an example where Cuttle's (2013) concept of Mean Room Surface Exitance (MRSE) does not properly render room brightness. Since the distributions used in this work were of equal average room surface luminance, it can be assumed that all six presented scenes had roughly the same mean room surface exitance. The different ratings show that an average quantity of reflected light alone cannot fully describe perceived adequacy of illumination. Work by Kato and Sekiguchi (2005) suggested that there is a difference in effectiveness for brightness perception between horizontal and vertical surfaces, e.g. walls compared to the ceiling. In this work, luminances on these two room surfaces were considered together. Interestingly, in the present setup the ceiling is not included in the described 40° horizontal band. Research subsequent to this work should consider the impact of luminance distributions on room appearance distinguishing between walls and ceiling to further investigate the importance of the 40° band.

The interaction between chronotype and time-point of observation has an effect on judgements of visual lightness and visual attractiveness

Probably due to the smaller sample size, the results from experiment I could not be confirmed since the interaction effect was not statistically significant. However, graphical examination of the data indicated that the participants' judgement of the space indeed changed depending on chronotype and time of observation. Boxplots showed a trend similar to the trend in experiment I, where morning types rated higher in the morning and evening types showed a reverse effect. Due to the smaller sample size and the randomized assignment to the different conditions there were only few participants in each group. To confirm or disprove the effect found in experiment I, more research with larger sample sizes is needed.

7 Possible Sources of Error and Measurement Uncertainties

Just like physical measurements, measurements of psychological and behavioural mechanisms are prone to errors and biases. Possible measurement uncertainties are discussed in this chapter. Considered sources of error include the experimental setup, procedure and questionnaire, sample characteristics, photometric measurements and statistical procedure.

7.1 Setup and Outline

All experiments took place in a laboratory environment. The experimental setup was equipped with a very minimalist interior, which included no furniture other than two desks. The advantage of this is the lack of distracting objects and the possibility of free variation of photometric variables with minimal furniture interference. However, there are some disadvantages. The laboratory space is clearly not a real office, so no general definitions for real offices can come from this work. A very monotonous environment can lead to floor effects where the space is perceived unattractive regardless of the variation of variables. Such effects could not be identified from the data. Still it is possible that some experimental outcomes are biased. Since there were no additional pieces of furniture or other stimuli, it was possible for participants to notice that they took part in an experiment about changes in lighting. So even if participants were only asked about the appearance of the space, it is possible that changes in lighting were consciously evaluated.

In the laboratory, back-lit walls and ceiling simulate reflecting surfaces, which could be perceived by the participants. Thus, the overall impression of the experimental space differs from illuminated reflecting surfaces. No research could be found on this issue. A difference in apparent brightness between illuminated and back-lit surfaces of equal luminance is possible. Thus, a possible influence cannot be estimated and the accuracy of obtained quantitative values can be questioned.

The desktop illumination provided by the projectors was noticeably different from the LED-lighting due to the higher correlated color temperature. Since the projectors' spectral power distribution was constant throughout all experiments, no experimental bias occurs from the difference in color temperature for the comparison between scenes.

Regarding the designed scene exposure schedule, it was assumed that a five-minute scene sufficiently modeled office working day conditions. Effects of fatigue and boredom could not be examined in this work. Finally, the exposure schedule could not completely guarantee that participants' room perceptions were completely unaffected by previous scene memory. Distraction scenes were used to minimize this effect.

The office tasks were not challenging enough to evaluate the effects of lighting on task performance. The lighting setup, with the projectors being the only light source for task lighting, created disturbingly sharp shadows on the desk, especially for lower wall and ceiling luminances. When background luminance increased, shadows were softened to some degree by a reduced projected illuminance and increased diffuse lighting. This may have contributed to the higher attractiveness scores obtained with higher background luminances.

In experiment II, different luminance distributions on the walls and ceiling were presented at equal average luminances in a 40° horizontal band. The distributions 'gradient subject' and 'gradient room depth' ('step subject' and 'step room depth' respectively) show similar distributions mirrored on the facing wall's cross axis. Due to the geometry of the experimental space and the observer position in the room, the aim was not to create symmetrically mirrored distributions but present different lighting hierarchies and uniformities. Thus, the conclusions drawn from experiment II are qualitative in nature, and do not compare absolute luminance or luminance ratio values to participant perception directly.

7.2 Sample

As shown in the power analysis, the different sample sizes were sufficiently large for the various experiments with statistical powers of 0.95 or greater. However, the designed power value is only valid if the estimated effect size is held. Since the non-significant main effects in this work often had a lower effect size, the power of 0.95 may not have been achieved. Thus, a non-significant effect does not determine that the measured variable has no influence on the evaluation of the room. Effect sizes for the between groups effects of chronotype and time were medium to large. Thus, the sample size was large enough to explore main effects and interactions. However, observations derived from further sub-divisions of the groups (e.g. morning types at a certain time of day observing one specific lighting scene) use significantly smaller sample sizes, and can only be used as an indicators in a pilot study. This is especially the case for morning and evening types since they make up a smaller portion of the overall population and thus, the sample as compared to neutral types. One approach to obtain a larger number of responses by morning and evening types would be to determine participants' chronotypes in advance and discard the neutral types. This was not possible in this work.

No controlled effects of fatigue could be investigated with the available sample size. Possibly, some participants in the evening responded lower due to the work performed during the day. This possible bias does not challenge the qualitative results of the experiment, since all participants should have been equally affected. Still, the results may be biased if the fatigue effect was different for different chronotypes.

Although a sufficient diversity of working backgrounds was included, the sample does not fully represent the overall population. Only young-to-middle-age Western European persons participated in the study. Thus, the study cannot be seen as a fundamental perception experiment, and is valid only within its boundaries.

7.3 Questionnaire

The questionnaire used in this experiment has evolved over time and experimental iteration by different researchers. Nonetheless, bipolar scales and factor analysis can only be used to evaluate the factors specifically mentioned in the survey. It is possible and more than likely that there are more dimensions to room appearance than the ones found here.

From the overall results, it can be inferred that, to some extent, attractiveness is determined by the appraisal of lightness. Although the conducted PCA reduced the dimensionality of visual appearance to these two factors, these factors vary in similar ways. An explanation may be that the potential to work and perform well within a space leads to a degree of satisfaction that, in turn, makes the space appear attractive.

It is also noted that the usage of bipolar scales has several drawbacks. These problems were discussed in 5.1. Lighting preference derivation is not in the scope of this work. Although previous investigations have used scale midpoints to identify preference or acceptance, it is entirely unknown if the midpoints used in this work indeed represent acceptance or preference. Rather, the results in this study refer to the midpoint as a reversal point only (e.g. the point where room appearance changes from generally bright to generally dim) and do not imply acceptance or preference.

7.4 Statistical Procedure

All basic assumptions for the PCA and parametric tests were tested and assumed fulfilled. Large sample sizes often lead to normal sampling distributions regardless of the actual distribution of the collected data. Field (2009, p.134) quantified a critical sample of 30 or more. Regardless, F-tests have often been claimed to be robust to skewed distributions (e.g. Glass, Peckham, & Sanders, 1972).

The performed multivariate analysis of variance (MANOVA) with orthogonal pre-planned comparisons avoids an accumulation of type I errors. However, in some cases, orthogonal contrasts could not lead to the planned comparisons and non-orthogonal contrasts were used. This can lead to type I error accumulations that cannot be quantified. Significance levels in this case were lowered from 0.05 to 0.01. It can be assumed that this is sufficient to counterbalance potentially higher type I errors in non-orthogonal planned comparisons. Due to a smaller significance level than used in the power analysis, power assumptions cannot be held for non-orthogonal contrasts.

As already stated in section 7.2, power analysis led to statistical powers of >0.95 for all tests and the given effect sizes. However, for non-significant effects, effect sizes were often smaller than the estimated sizes, which decreased statistical power. Therefore, type II error probabilities cannot be determined clearly; for variables with non-significant test results, it cannot always be concluded that the effect is non-existent.

Generally, regarding the statistical tests performed in this work one must bear in mind that statistics do not imply causality, but rather serve as an indicator for an actually existing correlation. However, participants were randomly assigned to the different experimental conditions. Thus, according to Cook and Campbell (1979) for significant between-group differences causality with experimental manipulations can be assumed. Regarding the random assignment of participants to different times of day it can be seen that there were generally more participants conducting the experiment in the morning (9 am - 11 am) and evening (5 pm - 7 pm). This was probably due to working hours or university class schedules; participants simply took part in the experiments before or after their daily schedule. On the one hand this results in a higher group affiliation and thus, a greater sample size for comparisons between these two groups. On the other hand the randomness of assignments may be compromised to some extent.

7.5 Uncertainty of Photometric Measurements

All photometric measurements are subject to a certain degree of uncertainty. An estimation of the uncertainties and errors for the different measurements in this work is presented here. The measurement uncertainty u of a quantity X can be estimated using the root mean square of systematic uncertainty u_{sys} and random uncertainty u_{stat} (Geschke, 2001):

$$u(X) = \sqrt{u_{sys}^2(X) + u_{stat}^2(X)} \tag{7-1}$$

Systematic uncertainties include errors due to deficiencies of measuring equipment and setting; statistical uncertainties arise from the statistical dispersion of random environmental factors.

Uncertainty of Illuminance Measurements

Photometer heads of error class A were used to measure surrounding area illuminances. Thus, the mean square error according to DIN 5032-7 (DIN, 1985) should not exceed 5% (Table 7-1). Since the LED-panels do not emit UV-radiation and coated glass lenses shield the projector lamps, the measurement error due to UV-radiation can be regarded as insignificant. IR-radiation could not be ignored since the projectors generated noticeable heat. Temperature was held at a roughly constant 25°C during all measurements; the temperature coefficient was estimated to 0.4%, corresponding to a temperature deviation of 2 K. LED-panel dimming was implemented using pulse width modulation. The shape of modulation was randomized for each individual panel to avoid noticeable flicker. The scanner-readout was integrating with an integration time of 200 ms. Thus, the error due to light modulation was estimated to 0.1%.

Table 7-1: Maximum and estimated error types for class A photometer heads

Error Type	Error margin according to DIN 5032, error class A	Estimated error in this work
f_1: $V(\lambda)$-adjustment	3%	3%
u: UV-sensitivity	1%	-
r: IR-sensitivity	1%	1%
f_2: cosine adjustment	1.5%	1.5%
f_3: linearity error	1%	1%
f_4: indication error	3%	3%
a: temperature coefficient	0.2%/K	0.4%, ±2 K
f_5: fatigue	0.5%	0.5%
f_7: light modulation	0.2%	0.1%
f_{11}: adjustment error	0.5%	0.5%
Mean square error:	**5%**	**4.78%**

All investigated types of error are independent from each other. Thus, the systematic mean square error can be calculated from the maximum error values:

$$u_{sys}(E) = \sqrt{f_1^2 + u^2 + f_2^2 + f_3^2 + f_4^2 + a^2 + f_5^2 + f_7^2 + f_{11}^2} = 4.78\% \tag{7-2}$$

with u, r, a, f_i described in Table 7-1.

Descriptive statistics of a test series cannot be determined in this work since every measurement was only taken once. Thus, the errors due to statistical variations in the laboratory setup cannot be estimated. However, additional sources of random errors include deviations of the photometer-head position from an exactly horizontal position, and work plane height. It can be assumed that the maximum tilt did not exceed 5°. Illuminance measurements were taken under different angles to the horizontal plane for error estimation (Table 7-2). In the following tables the underlined values mark the maximum deviation.

Table 7-2: Illuminance measurements under different angular deviations

Angular deviation from horizontal plane (f_a)			
0°	**-5°**	**+5°**	**Deviation**
25.7 lux	25.7 lux	25.7 lux	0.0%
137.6 lux	137.5 lux	137.5 lux	0.07%
180.1 lux	180.2 lux	179.7 lux	<u>0.2%</u>
237.4 lux	237.0 lux	236.8 lux	0.02%
542.3 lux	541.5 lux	540.9 lux	0.02%

The deviation in measurement positioning in each direction is assumed to not exceed ±5 cm. The uncertainties due to faulty positioning are estimated by taking reference measurements at different heights and horizontal positions in the space (Table 7-3).

Table 7-3: Illuminance measurements at different positions

Deviation in Height from 0.8 m work plane (f_z)			
0 cm	**-5 cm**	**+5 cm**	**Deviation**
25.7 lux	25.6 lux	25.8 lux	<u>0.3%</u>
137.6 lux	137.5 lux	137.9 lux	0.2%
180.1 lux	180.0 lux	180.4 lux	0.1%
237.4 lux	237.4 lux	238.1 lux	<u>0.3%</u>
542.3 lux	541.5 lux	542.9 lux	0.1%
Deviation in x-direction (f_x)			
0 cm	**-5 cm**	**+5 cm**	**Deviation**
25.7 lux	25.9 lux	26.1 lux	1.5%
137.6 lux	138.1 lux	136.3 lux	0.9%
180.1 lux	180.7 lux	183.4 lux	<u>1.8%</u>
237.4 lux	240.3 lux	235.9 lux	1.2%
542.3 lux	545.8 lux	540.1 lux	0.6%
Deviation in y-direction (f_y)			
0 cm	**-5 cm**	**+5 cm**	**Deviation**
25.7 lux	25.8 lux	25.5 lux	0.7%
137.6 lux	138.1 lux	136.4 lux	0.8%
180.1 lux	181.7 lux	181.4 lux	0.8%
237.4 lux	241.3 lux	235.9 lux	<u>1.6%</u>
542.3 lux	546.6 lux	541.3 lux	0.8%

The random mean square error can be calculated using the maximum measured deviations.

$$u_{\text{stat}}(E) = \sqrt{f^2_{\text{a, max}} + f^2_{\text{z, max}} + f^2_{\text{x, max}} + f^2_{\text{y, max}}} = 2.44\% \tag{7-3}$$

From equation (5-2) on page 60), the total measurement uncertainty for the illuminance measurements can be estimated to

$$u_{\text{total}}(E) = \sqrt{u^2_{\text{sys}}(E) + u^2_{\text{stat}}(E)} = 5.37\% \tag{7-4}$$

The maximum illuminance deviation of 5.37% does not affect subjective responses on brightness perception, as participants cannot perceive differences on this order of magnitude (cf. Hentschel 1994, p.51).

Uncertainty of Luminance Measurements

The LMK 98 luminance camera was calibrated by the manufacturer according to DIN 5032 (DIN, 1985). Standard error class designations for space-resolved luminance measurement instrumentation does not currently exist. To estimate the error budget, a calibrated LMT luminance meter was used. Since a procedure for error classifications of luminance meters exists, the outcomes of both measurements can be compared. To achieve relevant results, the comparison took place in the experimental laboratory used in this work. A luminance camera was used to identify 12 areas of different luminances ranging from 9 cd/m^2 to 100 cd/m^2, which were used to investigate the full luminance range used in this work. To exactly define the measurement area, a rectangular field with an angle of aperture of approximately 1° corresponding with the 1°-aperture of the luminance meter was marked with masking tape (Figure 7-1).

