Lighting up the ‘great place to work’

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HOW THE ILLUMINATION OF DIFFERENT ROOM SURFACES AFFECTS OFFICE WORKERS IN OPEN PLAN OFFICES

ADRIE DE VRIES

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Contents

CHAPTER 1

Introduction

Although we experience light every single day, we hardly reflect on the impact it has on our daily lives. From the moment we are born we simply accept the fact that daytime brings light, and nighttime comes with darkness. Yet, in our daily lives we are depriving ourselves more and more of natural light as we move inside for the sake of shelter and control over our environment. By living inside, we reduce our exposure to sunlight and try to replace it by an economical solution which, although usually sufficient to see well, does not have the richness of a daylit environment, nor does it stimulate our senses the same way in terms of brightness contrasts, absolute levels, dynamics and many other aspects [1].

For office workers, this deprivation is even more severe than for those with an outdoor job as sources indicate that office workers in for example the US and Europe spend > 90 % of their workdays indoors [2–4], often under less than ideal conditions, using electric lighting. This is not to say that electric lighting is bad by default, but it often is not optimized for human health and wellbeing. The World Health Organization (WHO) states that "health