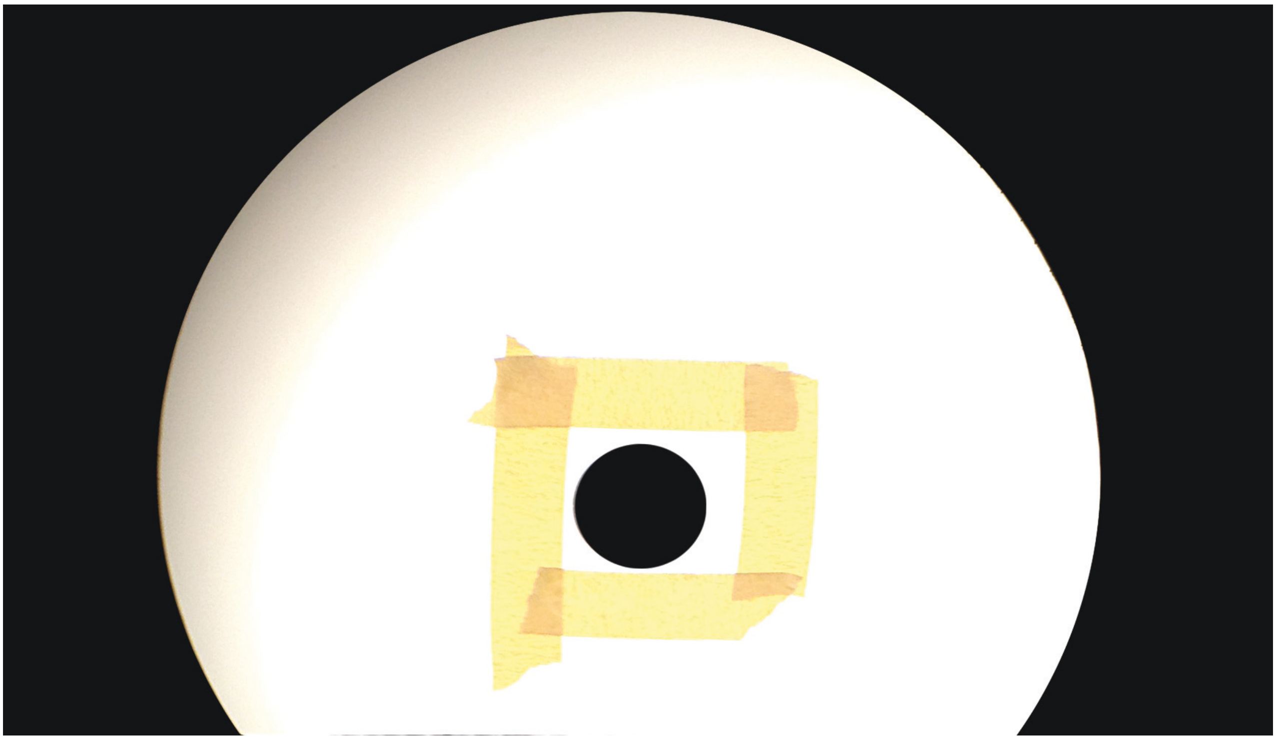

Figure 7-1: Aperture of luminance meter inside the measurement area

The edges of the tape were used to enhance the luminance meter focus. The same circle shaped area was defined as a 'region' in the LMK Labsoft software for the luminance camera. The results of the different measurements can be seen in Table 7-4. The deviation between the camera and the luminance meter loosely depended on the absolute luminance and was highest for a luminance of about 95 cd/m² (5.17%).

Table 7-4: Comparison of luminance camera and luminance meter

LMK 98 luminance camera measurement in cd/m²	LMT luminance meter measurement in cd/m²	Deviation
9.05	8.93	1.37%
25.08	25.9	3.17%
45.22	47.2	4.19%
71.9	68.6	4.81%
92.55	97.6	5.17%
25.33	25.9	2.20%
45.87	47.5	3.43%
70.87	69.1	2.56%
9.11	8.75	4.14%
25.32	26.6	4.81%
45.53	47.8	4.75%
69.06	72.2	4.35%

Table 7-5 contains error parameters derived from DIN 5032 (DIN, 1985) for the luminance meter and estimated errors for the measurement setup in this work. Assumptions previously made for the illuminance measurements regarding UV- and IR-radiation, temperature deviations and light modulation are kept. To reduce spatial assessment errors and errors due to deviating surrounding luminances, only areas with small luminance heterogeneity were chosen. This was estimated to reduce these two error types to 2% (spatial assessment) and 1% (surrounding luminance). Since no polarized light was emitted directly from the light sources, a reduced polarization error (0.5%) was estimated. Focusing on the diffuse walls of the laboratory turned out to be almost impossible. Thus, a test pattern often used for the evaluation of photo cameras was used as an aid for exact focusing. The estimated focusing error was reduced to 0.5%.

Table 7-5: Maximum and estimated error types for class A luminance meters

Error Type	Error margin according to DIN 5032, error class A	Estimated error in this work
f_1: V(λ)-adjustment	3%	3%
u: UV-sensitivity	1%	-
r: IR-sensitivity	1%	1%
$f_{2(g)}$: spatial assessment	3%	1%
$f_{2(u)}$: surrounding luminance	1.5%	1.5%
f_4: indication error	3%	3%
a: temperature coefficient	0.2%/K	0.4%, ±2 K
f_5: fatigue	0.5%	0.5%
f_7: light modulation	0.2%	0.1%
f_8: polarization error	1%	0.5%
f_{11}: adjustment error	0.5%	0.5%
f_{12}: focusing error	1%	0.5%
Mean square error:	**7.5%**	**4.84%**

The mean square error from DIN 5032 includes a calibration error, so an estimated calibration error for the luminance meter has to be taken into account as well. The last calibration was in the year 2000 by PTB (German national metrology institute), which found a calibration error of 1.4%. Since all error types are independent from one another, the mean square error can be calculated according to 5.4.1, leading to a total mean square error of 5.04%. With the results for the maximum error of the luminance meter, the measurement error of the space-resolved procedure can be estimated using Table 5-4. Thus, the estimated systematic mean square error $u_{sys}(L)$ of the luminance camera within the range used in this work is estimated to

$$u_{sys}(L) = \sqrt{(5.04\%)^2 + (5.17\%)^2} = 7.22\% \tag{7-6}$$

Like with illuminance measurements, random errors in luminance measurements can only be estimated to a certain degree. A deviation between measurement values due to positioning or measurement angle can be ruled out. The position of the luminance camera was not changed during all measurements and the camera was not moved in any way. An error with possible influence on the outcomes of the experiment is the difference between the camera position and the participants' viewing position. The first deviation concerns the angular deviation from the participants' axis of vision. A maximum tilt of ±2.5° was assumed for both, vertical and horizontal tilts. Table 7-6 shows measurements of the 40° horizontal band under different angles.

Table 7-6: Luminance measurements under different angular deviations

Horizontal deviation from axis of vision ($f_{a,\mathrm{hor}}$)			
0°	**-2.5°**	**+2.5°**	**Deviation**
25.44 cd/m²	25.37 cd/m²	25.8 cd/m²	1.3%
37.38 cd/m²	37.83 cd/m²	36.97 cd/m²	1.2%
52.68 cd/m²	53.21 cd/m²	52.76 cd/m²	1%
70.12 cd/m²	71.01 cd/m²	69.89 cd/m²	1.3%

Vertical deviation from axis of vision ($f_{a,\mathrm{vert}}$)			
0°	**-2.5°**	**+2.5°**	**Deviation**
25.44 cd/m²	25.45 cd/m²	25.87 cd/m²	1.7%
37.38 cd/m²	37.21 cd/m²	36.81 cd/m²	1.5%
52.68 cd/m²	52.81 cd/m²	52.29 cd/m²	0.7%
70.12 cd/m²	70.35 cd/m²	69.72 cd/m²	0.5%

The deviation of the participants' eye position from the camera position was estimated to not exceed 10 cm in each direction (Table 7-7).

Table 7-7: Deviations in x,y and z-direction

Deviation in height (f_z)			
0 cm	**-10 cm**	**+10 cm**	**Deviation**
25.44 cd/m²	25.42 cd/m²	25.53 cd/m²	0.3%
37.38 cd/m²	37.68 cd/m²	36.98 cd/m²	<u>0.8%</u>
52.68 cd/m²	52.84 cd/m²	52.76 cd/m²	0.3%
70.12 cd/m²	70.33 cd/m²	69.91 cd/m²	0.3%

Deviation in x-direction (f_x)			
0 cm	**-10 cm**	**+10 cm**	**Deviation**
25.44 cd/m²	25.49 cd/m²	25.45 cd/m²	0.2%
37.38 cd/m²	37.42 cd/m²	37.40 cd/m²	0.1%
52.68 cd/m²	52.94 cd/m²	52.63 cd/m²	<u>0.5%</u>
70.12 cd/m²	70.22 cd/m²	70.01 cd/m²	0.1%

Deviation in y-direction (f_y)			
0 cm	**-10 cm**	**+10 cm**	**Deviation**
25.44 cd/m²	25.57 cd/m²	25.55 cd/m²	<u>0.5%</u>
37.38 cd/m²	37.50 cd/m²	37.31 cd/m²	0.3%
52.68 cd/m²	52.79 cd/m²	52.78 cd/m²	0.2%
70.12 cd/m²	70.19 cd/m²	70.19 cd/m²	0.1%

The random mean square error is again calculated using the maximum measured deviations.

$$u_{\text{stat}}(L) = \sqrt{f^2_{\text{a, hor, max}} + f^2_{\text{a, vert, max}} + f^2_{\text{z, max}} + f^2_{\text{x, max}} + f^2_{\text{y, max}}} = 2.39\% \quad \textbf{(7-7)}$$

The total mean square error is calculated using equation (7-1) on page 90.

$$u_{\text{total}}(L) = \sqrt{u^2_{\text{sys}}(L) + u^2_{\text{stat}}(L)} = 7.61\% \quad \textbf{(7-8)}$$

A luminance difference of 7.61% at luminance levels used in this work cannot be perceived by the participants (cf. Hentschel, 1994, p.51) and thus, can be assumed to not influence subjective responses.

8 Overall Discussion and Practical Application

The experiments in this work investigated the influence of different photometric criteria and individual differences on room appearance. Room appearance was quantified by two components: visual lightness and visual attractiveness. These are not the only dimensions of the appraisal of a lit scene, but include an environmental appraisal (visual lightness) and an affective response (visual attractiveness).

The studies were designed to separate independent variables to connect changes in the participants' judgements to specific photometric quantities. Independent measures included surrounding area illuminances, luminances and luminance distributions in different areas of the visual field, and luminance uniformities. An elaborate laboratory design, which did not include any commercially available office lighting fixtures, was used to create customized lighting scenes. The experimental space was sparsely furnished in order to enable participants to experience the luminous environment without distracting objects. Thus, a comparison to an actual office with typical office luminaires and furniture is only possible in a qualitative sense.

The overall interpretation of results showed that the appraisal of an office scene only depends marginally on changes in horizontal illuminances on the work plane when the actual workplace is excluded. Lighting standards like EN 12464-1 (2011) give minimum recommendations for task to surrounding area illuminance ratios that are in the order of 1.7:1. A typical task area illuminance of 500 lux results in a surrounding area illuminance recommendation of 300 lux. The results of this experiment indicate that a decrease to 100 lux only marginally affects the way an office is experienced. The thereby 'saved' luminous flux could be used to enhance the appearance of the space in a more effective way.

A strong dependency of human responses on vertical luminances suggests that for a room to appear light and attractive, wall and ceiling luminances greater than 30-40 cd/m^2 should be achieved in the lighting design process. To increase luminances on vertical surfaces is a more effective lighting design technique to enhance the appearance of a space than increasing horizontal illuminances. The European standard EN 12464-1 recommends a minimum wall illuminance of 75 lux and a ceiling illuminance of 50 lux, resulting in luminances in the order of 11 cd/m^2 (s. section 2.2, p.24 for explanation). The results of this work indicate that these levels are insufficient for the creation of bright and attractive spaces. However, to achieve adequate vertical luminances, an increased energy usage, as compared to an installation exclusively fulfilling EN 12464-1, is unavoidable. Partially, the additional costs and overhead energy consumption can be balanced out by decreasing horizontal illuminances in non-task areas as well as increased reflectance of room surfaces. In terms of energy efficiency these two hypothetical situations cannot directly be compared. Since they work on different lighting quality levels, a different measure (e.g. lighting quality per kWh) would be necessary.

Regarding the luminance distribution in the visual field, the results obtained in this study suggest a preference for coherent distributions that include the whole room, rather than non-uniform distributions and distinct high-contrast zoning of the space. While lighting standards usually recommend average illuminances and uniformities, the results obtained in the second experiment of this work suggest that the coherence of surfaces in the visual field is also an important factor in terms of visual appearance. Maximum to minimum luminance ratios as well as the composition of illuminated areas in the field of view should be considered when an office lighting installation is designed. The observed effect of the interaction between desktop and background luminance supports the demand for adequate zoning of the space also depending on overall luminance levels. Direct implications for interior lighting design regarding this interaction effect cannot be quantified here. However, since desktop illuminance was kept at a constant level throughout the study, it supports the theory that designing by illuminances alone is not an appropriate lighting design approach. Luminances on all surfaces of a space, along with uniformities, ratios and between-surface contrasts should be taken into account to create bright and attractive workplaces supporting human needs and well-being.

Differences in subjective ratings of room appearance were also found for groups of different individual characteristics. An examination of between-groups variables showed a significant interaction between chronotype and time of day in the first experiment, where morning-types judged the space as lighter and more attractive in the morning while evening-types rated higher in the evening. The interaction effect could not be reproduced in the second experiment since it was not statistically significant. However, graphical interpretation showed trends similar to the outcomes of the first experiment. This may indicate a non-significant effect only due to an insufficient sample size.

A hierarchical model and subsequent curve fit indicated, that for participants affiliated to different groups the necessary average luminance in a 40° horizontal band for a room to appear generally bright and attractive varied significantly. For evening types, luminances in the 40° horizontal band may be lower in the evening than in the morning for a space to appear generally bright (33.0 cd/m^2 in the evening and 56.5 cd/m^2 in the morning) and generally attractive (28.7 cd/m^2 / 47.0 cd/m^2). For morning types, luminances may be lower in the morning for a general perception of visual lightness (34.5 cd/m^2 / 52.0 cd/m^2) and visual attractiveness (36.0 cd/m^2 / 50.0 cd/m^2). Although not conclusively observed due to the available sample size, a chronotype and time of day interaction implies the need for a higher level of lighting control. It is likely for occupants to adjust the light settings according to their chronotype and the time of day if provided with the opportunity. The resulting energy savings potential can only be utilized with highly adaptive lighting installations and the use of practicable lighting control systems. Together with a better understanding of the office workers' individual characteristics, this approach has the potential to create visually more effective spaces with lower energy usage. A higher individual controllability also forms an additional mechanism determining lighting quality (Veitch, 2001) that was not investigated in this work. Bearing an energy savings potential, research on the topic is still necessary to quantify the effect.

It becomes clear that the appearance of an office space is affected by lighting in a more complex way than considered by current lighting standardization. Solid-state lighting, as a highly adaptable technology, both in the sense of lighting control systems and optics, has the potential to fulfill complex and detailed requirements. However, lighting standardization should adapt to the possibilities, giving recommendations in a more detailed way.

As a summary can be stated: If energy efficiency in lighting can be defined as the fulfillment of all necessary lighting quality criteria with the least possible amount of energy usage, finding a way to efficiently control and guide light according to human needs is a necessary and sufficient condition to achieve energy efficient lighting installations.

This work can serve as a pilot study for further research on the topic. For subsequent investigations a higher diversity of luminance distributions in the visual field is recommended to further examine the effect of coherence and zoning of an office space. In this work, luminances on facing wall and ceiling were manipulated together. Thus, it is not surprising that the luminance in the 40° horizontal band was the critical factor determining human responses. If both surfaces are manipulated separately, ceiling luminance, although not a part of the 40° band, will naturally have an additional impact on room appearance. To elaborate the importance of the different surfaces available in the space for room appearance in a more detailed way, additional studies are necessary. Follow-up experiments with a much larger sample size could confirm the interaction effect between chronotype and time of day. An analysis of the sample distribution in this work could support a power analysis and research design, where all 15 groups (3 chronotypes x 5 times of day) are of adequate size. As an important step towards the practical application of the empirical findings of this work, a field experiment is necessary to transfer the results from the laboratory into an actual office.

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Appendix A

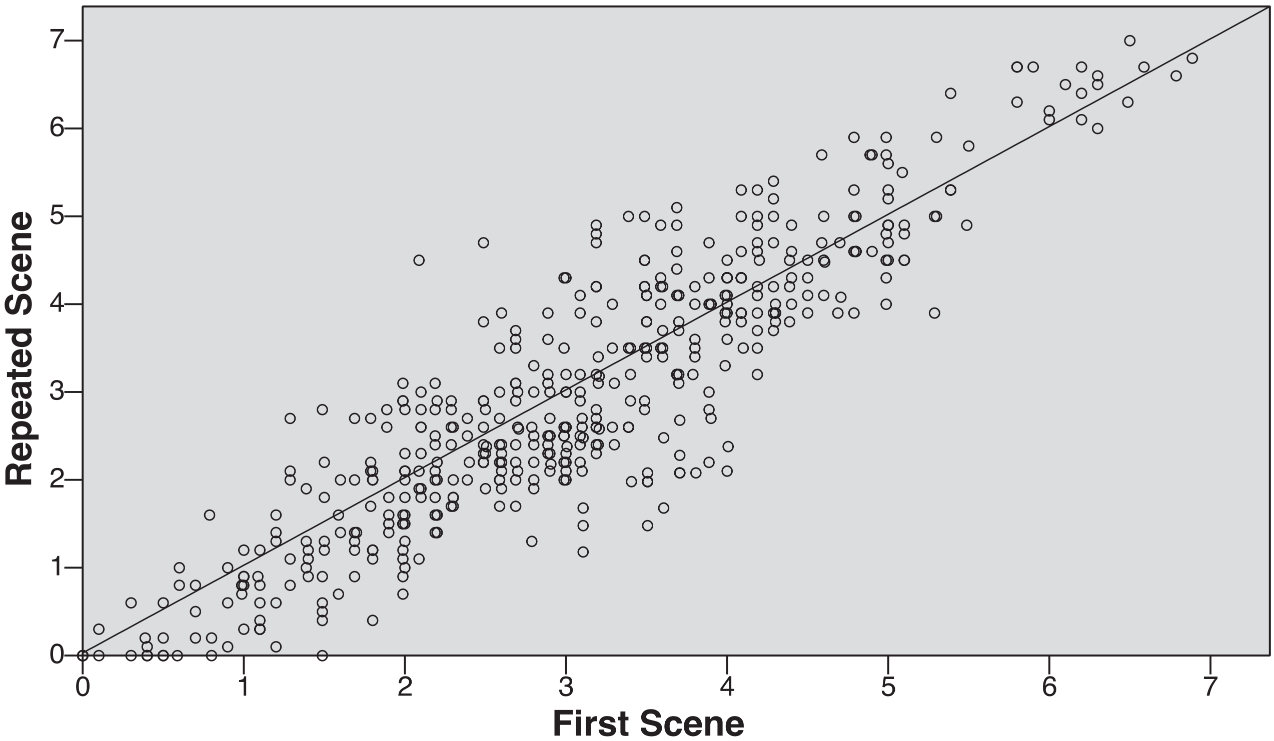


Figure A-1: Scatter plot of Repeated Scenes from experiment I with reference line y=x

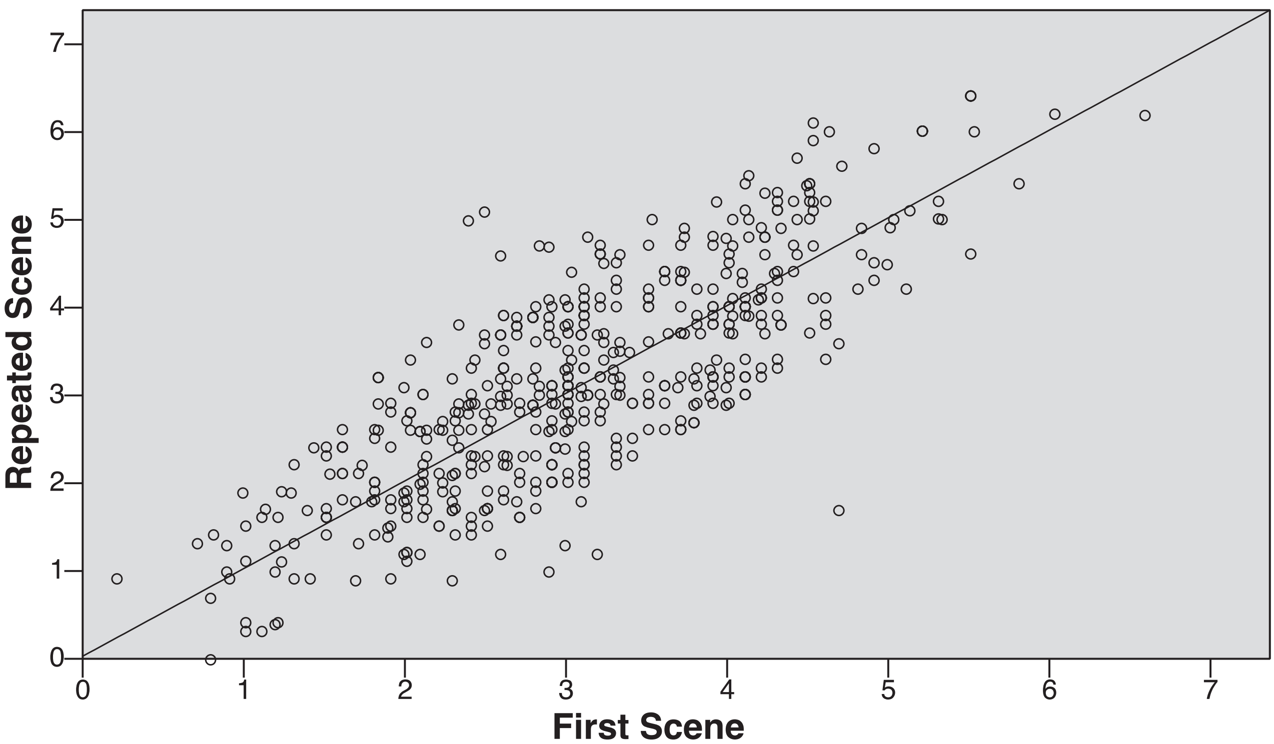


Figure A-2: Scatter plot of Repeated Scenes from experiment II with reference line y=x.

Boxplots and Outliers

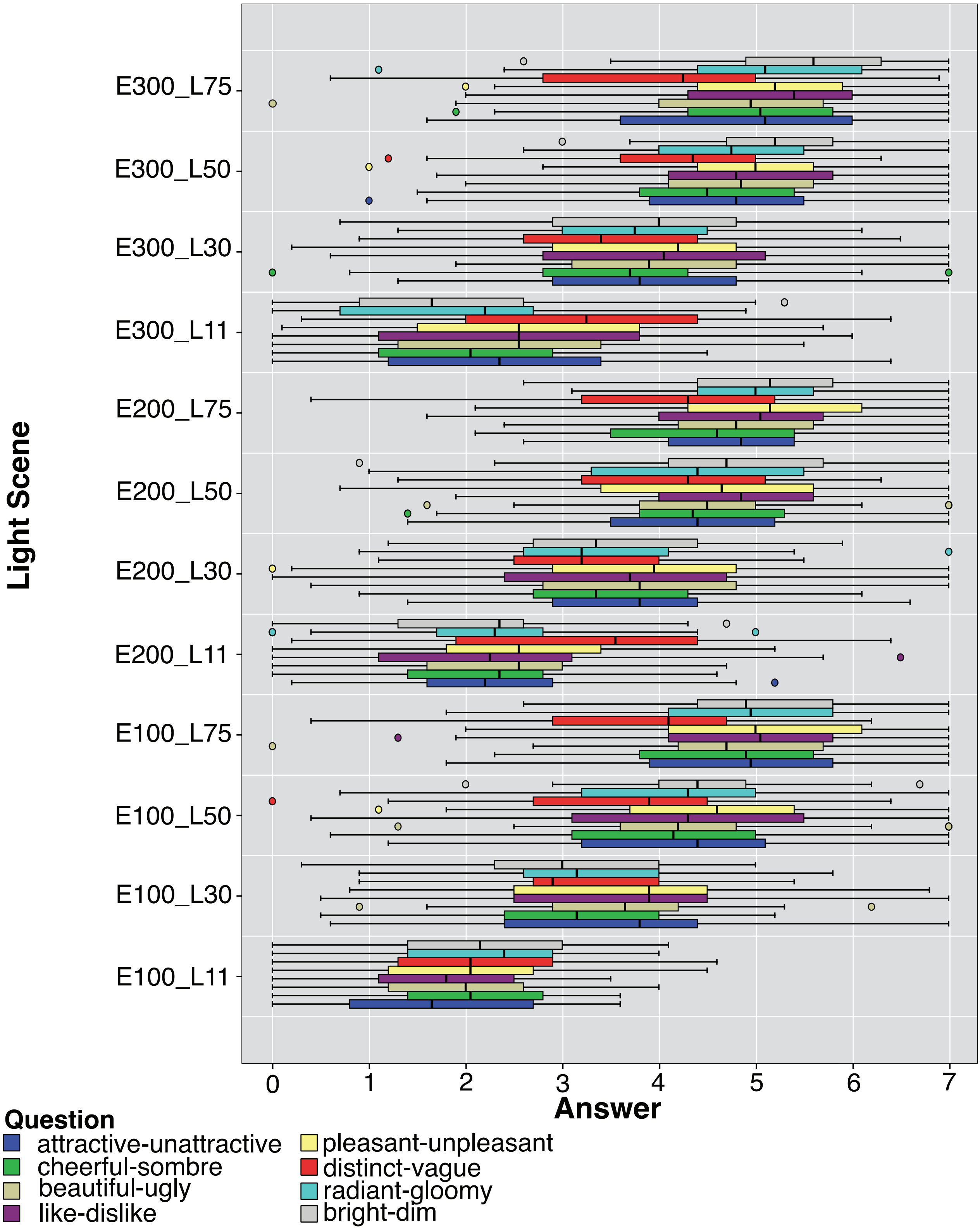


Figure A-3: Boxplot with outliers of Experiment I

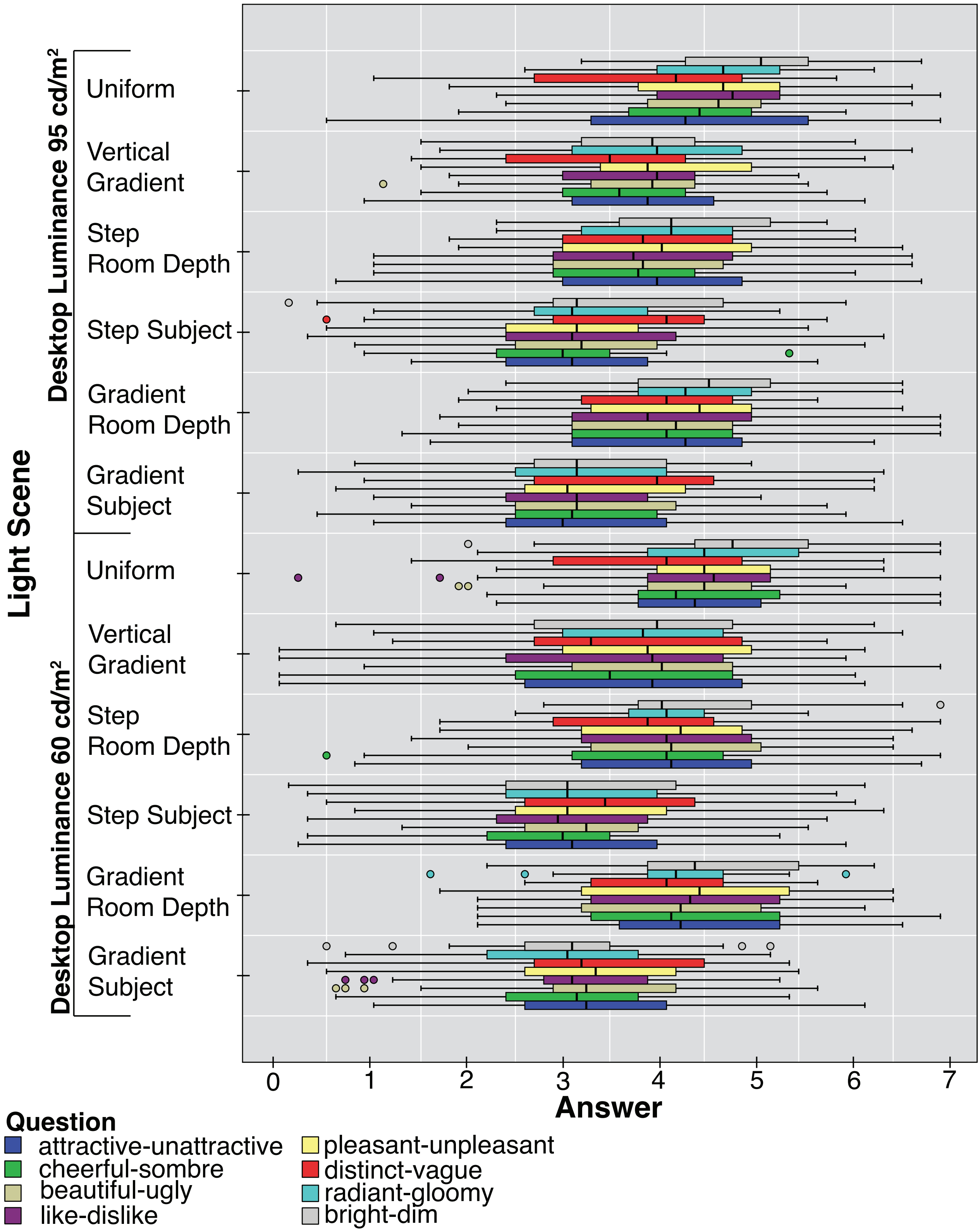


Figure A-5: Boxplot with outliers of experiment II

Assumptions for Principal Component Analysis (PCA)

A principal component analysis is conducted on a matrix of Pearson correlation coefficients. Thus, to achieve meaningful results, a number of assumptions have to be satisfied.

Normality

One assumption made to run a PCA and the subsequent parametric tests is the multivariate normality of the explored data. Normality was tested using a Kolmogorov-Smirnov-Test. Data was grouped by the different light scenes to compare distributions in each group, rather than the overall distribution of the data. The Kolmogorov-Smirnov-Test only tests for univariate normality. However, univariate normality is a necessary condition for multivariate normality, which cannot be tested directly using statistics software such as SPSS (Field, 2009). The test was significant for three out of 36 scenes, indicating that, for these three scenes, the assumption of normality is invalid. Thus, no parametric tests can be conducted for these scenes. However, a large sample size can lead to significant violations of the normality assumption, even if deviations are small (Field, 2009). The Q-Q plots and histograms for these scenes were explored, and it was decided that deviations from normality were sufficiently small to run a PCA and parametric tests. This is also supported by the central limit theorem (Dodge, 2008).

Scales

The scales used in this work are semantic differential scales. They are assumed to provide the interval level, and are therefore suitable for factor analysis and parametric tests.

Sample Size and Subject-to-Variables (STV) Ratio

To extract robust and meaningful factors, a number of assumptions regarding the sample size and data had to be made. Total sample size and STV ratio significantly influence the results of a PCA. Gorsuch (1983), Arrindell and van der Ende (1985) recommend a minimum sample size of 100 (rule of 100). Hatcher (1994) confirms this and additionally suggests an STV ratio of 5:1. According to Hutcheson and Sofroniou (1999) suggest at least 150-300 cases, depending on the correlation of variables to get robust results (rule of 150). In different studies rules of 200, 300, and 500 cases can be found. Thus, recommendations derived from literature are inconsistent. Regarding the STV ratio, recommendations in the literature range from of 2:1 (Kline, 1979) to 20:1 (Hogarty, Hines, Kromrey, Ferron, & Mumford, 2005). However, most research employs an STV ratio of 10:1 (Everitt, 1975; Kerlinger, 1986; Kunce, Cook, & Miller, 1975; Velicer & Fava, 1998).

In this work, a total sample size of 102 participants was used leading to 784 cases for one scene observed by all participants (816 participants x 8 items). With a total of eight items and the assumption that an STV ratio of 10:1 is sufficient, the PCA can achieve robust results.

Sphericity

Bartlett's test of sphericity tests the null hypothesis that the correlation matrix is the identity matrix. The test was significant with $p<0.05$ (Field, 2009). Thus, it can be assumed that variances are similar across groups.

Sampling Adequacy

The Kaiser-Meyer-Olkin Measure of Sampling Adequacy (Table A-1) was greater than 0.8 ("meritorious"). In the anti-image matrix of covariances and correlations, the measure of sampling adequacy was greater than 0.5.

Table A-1: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.889
Bartlett's Test of Sphericity	Approx. X^2	855.587
	df	28
	Sig.	**0.000**

With one exception, all measures of sampling adequacy are greater than 0.8 (good). Bright-dim with an *MSA*=0.791 is considered medium to good (Kaiser & Rice, 1974). Therefore a principal component analysis can be applied (Hutcheson & Sofroniou, 1999), (Field, 2009).

Number of Factors to be Retained

The Guttman-Kaiser rule recommends retaining only factors with an eigenvalue larger than unity. Factors should in total account for 70-80% of variance (79.874% in this case).

Communalities

MacCallum, Widaman, Preacher, and Hong (2001) show that the minimum sample size should also be constrained by communalities and variable loadings. This was confirmed by Mundfrom, Shaw, & Ke (2005). In this work all communalities were greater than 0.6 (Table A-2), so a sample size of more than 60 is sufficient for a robust PCA.

Table A-2: Communalities

Item	Extraction
attractive - unattractive	0.866
cheerful - sombre	0.886
beautiful - ugly	0.874
like - dislike	0.897
pleasant - unpleasant	0.860
distinct - vague	0.673
radiant - gloomy	0.764
bright - dim	0.770

Factor Loadings

Stevens (2002) recommends to interpret only factor loadings that are greater than 0.4. At least three items loading on a factor is seen as critical (Velicer & Fava, 1998).

Results of PCA

Since the conditions for a robust extraction are fulfilled, a principal component analysis was conducted on the explored data. One procedure derived from research is to use the data of all scenes in the PCA (e.g. Loe *et al.* 1994). However, this approach confounds the variances between participants and scenes. Therefore in this work, a PCA was conducted on the data of only one scene. This shows how the 8 items of the questionnaire are structured when each person responds to one scene. Responses to the scene with E_{sur}=100 lux and $L_{walls/ceiling}$=50 cd/m^2 with a uniform distribution were used, since all 102 participants saw and responded to this scene. Only factor loadings greater than 0.5 were interpreted for each component. In accordance with (Velicer & Fava, 1998) at least three items loaded on each factor. The component matrix was rotated using orthogonal Varimax rotation to maximize the sum of variances of the squared loadings on the variables.

Two factors were extracted. The first factor contains items that are connected to the subjective 'liking' of a scene; this factor is designated as 'visual attractiveness'. The second factor involves items regarding the scene's brightness and lightness, which in this case, is also related to a concept of visibility (see. 1.3.1). This factor was labeled according to research in the field as 'visual lightness' (e.g. Loe *et al.* 1994). The rotated factor loadings are shown in Table A-3. The color-code (blue for 'visual attractiveness' and green for 'visual lightness') is kept throughout this work.

The visual attractiveness subscale had excellent reliability, *Cronbach's alpha*=0.962. Internal consistency was good for the visual lightness subscale, with *Cronbach's alpha*=0.718. Figure A-6 shows the rotated factor components.

Table A-3: Rotated factor loadings from principal component analysis

	Visual lightness	Visual attractiveness
distinct - vague	0.687	
radiant - gloomy	0.803	
bright - dim	0.817	
attractive - unattractive		0.866
cheerful - sombre		0.882
beautiful - ugly		0.898
like - dislike		0.935
pleasant - unpleasant		0.918
Cronbach's alpha	0.718	0.962

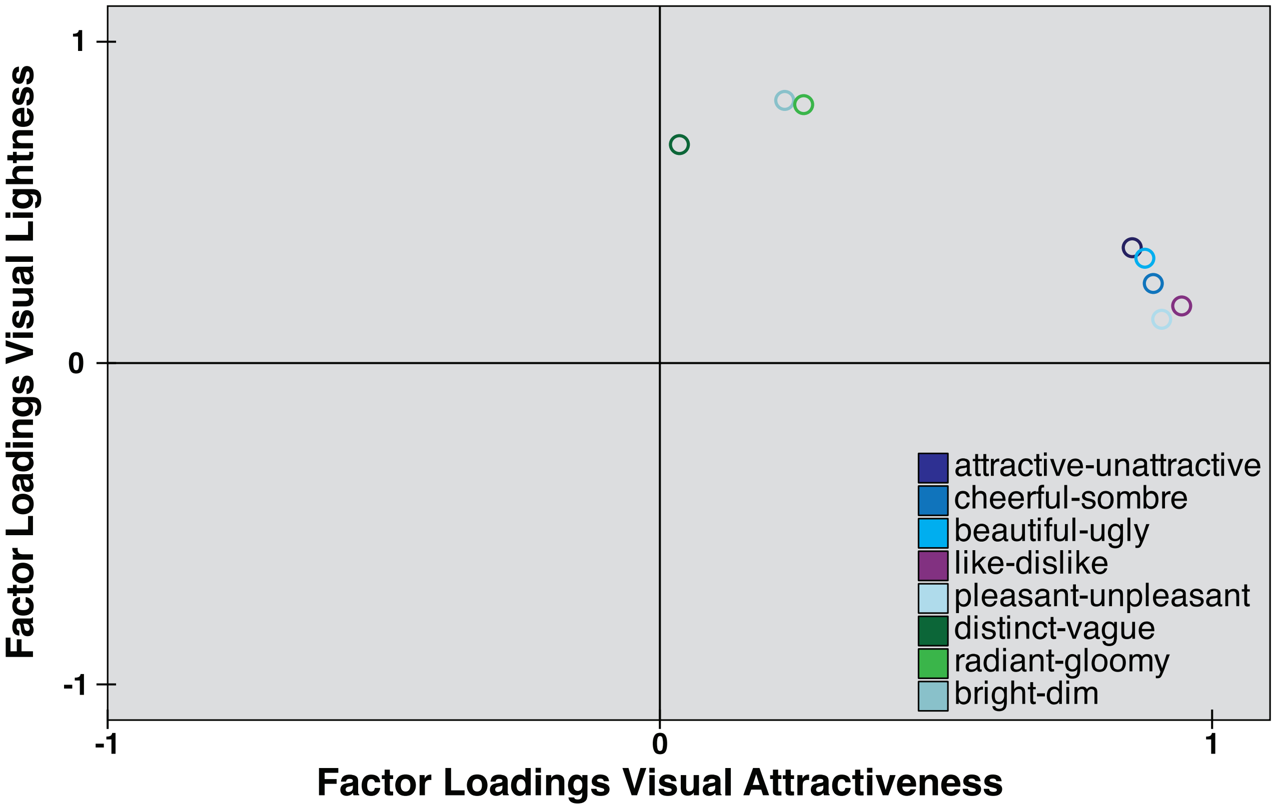


Figure A-6: Component Plot of Factors

Appendix B

Null Hypotheses H_0 and Alternative Hypotheses H_1 for Experiment I

H_0: $\mu_{11\ cd/m^2} = \mu_{30\ cd/m^2} = \mu_{50\ cd/m^2} = \mu_{75\ cd/m^2}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'wall/ceiling luminance'.

H_0: $\mu_{100\ lux} = \mu_{200\ lux} = \mu_{300\ lux}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'surrounding area illuminance'.

H_0: $\mu_{60\ cd/m^2} = \mu_{95\ cd/m^2}$

H_1: $\mu_{60\ cd/m^2} \neq \mu_{95\ cd/m^2}$

where μ is the expected value of the independent variable 'desktop luminance'.

H_0: $\mu_{9\ am\ -\ 11\ am} = \mu_{11\ am\ -\ 1\ pm} = \mu_{1\ pm\ -\ 3\ pm} = \mu_{3\ pm\ -\ 5\ pm} = \mu_{5\ pm\ -\ 7\ pm}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'time of day'.

H_0: $\mu_{Morning\ Types} = \mu_{Neutral\ Types} = \mu_{Evening\ Types}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'chronotype'.

Planned Comparisons for Experiment I

Univariate planned comparisons with one degree of freedom (*df*=1) are used to explore the general hypotheses in greater detail.

For the surrounding area illuminance, lower illuminances are compared to all higher levels. Orthogonal Helmert contrasts are used to avoid increased type I errors:

- 100 lux vs. higher
- 200 lux vs. 300 lux

	Null hypothesis H_0	Alternative hypothesis H_1
1	$\mu_{100\ \text{lux}} = \mu_{\text{higher}}$	$\mu_{100\ \text{lux}} \neq \mu_{\text{higher}}$
2	$\mu_{200\ \text{lux}} = \mu_{300\ \text{lux}}$	$\mu_{200\ \text{lux}} \neq \mu_{300\ \text{lux}}$

where μ is the expected value of the independent variable 'Surrounding Area Illuminance'

For the Walls/Ceiling Luminance each level was compared to the next in ascending order using repeated contrasts. Since repeated contrasts are non-orthogonal, type I error probabilities may accumulate to some extend (Field 2009). To receive statistically meaningful results, a more conservative significance level of 0.01 is used.

- 11 cd/m^2 vs. 30 cd/m^2
- 30 cd/m^2 vs. 50 cd/m^2
- 50cd/m^2 vs. 75 cd/m^2

	Null hypothesis H_0	Alternative hypothesis H_1
1	$\mu_{11\ \text{cd/m}^2} = \mu_{30\ \text{cd/m}^2}$	$\mu_{11\ \text{cd/m}^2} \neq \mu_{30\ \text{cd/m}^2}$
2	$\mu_{30\ \text{cd/m}^2} = \mu_{50\ \text{cd/m}^2}$	$\mu_{30\ \text{cd/m}^2} \neq \mu_{50\ \text{cd/m}^2}$
3	$\mu_{50\ \text{cd/m}^2} = \mu_{75\ \text{cd/m}^2}$	$\mu_{50\ \text{cd/m}^2} \neq \mu_{75\ \text{cd/m}^2}$

where μ is the expected value of the independent variable 'wall/ceiling luminance'.

Null Hypotheses H_0 and Alternative Hypotheses H_1 for Experiment II

H_0: $\mu_{60cd/m^2} = \mu_{95cd/m^2}$

H_1: $\mu_{60cd/m^2} \neq \mu_{95cd/m^2}$

where μ is the expected value of the independent variable 'desktop luminance'.

H_0: $\mu_{\text{Gradient Subject}} = \mu_{\text{Gradient Room Depth}} = \mu_{\text{Step Subject}} = \mu_{\text{Step Room Depth}} = \mu_{\text{Vertical Gradient}} = \mu_{\text{Uniform}}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'background luminance distribution'.

H_0: $\mu_{\text{9 am - 11 am}} = \mu_{\text{11 am - 1 pm}} = \mu_{\text{1 pm - 3 pm}} = \mu_{\text{3 pm - 5 pm}} = \mu_{\text{5 pm - 7 pm}}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'time of day'.

H_0: $\mu_{\text{Morning Types}} = \mu_{\text{Neutral Types}} = \mu_{\text{Evening Types}}$

H_1: $\exists\, i, j$: $\mu_i \neq \mu_j$

where μ is the expected value of the independent variable 'chronotype'.

Planned Comparisons for Experiment II

Simple contrasts were used to compare all distributions to the totally uniform distribution. Simple contrasts are non-orthogonal, thus a significance level of 0.01 is used (s. section 5.1, p.40 for explanation).

- Gradient Subject vs. Uniform
- Gradient Room Depth vs. Uniform
- Step Subject vs. Uniform
- Step Room Depth vs. Uniform
- Vertical Gradient vs. Uniform

	Null hypothesis H_0	Alternative hypothesis H_1
1	$\mu_{\textit{Gradient Subject}} = \mu_{\textit{Uniform}}$	$\mu_{\textit{Gradient Subject}} \neq \mu_{\textit{Uniform}}$
2	$\mu_{\textit{Gradient Room Depth}} = \mu_{\textit{Uniform}}$	$\mu_{\textit{Gradient Room Depth}} \neq \mu_{\textit{Uniform}}$
3	$\mu_{\textit{Step Subject}} = \mu_{\textit{Uniform}}$ $\mu_{\textit{Step}}$	$\mu_{\textit{Step Subject}} \neq \mu_{\textit{Uniform}}$ $\mu_{\textit{Step}}$
4	$_{\textit{Room Depth}} = \mu_{\textit{Uniform}}$ $\mu_{\textit{Vertical}}$	$_{\textit{Room Depth}} \neq \mu_{\textit{Uniform}}$ $\mu_{\textit{Vertical}}$
5	$_{\textit{Gradient}} = \mu_{\textit{Uniform}}$	$_{\textit{Gradient}} \neq \mu_{\textit{Uniform}}$

where μ is the expected value of the independent variable 'Background Luminance Distribution'.

Appendix C

This Appendix contains all photometric measurements including horizontal illuminances, illuminances at eye level and luminance images. Identifiers for the different lighting scenes presented in this work are shown in Table C-1.

Table C-1: Scene identifiers

	$L_{walls/ceiling}$=11 cd/m^2	$L_{walls/ceiling}$=30 cd/m^2	$L_{walls/ceiling}$=50 cd/m^2	$L_{walls/ceiling}$=75 cd/m^2
E_{sur}=100 lux	L11_E100	L30_E100	L50_E100	L75_E100
E_{sur} =200 lux	L11_E200	L30_E200	L50_E200	L75_E200
E_{sur} =300 lux	L11_E300	L30_E300	L50_E300	L75_E300

Horizontal Illuminance Measurements

20	20	20	20	20	19	19	19	19	19	19	19	20	21	20	20	22	22	22	24
18	136	136	142	141	140	135	19	18	103	102	105	109	111	20	109	137	147	142	23
18	132	137	138	133	130	127	18	18	106	105	103	101	102	20	111	129	132	133	23
17	130	133	134	127	124	120	18	17	104	100	97	92	88	20	115	123	124	122	23
18	125	130	129	134	119	121	18	106	102	93	93	88	81	19	116	121	118	109	23
19	463	460	466	467	423	456	18	100	98	99	90	85	78	19	113	111	112	118	22
19	426	431	435	400	431	384	18	95	92	89	85	80	75	19	107	105	106	106	22
18	398	395	406	459	403	395	18	90	17	17	18	19	19	19	20	20	20	21	23
19	530	528	525	507	480	489	18	85	17	17	17	19	19	18	18	20	20	21	21
19	541	531	535	516	489	440	17	83	103	98	93	89	86	18	104	103	100	94	21
20	548	553	542	524	497	461	17	17	99	97	93	91	88	18	107	105	102	97	21
18	135	134	129	128	126	118	18	16	99	98	96	94	93	18	108	103	103	101	21
17	129	123	126	124	122	115	18	17	100	94	99	97	95	18	103	99	99	96	21
17	125	132	123	119	119	120	18	17	97	100	98	97	95	18	100	96	97	102	21
17	118	118	117	113	113	113	18	17	90	92	96	97	95	17	96	93	93	94	20
17	17	18	18	18	18	18	18	17	17	18	18	18	17	16	17	17	18	18	19

Figure C-1: : Illuminance measurements for scene L11_E100: E_{task}= 470 lux, E_{sur}=86 lux

91	92	93	93	94	95	95	94	96	97	97	96	99	99	99	99	101	102	103	101
87	124	95	98	99	99	98	100	95	102	101	104	105	106	98	103	106	108	107	104
85	122	95	96	98	98	100	96	95	102	103	103	104	105	99	103	105	107	109	104
85	122	94	92	96	98	98	96	93	102	102	103	102	104	98	104	102	106	107	104
86	122	95	96	95	96	99	96	93	100	99	103	101	102	96	104	100	104	103	104
86	509	486	489	492	514	494	95	98	100	102	102	100	101	99	103	101	104	107	102
86	491	499	506	486	477	470	95	98	99	100	101	101	101	97	103	102	103	104	101
85	464	463	468	453	446	438	94	98	93	94	95	96	96	97	98	97	98	99	104
86	500	501	509	506	504	502	92	97	93	94	93	96	96	96	96	98	99	99	98
86	512	501	518	512	511	521	93	91	98	97	99	100	100	94	97	98	99	98	99
86	508	510	501	517	509	494	92	90	97	98	98	99	99	95	96	97	97	99	98
83	91	92	86	93	95	96	91	89	97	97	98	97	99	93	96	95	97	98	99
82	88	89	91	92	93	92	90	88	96	95	98	97	98	90	95	94	95	93	98
80	88	91	92	91	92	95	89	88	95	97	97	96	97	93	93	92	94	97	96
81	87	88	88	91	91	92	89	88	92	90	90	95	95	89	91	91	91	92	93
82	83	84	85	86	86	87	88	87	88	89	90	88	86	86	87	87	88	88	89

Figure C-2: Illuminance measurements scene L30_E100, E_{task}= 494 lux, E_{sur} =97 lux

97	100	102	102	105	107	107	106	109	111	111	110	114	115	115	114	117	119	119	117
90	95	96	102	104	106	104	108	109	111	108	113	114	115	112	117	117	118	116	122
88	92	98	100	103	105	107	108	109	110	112	113	113	114	116	117	116	117	120	121
88	92	96	101	102	105	106	110	108	111	111	115	112	115	115	119	114	118	118	122
89	93	98	101	102	104	108	110	108	109	109	115	112	113	112	119	114	116	114	121
91	497	496	494	488	501	500	109	107	109	113	114	111	113	116	118	112	115	119	119
90	499	480	490	493	486	480	109	108	109	110	114	112	113	113	117	113	114	115	118
89	474	475	482	460	455	450	108	108	109	111	113	112	113	114	116	113	113	115	122
92	504	507	507	532	530	517	107	108	109	110	109	113	113	113	112	114	115	115	113
92	515	506	517	516	499	534	108	107	108	106	110	111	112	109	113	112	113	111	114
94	524	532	522	542	529	512	108	106	108	110	110	110	110	111	111	110	111	113	113
91	95	98	97	102	105	107	110	106	108	109	112	108	110	109	112	107	110	111	115
89	93	98	98	102	105	106	111	106	108	108	112	109	108	104	111	105	107	105	114
89	95	99	104	103	106	108	111	106	109	111	112	107	107	109	108	101	105	111	111
92	98	101	106	106	106	108	111	108	109	110	112	108	105	102	103	98	100	103	107
100	102	105	108	106	107	109	110	108	110	112	113	106	101	94	95	90	93	99	101

Figure C-3: Illuminance measurements for scene L50_E100: E_{task}= 501 lux, E_{sur}=109 lux

101	106	109	108	113	116	117	115	120	123	124	122	126	129	129	127	131	134	134	131
91	99	101	110	112	115	112	119	120	122	119	126	127	128	124	131	131	133	129	137
88	95	103	107	110	113	118	119	119	121	125	126	126	128	130	131	130	132	135	136
87	94	100	103	107	113	116	122	117	122	123	129	122	128	129	135	127	132	133	137
89	94	102	96	104	111	119	123	110	120	119	130	118	126	124	135	113	129	126	136
90	540	536	550	531	527	504	122	109	120	126	129	120	126	131	133	118	128	134	133
88	499	508	519	497	491	485	120	116	119	121	127	124	125	126	131	125	126	127	131
87	472	473	481	465	461	456	119	116	118	122	125	123	125	126	129	124	125	127	137
91	506	509	507	501	578	548	112	117	120	121	119	123	125	125	122	124	126	125	121
90	517	507	520	506	586	533	114	115	117	114	121	121	122	117	123	122	122	117	123
90	523	532	523	510	593	561	112	111	115	118	118	118	119	121	120	118	119	121	121
85	92	96	100	100	107	109	113	110	114	115	120	111	117	116	121	111	116	117	122
82	88	91	90	97	103	103	113	108	111	108	118	109	113	106	118	95	110	105	120
79	88	96	99	96	102	109	110	106	109	115	115	107	110	116	112	99	106	116	114
82	88	93	100	98	101	103	108	105	107	108	112	106	105	103	106	97	99	100	104
87	91	94	99	96	99	102	105	103	105	108	110	103	98	93	96	87	89	90	92

Figure C-4: Illuminance measurements scene L75_E100, E_{task}= 515 lux, E_{sur} =115 lux

23	23	23	23	23	22	23	22	22	22	22	22	23	23	23	23	25	25	25	25
22	313	312	327	332	336	326	52	21	230	228	237	249	260	22	52	314	337	319	26
21	302	315	322	317	311	306	23	21	240	240	238	233	240	23	55	291	303	300	26
20	299	309	308	298	291	278	23	20	242	234	228	212	205	22	57	274	274	269	26
21	285	298	296	287	275	275	22	21	235	217	211	198	184	21	54	267	262	239	26
22	467	464	473	460	446	425	22	238	231	228	207	192	177	22	64	251	249	258	25
22	430	436	438	421	409	398	22	224	216	208	196	182	169	22	70	232	232	232	25
22	403	400	401	389	378	368	22	211	21	21	21	22	22	22	23	23	24	24	26
23	534	534	532	517	493	458	22	184	21	21	21	22	22	22	22	24	24	25	24
23	543	536	543	523	502	449	22	20	221	205	198	189	183	21	201	239	228	211	25
24	549	557	548	527	508	474	21	20	215	213	203	196	189	22	249	244	233	218	25
22	314	314	305	293	292	276	22	19	218	215	210	204	200	21	248	237	239	231	25
21	300	286	295	284	282	264	21	20	215	204	216	210	205	21	239	229	228	214	24
20	290	309	284	271	272	278	21	20	208	217	213	210	205	21	233	221	221	228	24
20	261	258	252	68	99	102	21	20	190	197	208	208	206	21	224	212	209	210	22
21	21	21	22	21	21	21	21	20	20	21	21	21	20	20	21	21	21	21	22

Figure C-5: Illuminance measurements scene L11_E200, E_{task}= 470 lux, E_{sur} =181 lux

62	63	64	63	65	66	66	65	65	66	67	66	68	69	69	69	71	72	72	71
58	290	290	302	306	306	297	68	65	228	226	235	242	249	67	165	295	314	308	74
56	283	293	297	292	287	283	66	64	234	235	233	228	229	69	165	281	288	293	74
56	278	285	280	277	273	264	67	63	233	229	227	210	204	68	168	268	270	268	75
57	268	277	272	261	261	262	66	63	227	212	214	200	189	66	161	262	259	242	74
57	507	503	510	488	479	455	66	225	224	224	209	195	183	68	173	247	248	260	72
57	468	474	477	451	442	434	65	216	212	206	200	188	176	66	182	234	234	234	71
55	441	437	442	420	412	405	65	205	63	64	65	65	66	66	67	67	68	69	75
57	569	568	566	553	527	496	62	189	63	63	63	66	66	66	65	67	68	69	68
57	578	568	575	558	535	485	63	61	217	206	203	195	169	63	214	213	206	194	69
57	586	591	580	564	542	509	62	60	213	212	206	198	175	64	218	216	208	199	68
54	284	283	275	273	272	260	62	58	215	213	212	204	186	63	217	209	212	207	68
52	271	261	270	265	264	251	61	58	212	201	215	209	197	60	210	201	203	192	67
51	263	280	264	254	257	263	60	57	204	215	211	208	201	63	204	196	198	205	65
51	250	252	246	244	245	247	59	57	190	196	206	206	203	59	197	190	188	188	62
52	53	55	56	56	56	57	58	56	57	58	59	57	56	56	58	56	56	56	57

Figure C-6: Illuminance measurements scene L30_E200, E_{task}= 505 lux, E_{sur} =189 lux

106	109	111	110	114	115	116	114	118	119	120	119	121	123	123	122	127	129	129	127
99	277	278	270	275	277	289	118	118	238	235	244	251	256	120	144	280	275	273	133
97	269	281	286	285	282	281	117	117	243	246	246	240	244	124	161	287	297	296	131
97	256	275	276	274	272	265	118	116	245	242	243	228	225	123	183	275	279	276	132
97	259	271	272	266	261	264	118	115	239	230	234	219	212	120	198	270	269	255	131
99	501	509	503	504	537	514	117	237	238	240	231	215	209	124	218	260	262	270	129
99	493	501	498	509	498	491	117	231	229	227	224	210	202	121	226	250	250	250	128
98	487	485	490	477	467	461	117	224	117	119	122	118	120	121	123	122	124	125	132
102	514	518	519	509	519	534	149	209	118	118	118	116	116	116	116	124	125	125	123
103	525	517	531	515	536	542	117	115	236	224	223	217	213	114	223	225	220	209	125
104	531	513	534	519	544	540	116	114	233	232	227	221	216	117	226	226	221	215	123
100	271	274	273	267	268	261	117	113	235	233	233	225	223	116	227	219	222	219	125
99	262	258	267	262	263	254	118	112	232	225	237	227	224	111	221	213	214	205	124
98	258	273	263	255	258	264	119	112	228	236	235	227	224	116	215	206	209	218	121
102	207	190	177	226	240	246	119	115	219	224	230	227	222	109	207	198	199	202	116
109	112	114	117	114	115	117	118	115	117	120	121	114	109	101	102	100	103	108	110

Figure C-7: Illuminance measurements scene L50_E200, E_{task}= 511 lux, E_{sur} =209 lux

134	139	142	141	148	151	152	149	156	158	159	158	162	164	164	162	166	169	169	167
125	231	231	245	249	252	246	234	155	226	221	231	233	238	159	167	264	274	266	172
122	224	235	239	242	242	245	166	155	227	230	230	228	230	166	166	256	261	265	171
121	222	228	230	233	237	236	157	153	227	226	230	219	221	164	170	248	253	252	173
122	217	227	228	223	230	236	157	151	223	216	225	209	213	159	170	241	246	236	172
123	522	521	548	526	511	537	155	217	221	226	222	207	211	166	168	236	241	250	169
121	532	545	517	531	524	516	152	215	215	215	218	209	207	161	166	233	234	234	167
120	506	509	518	502	492	486	148	210	154	157	161	158	159	161	164	160	161	162	173
124	540	539	537	528	503	565	164	206	154	156	154	159	161	160	157	160	161	161	157
123	550	539	546	533	509	559	151	149	219	211	215	212	210	153	236	234	230	219	159
124	560	564	554	538	517	484	148	146	215	217	214	211	210	156	236	232	229	226	157
119	222	224	220	223	229	225	150	141	215	215	218	210	212	152	235	225	228	227	158
114	213	211	205	216	222	218	149	138	212	205	218	210	210	142	230	212	219	209	156
113	210	222	217	213	219	228	147	139	208	217	214	207	208	152	222	205	212	225	150
115	205	209	214	208	213	217	144	139	200	203	209	205	203	140	213	200	201	203	141
119	123	127	131	128	133	137	141	138	140	143	145	138	134	131	133	123	125	126	128

Figure C-8: Illuminance measurements scene L75_E200, E_{task}= 528 lux, E_{sur} =205 lux

26	26	26	26	26	26	26	25	24	25	25	25	26	27	26	26	28	28	28	28
25	439	439	460	472	480	469	27	24	304	255	247	368	383	25	27	450	486	462	29
24	429	447	457	451	444	437	28	24	352	356	355	347	358	26	28	416	436	432	29
24	422	437	437	424	415	399	29	23	356	347	345	315	304	25	43	391	392	386	29
24	405	422	420	406	394	392	44	24	345	322	317	292	271	24	111	379	376	341	29
25	475	475	483	466	455	433	26	349	342	338	311	283	260	26	250	358	357	369	29
25	438	446	451	429	413	405	27	330	322	311	297	267	244	25	320	330	331	331	28
24	411	409	411	396	382	374	70	313	24	24	25	25	25	25	26	26	27	28	29
25	537	536	532	517	489	458	24	270	24	24	24	24	25	25	25	27	28	28	28
26	548	538	542	523	501	447	24	23	304	283	273	264	254	24	25	357	339	310	28
27	556	558	546	529	508	472	24	23	298	292	279	273	261	25	25	364	347	323	28
24	442	442	426	419	411	385	25	22	302	294	288	282	276	24	26	352	353	342	28
24	423	402	415	404	398	373	24	23	295	278	294	289	284	23	49	340	338	317	28
23	410	435	400	385	384	393	24	22	283	298	289	288	284	24	335	330	327	336	27
23	318	243	148	365	364	365	24	23	260	269	282	284	283	23	333	316	309	310	25
23	23	24	24	24	23	24	24	22	23	23	24	23	22	22	24	24	24	23	24

Figure C-9: Illuminance measurements scene L11_E300, E_{task}= 475 lux, E_{sur} =270 lux

73	75	76	75	77	78	79	77	77	78	79	78	80	81	81	80	83	84	85	84
70	409	409	425	433	434	420	117	77	321	318	329	341	350	79	311	404	433	418	87
68	399	413	416	411	406	400	86	76	329	329	327	320	326	81	330	381	386	391	86
68	392	398	399	390	384	372	81	74	328	319	314	293	316	80	328	365	367	360	86
69	375	388	383	377	367	365	80	94	321	298	298	278	311	78	301	354	351	322	85
69	495	500	486	503	494	471	79	318	313	315	290	291	313	80	326	331	333	348	84
68	477	483	486	470	455	450	79	301	295	286	277	288	311	78	317	315	316	315	83
67	451	447	450	437	425	418	78	286	75	76	77	77	78	78	79	79	80	81	86
69	527	526	574	528	546	515	76	261	75	76	75	78	79	78	77	80	81	81	80
69	538	529	555	542	526	504	77	273	297	279	274	295	298	75	303	327	313	314	81
70	538	528	535	550	503	530	76	272	293	290	280	302	303	77	308	332	320	302	80
67	400	399	393	382	379	362	76	81	296	291	288	289	295	75	341	325	327	317	81
65	384	370	378	369	368	348	77	91	290	274	292	288	303	72	329	310	314	296	80
64	372	394	370	356	357	366	77	80	309	292	285	285	301	75	319	302	304	315	78
63	354	356	355	339	339	342	85	69	300	293	323	333	281	71	308	293	312	291	74
64	66	67	69	68	69	70	72	68	69	70	71	69	68	69	71	69	69	68	69

Figure C-10: Illuminance measurements scene L30_E300, E_{task}= 500 lux, E_{sur} =271 lux

110	113	115	114	118	120	121	119	121	123	123	122	126	127	127	126	130	131	131	133
103	368	369	387	393	394	384	122	121	304	301	312	323	332	124	129	390	412	396	135
101	357	374	381	377	372	370	122	120	313	316	314	311	314	128	129	371	386	385	134
101	353	365	370	361	356	347	124	119	316	310	310	292	287	126	131	355	357	354	135
102	342	357	360	348	341	345	124	119	308	293	295	279	267	123	131	346	344	324	135
103	505	503	509	506	506	513	323	308	306	306	290	272	261	128	131	333	333	345	133
103	515	495	505	510	500	490	323	297	293	287	282	263	253	125	133	317	316	316	131
102	491	491	499	478	469	462	323	286	121	123	125	123	124	125	128	126	127	128	135
105	516	519	518	513	538	523	552	265	122	123	122	125	126	125	124	127	128	127	125
105	526	517	529	520	505	551	531	119	294	280	279	270	264	120	307	305	296	278	126
107	535	546	535	523	508	560	450	119	291	291	284	276	270	123	313	307	299	289	126
104	367	370	362	357	361	350	125	119	295	292	293	282	279	121	312	299	302	297	127
102	355	347	357	350	353	338	123	119	291	280	297	288	283	116	304	289	292	277	126
101	347	368	350	339	343	352	123	119	284	295	292	286	282	122	296	280	281	293	123
104	335	339	336	318	319	324	122	121	270	276	283	285	281	114	283	268	268	270	118
111	114	117	120	117	118	121	121	120	122	124	126	119	114	107	107	101	103	109	111

Figure C-11: Illuminance measurements scene L50_E300, E_{task}= 512 lux, E_{sur} =271 lux

165	169	172	171	177	180	181	179	184	187	188	186	190	192	192	190	195	198	197	197
155	362	362	377	382	385	376	184	184	327	322	334	339	347	187	199	391	411	399	201
151	352	366	371	368	368	368	183	183	331	334	333	328	334	194	213	377	387	391	200
150	347	357	360	356	357	352	186	181	331	327	329	312	312	192	250	364	370	367	202
151	338	352	352	303	327	349	187	178	325	311	319	301	296	187	288	355	358	339	200
153	509	504	520	535	540	529	186	319	322	325	314	298	291	194	320	344	348	361	197
151	536	576	536	561	554	547	184	312	311	306	306	292	284	189	337	334	335	335	195
149	539	540	549	530	524	519	183	303	183	186	189	187	188	189	192	189	190	191	202
152	538	541	531	524	509	510	176	291	183	184	181	188	189	188	186	189	190	189	186
152	508	539	542	539	508	505	178	178	315	301	302	297	291	181	313	310	304	289	188
152	506	503	525	524	504	523	176	175	309	310	303	299	294	185	314	309	303	297	186
146	349	353	353	348	353	343	178	168	310	307	309	301	300	181	314	300	304	301	187
143	336	330	343	339	343	332	177	166	305	293	311	304	301	170	305	288	294	280	185
141	330	350	339	331	337	347	174	166	298	310	305	301	299	180	296	280	285	299	180
143	305	284	267	322	325	329	172	168	284	289	299	297	294	168	285	272	272	273	171
148	152	155	160	159	162	165	168	165	167	169	171	166	162	159	162	153	155	156	158

Figure C-12: Illuminance measurements scene L75_E300, E_{task}= 528 lux, E_{sur} =286 lux

164	169	162	150	134	130	121	109	91	88	80	73	59	58	53	50	40	41	40	39
149	180	172	172	159	151	137	132	95	109	101	96	81	75	53	55	58	56	54	40
138	173	171	158	151	140	141	128	95	97	103	95	77	62	54	59	63	50	56	40
131	162	162	156	143	143	136	112	89	109	101	94	77	74	53	62	57	57	55	40
127	155	160	155	258	136	115	108	89	106	97	95	75	72	52	65	54	55	54	40
122	673	654	632	569	546	516	106	107	104	102	94	72	71	53	67	50	54	56	40
119	640	638	617	550	528	518	105	100	100	97	93	72	71	53	67	37	54	56	41
117	610	594	573	529	508	491	104	95	78	76	74	55	55	53	53	42	41	41	40
102	445	454	446	424	406	389	101	105	85	79	73	60	60	56	53	43	45	44	44
109	432	430	445	435	418	381	99	86	102	93	89	76	61	53	74	63	62	59	43
109	467	440	444	441	439	414	96	82	89	95	88	78	47	54	74	65	53	59	42
97	119	120	117	114	115	112	92	81	99	92	86	74	62	52	74	60	59	57	40
95	112	105	108	107	109	102	89	79	94	84	85	74	63	50	73	57	57	53	39
92	108	114	96	102	105	109	86	77	90	90	82	73	65	52	72	55	55	57	38
89	103	103	74	82	85	84	82	74	85	82	76	72	67	50	72	56	55	54	36
83	85	84	79	78	80	80	79	70	68	64	63	54	51	48	48	35	35	34	35

Figure C-13: Illuminance measurements scene 'Gradient Subject', E_{task}= 503 lux, E_{sur} =87 lux

63	64	66	69	76	82	90	96	115	126	137	142	156	166	175	178	190	199	203	197
60	63	63	61	68	84	89	103	104	126	131	128	124	134	138	142	147	157	168	181
40	64	68	67	71	90	95	104	100	115	121	125	115	139	154	152	148	158	152	173
63	67	71	77	77	86	95	95	97	111	112	115	114	130	140	142	145	149	142	175
68	70	70	83	79	87	97	96	97	109	116	115	113	117	122	142	145	145	144	156
70	609	594	579	531	519	503	96	96	108	123	112	111	115	130	148	143	143	164	156
66	577	576	560	514	503	502	93	96	106	116	108	109	112	122	144	142	140	154	145
66	531	627	585	496	486	481	88	96	105	114	111	108	110	120	136	141	148	152	146
67	511	466	490	474	480	453	86	96	103	112	114	115	113	131	132	132	137	143	137
66	488	485	455	484	491	456	100	95	111	115	129	112	122	133	147	132	135	143	142
49	480	438	472	472	493	453	97	85	114	116	125	123	125	135	142	121	130	146	128
62	66	68	72	73	82	88	96	92	104	112	122	126	121	129	139	131	134	130	126
60	63	63	71	71	78	81	94	90	100	102	120	123	115	116	136	128	138	125	127
58	62	67	68	69	77	87	91	87	97	110	114	119	111	127	130	124	133	128	106
58	60	62	64	67	74	80	88	85	93	100	109	113	114	103	105	102	106	108	104
58	59	60	60	66	73	78	82	83	91	97	101	108	114	128	138	136	139	134	133

Figure C-14: Illuminance measurements scene 'Gradient Room Depth', E_{task}= 509 lux, E_{sur} =110 lux

157	165	167	162	156	158	151	138	114	102	89	81	64	66	63	62	54	55	56	56
147	156	155	160	155	150	141	135	117	98	91	84	68	61	64	63	55	53	55	56
133	147	151	147	140	132	138	129	110	80	94	87	74	53	66	64	59	50	57	57
135	141	143	143	136	137	132	125	108	103	94	87	75	71	67	65	59	59	58	57
133	502	438	385	307	154	131	124	109	101	93	89	78	73	69	67	62	60	59	58
129	602	602	592	580	556	529	121	108	101	95	88	80	74	69	67	63	60	59	59
124	608	594	593	558	541	528	119	107	100	94	89	80	75	71	68	62	60	60	60
122	596	586	571	536	518	502	117	104	98	93	90	78	74	71	70	60	60	60	57
122	453	462	455	433	415	400	115	102	101	95	89	73	74	71	68	60	61	61	60
119	439	440	453	445	424	392	114	105	95	92	88	74	70	69	68	59	58	59	60
109	429	450	454	452	435	421	116	101	76	92	86	69	52	69	67	59	50	59	59
106	113	115	115	112	112	110	106	98	94	89	85	69	70	67	66	58	59	58	59
104	107	104	112	108	108	101	104	96	92	84	84	68	68	65	66	59	58	56	58
101	104	112	108	103	104	107	101	94	90	88	82	67	67	67	65	59	58	58	57
98	100	102	104	99	100	99	98	91	87	84	81	67	66	65	64	60	57	56	56
94	97	98	100	95	96	95	95	88	85	82	80	66	64	63	63	58	56	54	54

Figure C-15: Illuminance measurements scene 'Step Subject', E_{task}= 501 lux, E_{sur} =94 lux

65	64	65	65	77	81	88	75	86	96	113	127	132	143	171	171	178	186	189	185
55	66	64	54	70	84	89	83	80	103	113	134	137	131	162	177	167	175	172	194
53	71	71	73	72	91	96	87	81	114	119	132	123	136	156	173	155	178	177	191
63	68	72	79	79	89	97	91	92	107	119	134	127	142	151	171	163	176	181	188
67	71	76	82	82	90	101	93	94	107	116	134	127	139	152	170	161	171	170	186
70	610	593	578	531	519	503	93	94	107	122	132	125	137	151	166	159	168	180	180
67	582	581	564	517	505	505	92	95	107	117	130	124	135	150	162	158	145	149	175
66	553	538	523	499	489	484	87	96	107	116	123	124	133	150	154	157	143	147	144
70	452	410	425	428	423	398	85	99	106	115	118	106	112	118	125	131	135	145	151
66	428	420	416	428	435	399	91	88	105	109	123	123	111	123	110	129	127	157	166
57	434	423	411	426	439	421	88	79	109	111	119	111	106	118	101	134	129	159	162
64	67	69	74	77	87	95	86	84	97	106	116	118	111	115	107	118	123	153	160
61	64	63	73	76	84	88	85	83	93	96	114	115	105	92	104	112	108	138	158
59	62	69	67	73	82	94	81	80	90	105	108	110	110	96	98	107	121	151	150
57	59	60	60	71	79	86	77	77	86	93	102	104	113	101	93	99	101	131	137
56	57	56	54	70	77	84	71	75	83	89	93	99	103	113	124	119	123	117	115

Figure C-16: Illuminance measurements scene 'Step Room Depth', E_{task}= 480 lux, E_{sur} =112 lux

105	112	115	114	118	122	123	75	86	96	113	127	132	143	171	171	178	186	189	185
103	114	113	108	119	126	124	83	80	103	113	134	137	131	162	177	167	175	172	194
96	113	115	110	110	125	127	87	81	114	119	132	123	136	156	173	155	178	177	191
101	107	111	116	111	119	122	91	92	107	119	134	127	142	151	171	163	176	181	188
99	103	110	114	110	114	120	93	94	107	116	134	127	139	152	170	161	171	170	186
94	640	627	610	558	540	518	93	94	107	122	132	125	137	151	166	159	168	180	180
86	604	606	590	535	516	515	92	95	107	117	130	124	135	150	162	158	145	149	175
82	574	558	541	508	495	484	87	96	107	116	123	124	133	150	154	157	143	147	144
80	407	417	410	399	422	402	85	99	106	115	118	106	112	118	125	131	135	145	151
77	425	396	411	402	390	412	91	88	105	109	123	123	111	123	110	129	127	157	166
66	437	400	399	406	419	405	88	79	109	111	119	111	106	118	101	134	129	159	162
63	68	69	70	71	76	78	86	84	97	106	116	118	111	115	107	118	123	153	160
60	63	61	68	66	70	67	85	83	93	96	114	115	105	92	104	112	108	138	158
58	60	66	64	61	66	74	81	80	90	105	108	110	110	96	101	107	124	145	150
56	58	59	61	57	63	66	77	77	86	93	102	103	103	102	93	96	111	134	140
56	57	57	58	56	60	63	71	75	83	89	93	99	103	113	124	119	123	117	112

Figure C-17: Illuminance measurements scene 'Vertical Gradient', E_{task}= 483 lux, E_{sur} =115 lux

Illuminance Measurements at Eye Level

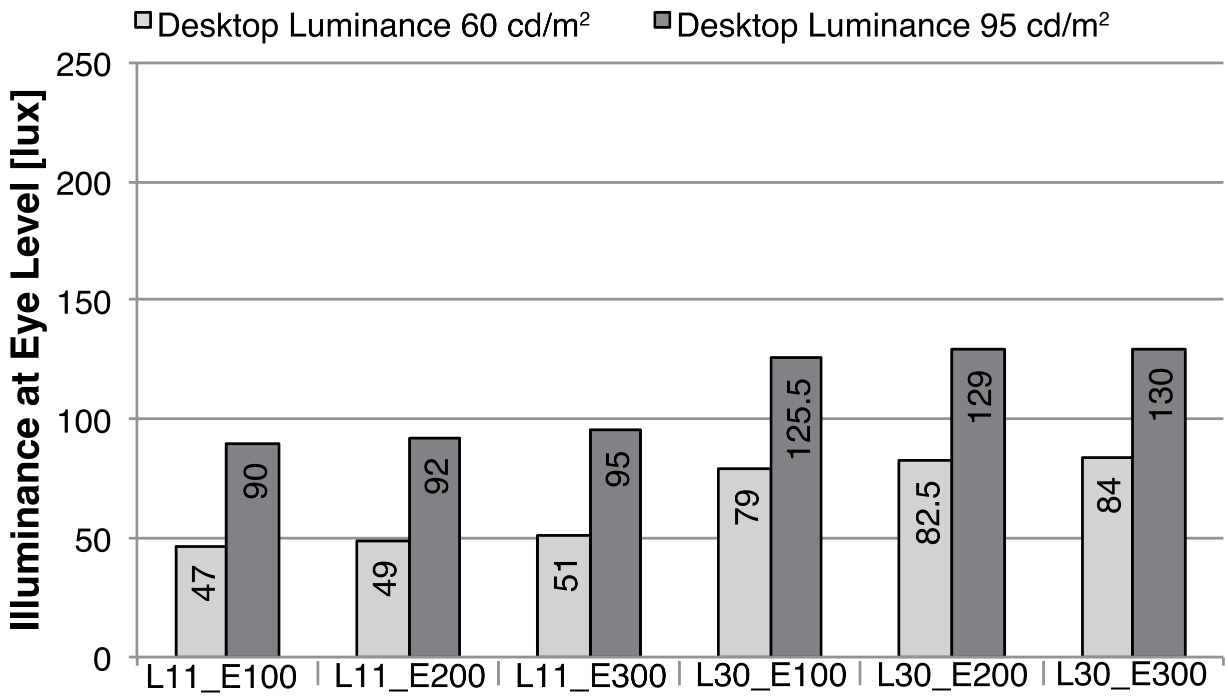


Figure C-18: Illuminances at eye level for experiment I, part 1

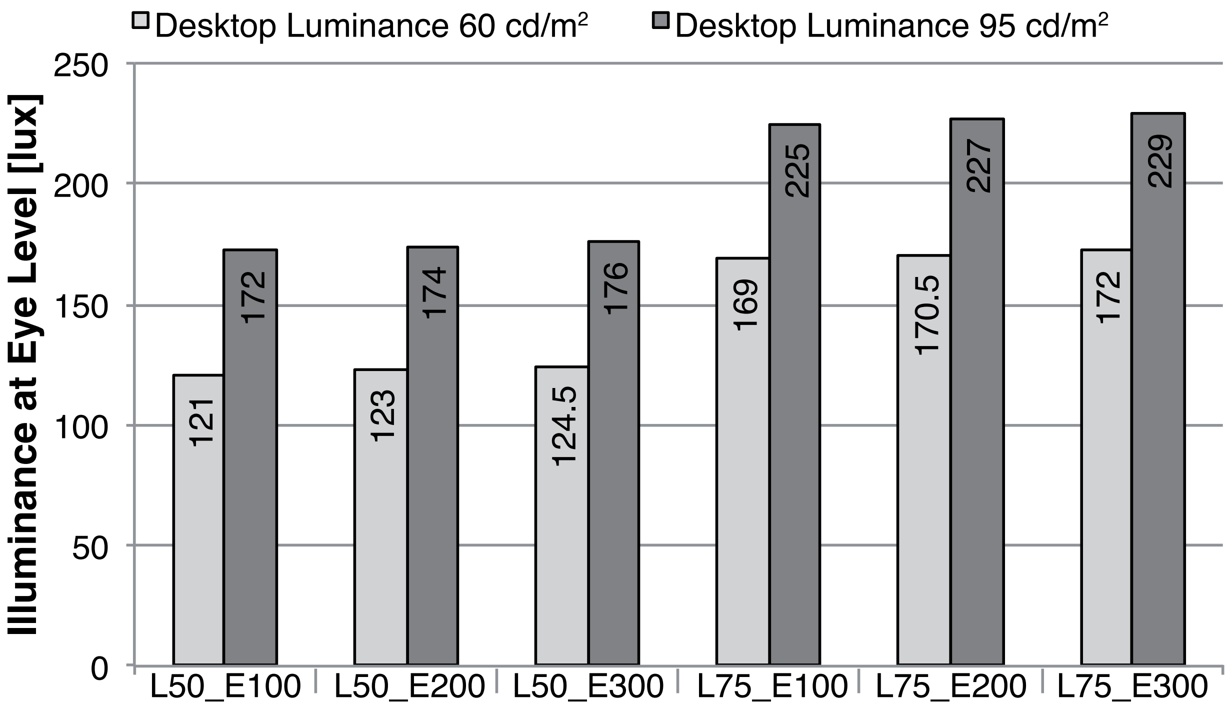


Figure C-19: Illuminances at eye level for experiment I, part 2

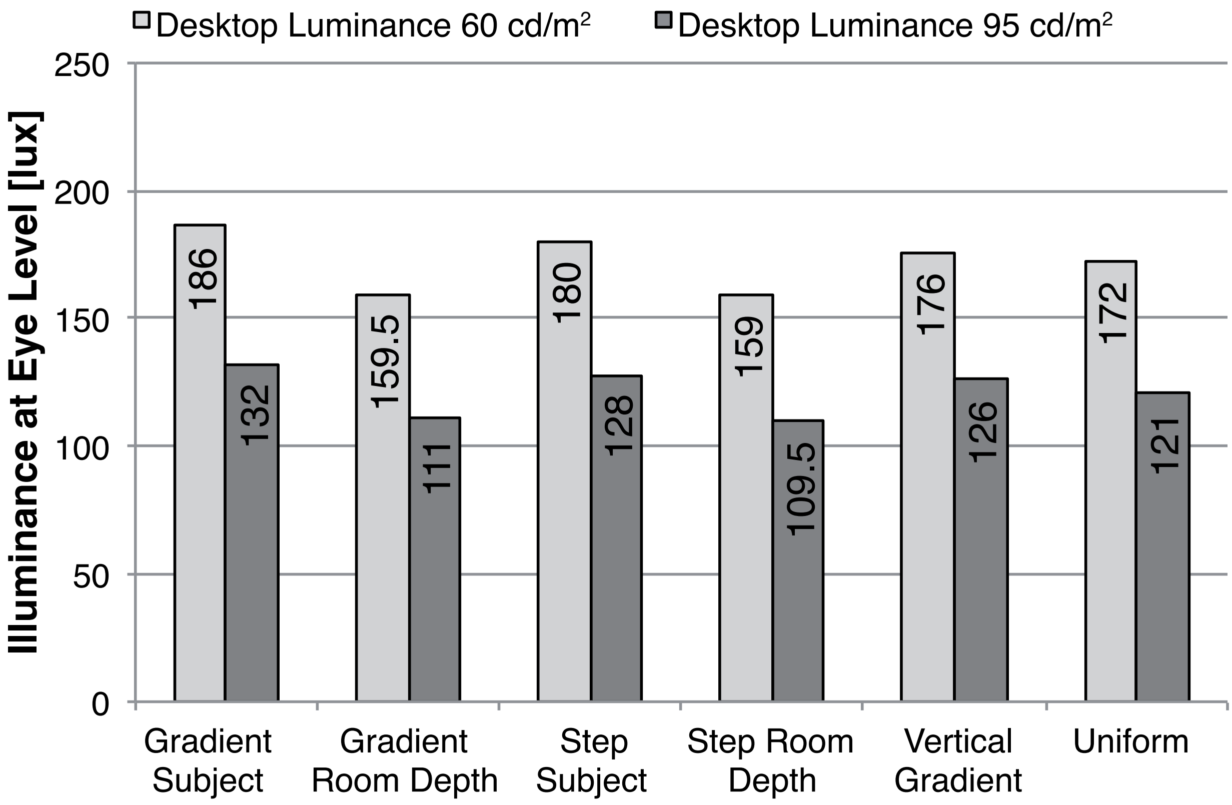
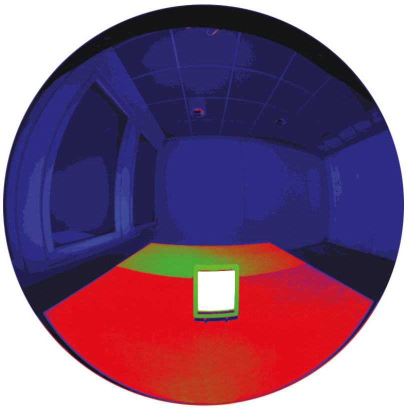


Figure C-20: Illuminances at eye level for experiment II

Luminance Measurements

Experiment I: Luminance Images with Darker Desktop



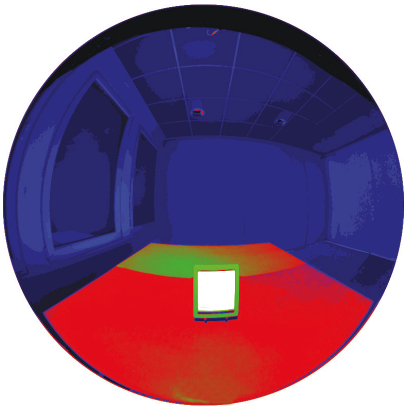
Scene L11_E100

$L_{Walls/Ceiling}$= 11.0 cd/m^2

$L_{40°}$= 17.6 cd/m^2

$L_{Visual\ Field}$= 18.8 cd/m^2

$L_{Desktop}$= 55.7 cd/m^2



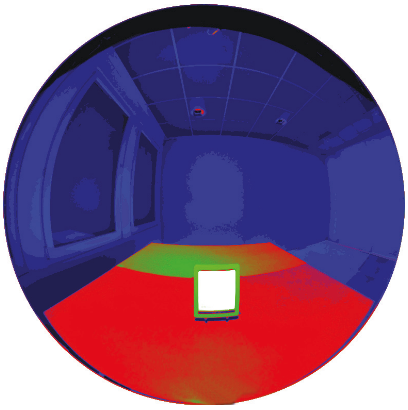
Scene L11_E200

$L_{Walls/Ceiling}$= 11.0 cd/m^2

$L_{40°}$= 18.3 cd/m^2

$L_{Visual\ Field}$= 19.3 cd/m^2

$L_{Desktop}$= 56.1 cd/m^2



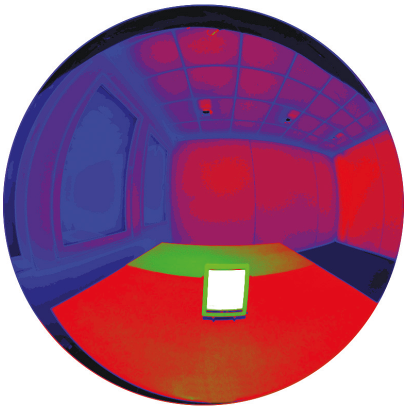
Scene L11_E300

$L_{Walls/Ceiling}$= 11.0 cd/m^2

$L_{40°}$= 18.8 cd/m^2

$L_{Visual\ Field}$= 20.5 cd/m^2

$L_{Desktop}$= 56.1 cd/m^2



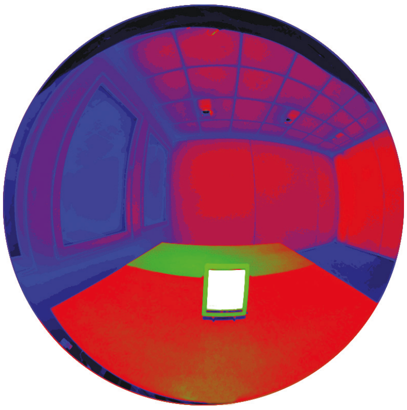
Scene L30_E100

$L_{Walls/Ceiling}$= 30.0 cd/m^2

$L_{40°}$= 28.4 cd/m^2

$L_{Visual\ Field}$= 28.8 cd/m^2

$L_{Desktop}$= 58.2 cd/m^2



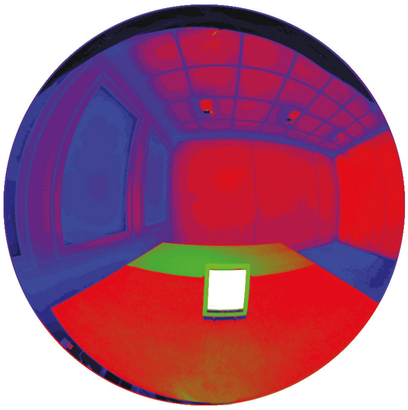
Scene L30_E200

$L_{Walls/Ceiling}$= 30.0 cd/m^2

$L_{40°}$= 29.7 cd/m^2

$L_{Visual\ Field}$= 29.8 cd/m^2

$L_{Desktop}$= 58.8 cd/m^2



Scene L30_E300

$L_{Walls/Ceiling}$= 30.0 cd/m^2

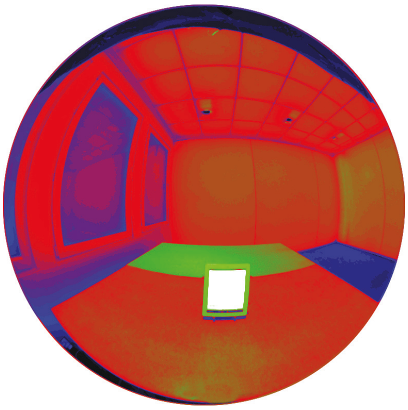
$L_{40°}$= 30.4 cd/m^2

$L_{Visual\ Field}$= 30.4 cd/m^2

$L_{Desktop}$= 59.1 cd/m^2

0 50 100 150 >200

Luminance [cd/m^2]



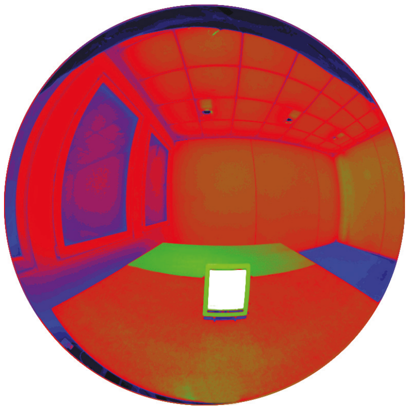
Scene L50_E100

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 42.8 cd/m^2

$L_{Visual\ Field}$= 41.5 cd/m^2

$L_{Desktop}$= 60.7 cd/m^2



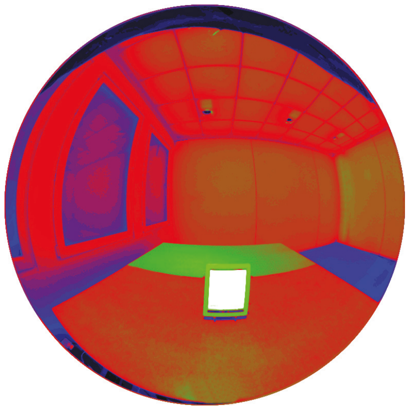
Scene L50_E200

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 43.8 cd/m^2

$L_{Visual\ Field}$= 42.3 cd/m^2

$L_{Desktop}$= 60.1 cd/m^2



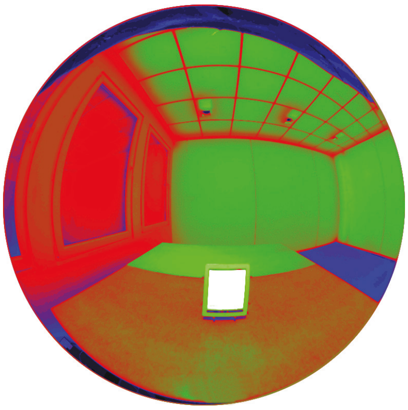
Scene L50_E300

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 44.5 cd/m^2

$L_{Visual\ Field}$= 42.7 cd/m^2

$L_{Desktop}$= 60.4 cd/m^2



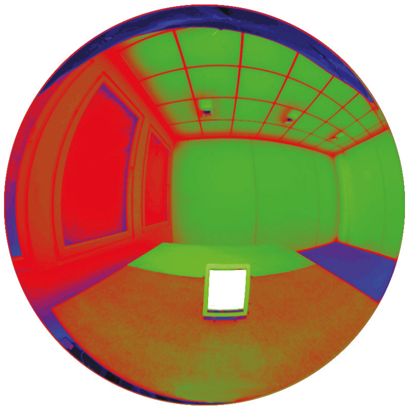
Scene L75_E100

$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 59.0 cd/m^2

$L_{Visual\ Field}$= 55.9 cd/m^2

$L_{Desktop}$= 61.3 cd/m^2



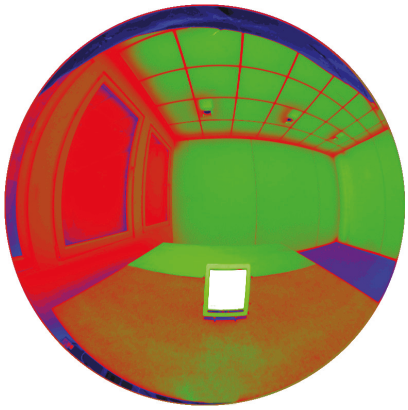
Scene L75_E200

$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 59.6 cd/m^2

$L_{Visual\ Field}$= 56.3 cd/m^2

$L_{Desktop}$= 61.5 cd/m^2



Scene L75_E300

$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 60.2 cd/m^2

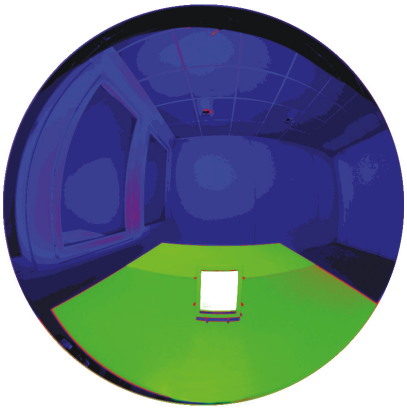
$L_{Visual\ Field}$= 56.8 cd/m^2

$L_{Desktop}$= 61.9 cd/m^2

0 50 100 150 >200

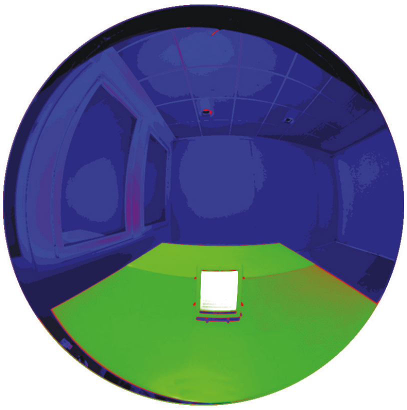
Luminance [cd/m^2]

Experiment I: Luminance Images with Brighter Desktop



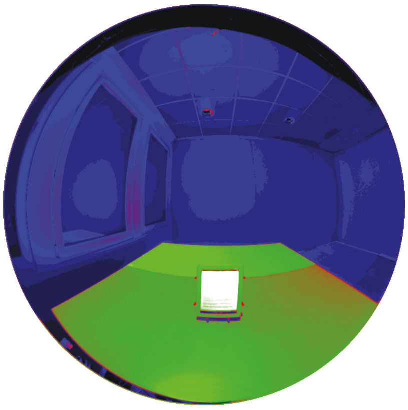
Scene L11_E100

$L_{Walls/Ceiling}$=	11.0 cd/m^2
$L_{40°}$=	25.4 cd/m^2
$L_{Visual\ Field}$=	43.3 cd/m^2
$L_{Desktop}$=	90.0 cd/m^2



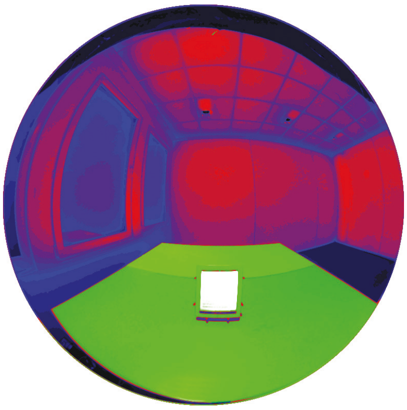
Scene L11_E200

$L_{Walls/Ceiling}$=	11.0 cd/m^2
$L_{40°}$=	26.2 cd/m^2
$L_{Visual\ Field}$=	35.0 cd/m^2
$L_{Desktop}$=	90.5 cd/m^2



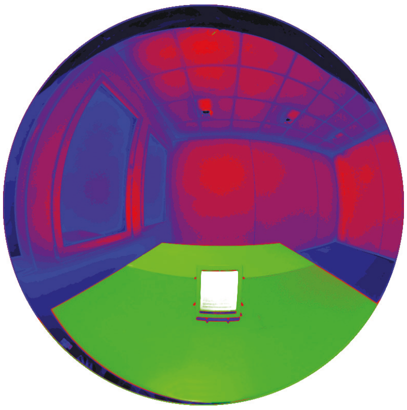
Scene L11_E300

$L_{Walls/Ceiling}$=	11.0 cd/m^2
$L_{40°}$=	27.2 cd/m^2
$L_{Visual\ Field}$=	35.8 cd/m^2
$L_{Desktop}$=	91.1 cd/m^2



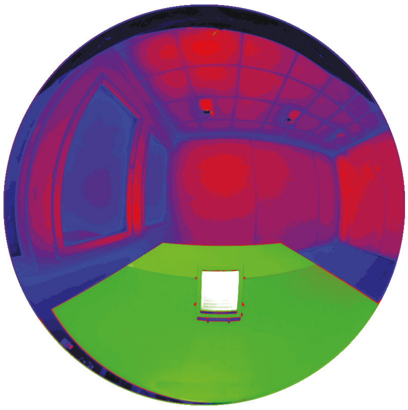
Scene L30_E100

$L_{Walls/Ceiling}$=	30.0 cd/m^2
$L_{40°}$=	37.4 cd/m^2
$L_{Visual\ Field}$=	45.3 cd/m^2
$L_{Desktop}$=	92.2 cd/m^2



Scene L30_E200

$L_{Walls/Ceiling}$=	30.0 cd/m^2
$L_{40°}$=	38.8 cd/m^2
$L_{Visual\ Field}$=	45.7 cd/m^2
$L_{Desktop}$=	92.5 cd/m^2

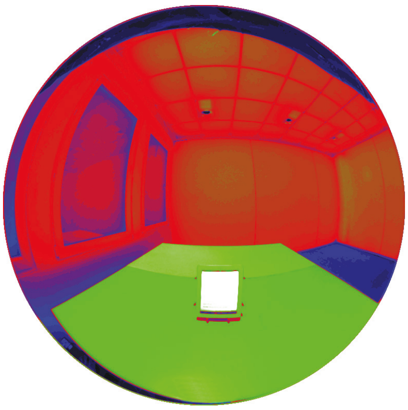


Scene L30_E300

$L_{Walls/Ceiling}$=	30.0 cd/m^2
$L_{40°}$=	39.3 cd/m^2
$L_{Visual\ Field}$=	46.5 cd/m^2
$L_{Desktop}$=	92.1 cd/m^2

0 50 100 150 >200

Luminance [cd/m^2]



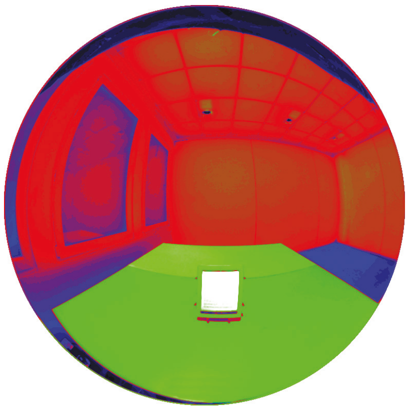
Scene L50_E100

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 52.7 cd/m^2

$L_{Visual\ Field}$= 59.6 cd/m^2

$L_{Desktop}$= 95.2 cd/m^2



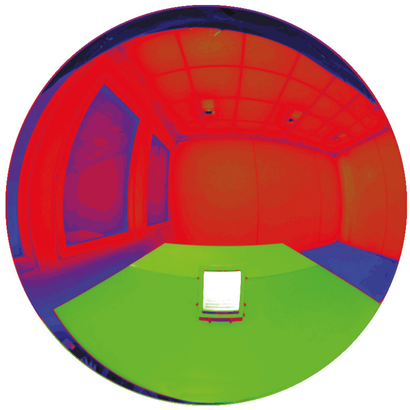
Scene L50_E200

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 53.9 cd/m^2

$L_{Visual\ Field}$= 60.7 cd/m^2

$L_{Desktop}$= 95.8 cd/m^2



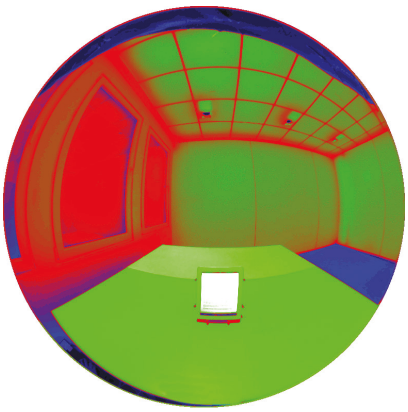
Scene L50_E300

$L_{Walls/Ceiling}$= 50.0 cd/m^2

$L_{40°}$= 54.7 cd/m^2

$L_{Visual\ Field}$= 61.1 cd/m^2

$L_{Desktop}$= 96.7 cd/m^2



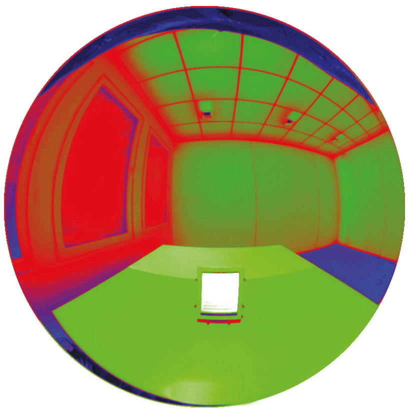
Scene L75_E100

$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 70.1 cd/m^2

$L_{Visual\ Field}$= 75.7 cd/m^2

$L_{Desktop}$= 102.4 cd/m^2



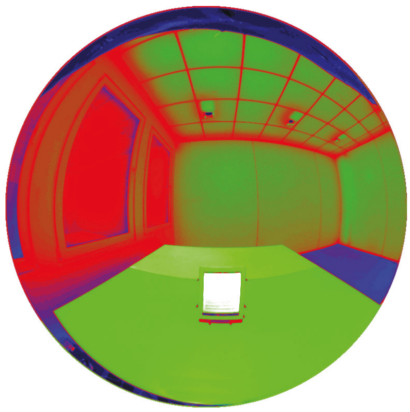
Scene L75_E200

$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 70.8 cd/m^2

$L_{Visual\ Field}$= 76.4 cd/m^2

$L_{Desktop}$= 102.9 cd/m^2



Scene L75_E300

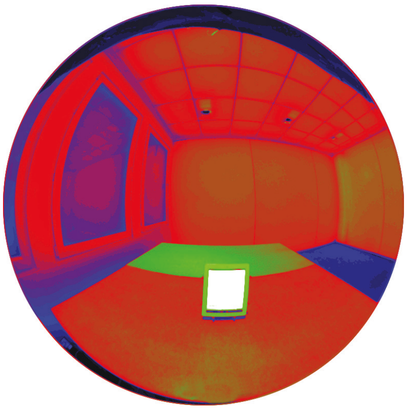
$L_{Walls/Ceiling}$= 75.0 cd/m^2

$L_{40°}$= 71.4 cd/m^2

$L_{Visual\ Field}$= 77.1 cd/m^2

$L_{Desktop}$= 102.8 cd/m^2

Experiment II: Luminance Images with Darker Desktop



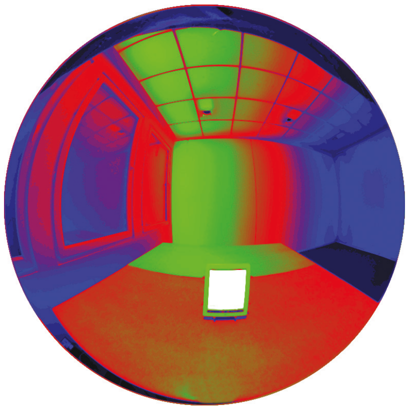
Scene 'Uniform'

$L_{40^\circ}=$ 42.8 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 60.2

$L_{Visual\ Field}=$ 41.5 cd/m^2

$L_{Desktop}=$ 60.7 cd/m^2



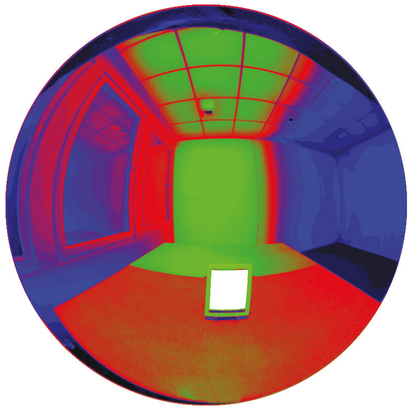
Scene 'Gradient Subject'

$L_{40^\circ}=$ 42.7 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 103.7

$L_{Visual\ Field}=$ 43.3 cd/m^2

$L_{Desktop}=$ 60.1 cd/m^2



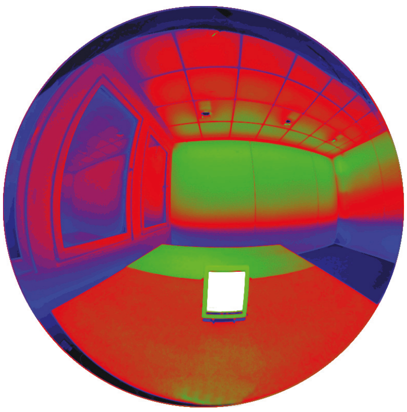
Scene 'Step Subject'

$L_{40^\circ}=$ 42.3 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 111.2

$L_{Visual\ Field}=$ 41.5 cd/m^2

$L_{Desktop}=$ 64.0 cd/m^2



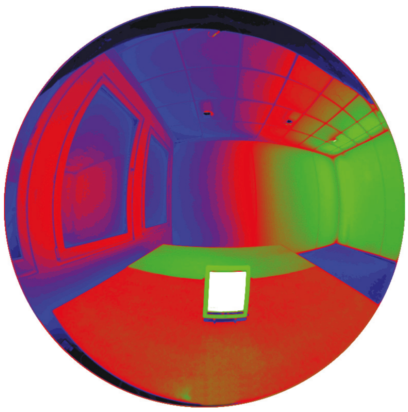
Scene 'Vertical Gradient'

$L_{40^\circ}=$ 43.1 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 73.0

$L_{Visual\ Field}=$ 40.6 cd/m^2

$L_{Desktop}=$ 62.9 cd/m^2



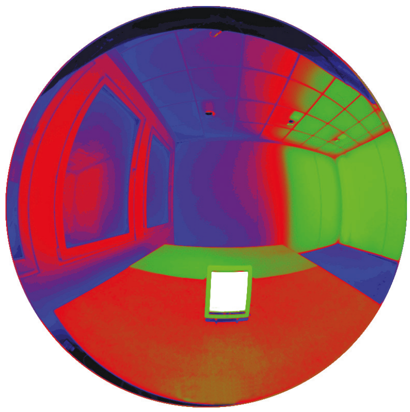
Scene 'Gradient Room Depth'

$L_{40^\circ}=$ 42.7 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 45.8

$L_{Visual\ Field}=$ 38.7 cd/m^2

$L_{Desktop}=$ 61.8 cd/m^2



Scene 'Step Room Depth'

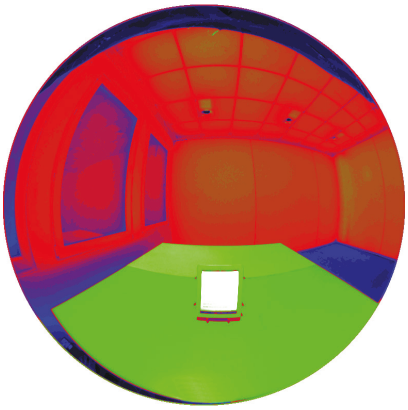
$L_{40^\circ}=$ 41.7 cd/m^2

$L_{40^\circ max}/L_{40^\circ min}=$ 45.0

$L_{Visual\ Field}=$ 39.1 cd/m^2

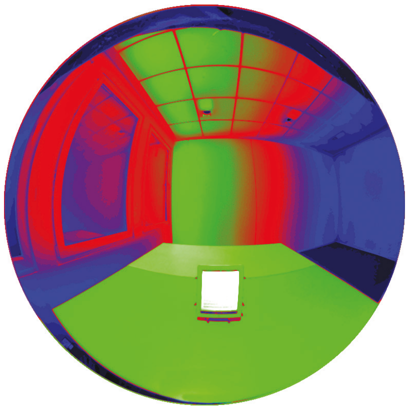
$L_{Desktop}=$ 58.2 cd/m^2

Experiment II: Luminance Images with Brighter Desktop



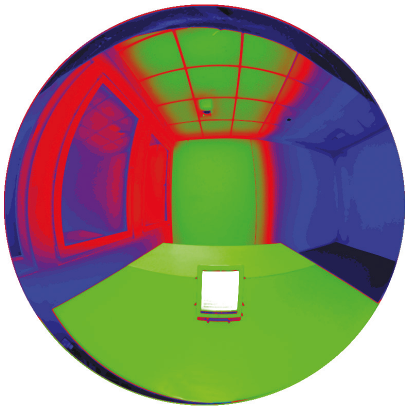
Scene 'Uniform'

$L_{40°}=$	42.7 cd/m^2
$L_{40°max}/L_{40°min}=$	54.0
$L_{Visual\ Field}=$	59.6 cd/m^2
$L_{Desktop}=$	95.2 cd/m^2



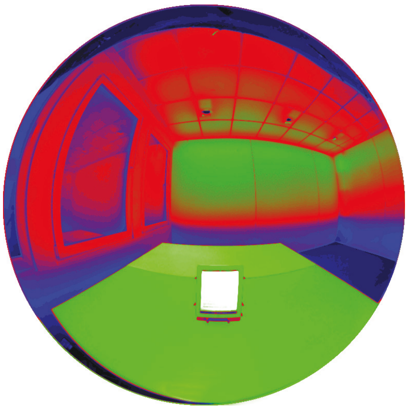
Scene 'Gradient Subject'

$L_{40°}=$	53.2 cd/m^2
$L_{40°max}/L_{40°min}=$	90.5
$L_{Visual\ Field}=$	62.0 cd/m^2
$L_{Desktop}=$	105.2 cd/m^2



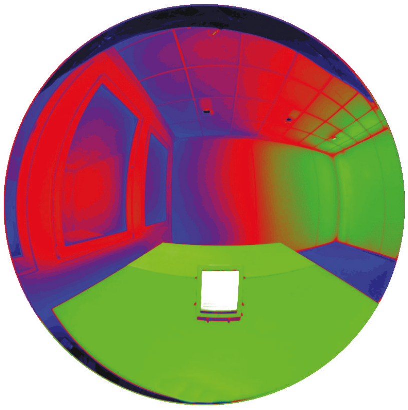
Scene 'Step Subject'

$L_{40°}=$	52.4 cd/m^2
$L_{40°max}/L_{40°min}=$	100.7
$L_{Visual\ Field}=$	59.8 cd/m^2
$L_{Desktop}=$	103.1 cd/m^2



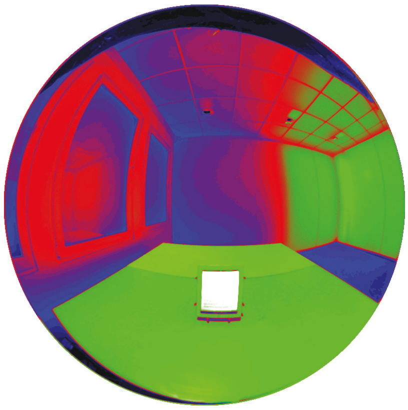
Scene 'Vertical Gradient'

$L_{40°}=$	52.7 cd/m^2
$L_{40°max}/L_{40°min}=$	66.1
$L_{Visual\ Field}=$	57.4 cd/m^2
$L_{Desktop}=$	97.5 cd/m^2



Scene 'Gradient Room Depth'

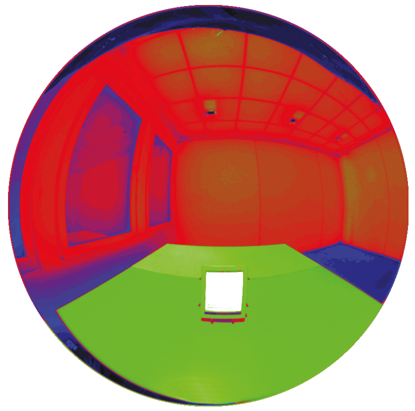
$L_{40°}=$	52.2 cd/m^2
$L_{40°max}/L_{40°min}=$	45.4
$L_{Visual\ Field}=$	56.0 cd/m^2
$L_{Desktop}=$	98.1 cd/m^2



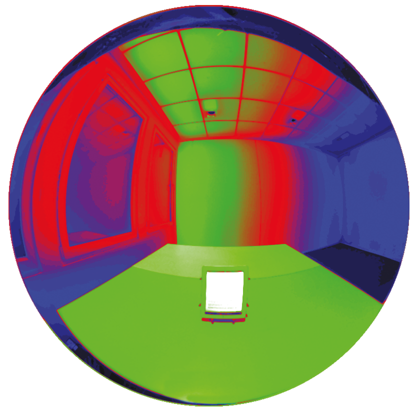
Scene 'Step Room Depth'

$L_{40°}=$	51.33 cd/m^2
$L_{40°max}/L_{40°min}=$	42.8
$L_{Visual\ Field}=$	56.0 cd/m^2
$L_{Desktop}=$	97.4 cd/m^2

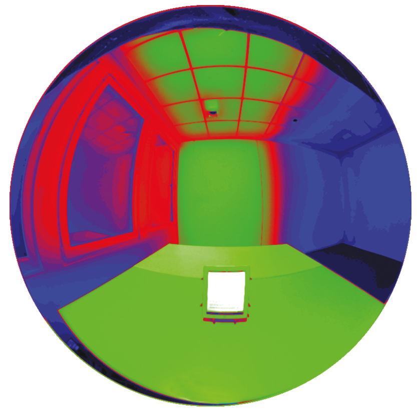
Lighting Scenes Presented in this Work



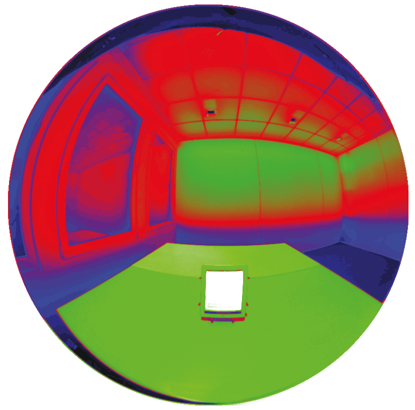
Scene ‘Uniform’



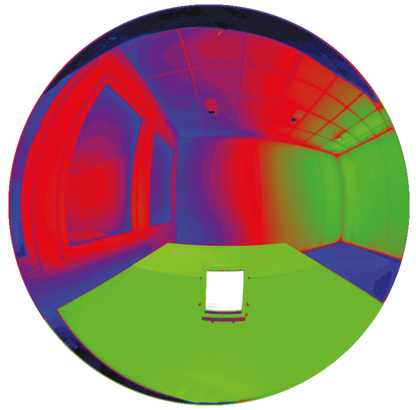
Scene ‘Gradient Subject’



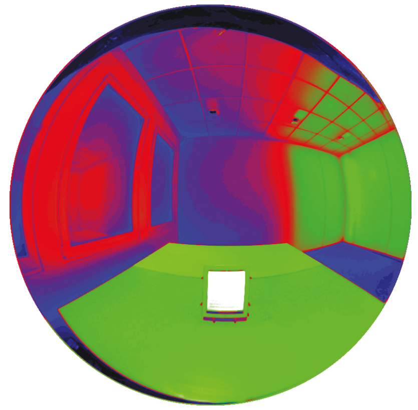
Scene ‘Step Subject’



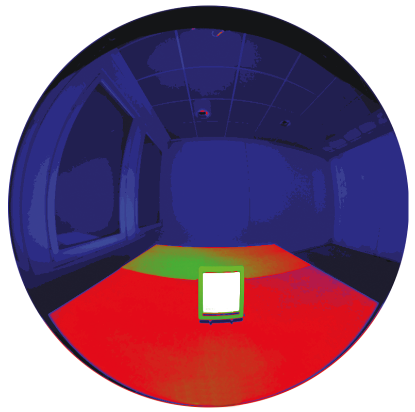
Scene ‘Vertical Gradient’



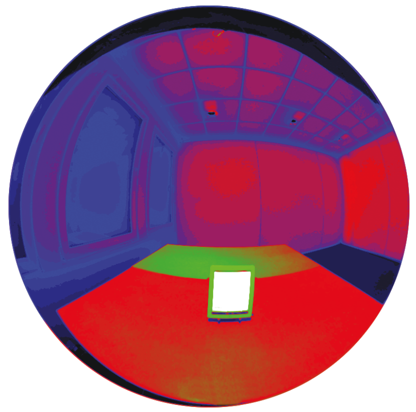
Scene ‘Gradient Room Depth’



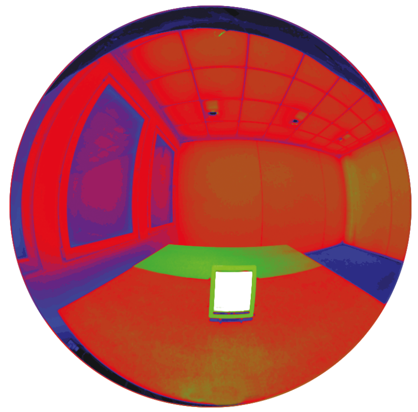
Scene ‘Step Room Depth’



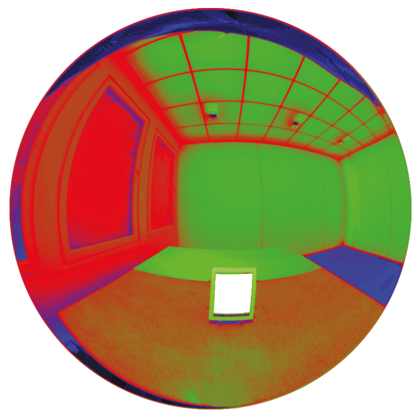
Scene ‘L11_E100/200/300’



Scene ‘L30_E100/200/300’



Scene ‘L50_E100/200/300’



Scene ‘L75_E100/200/300’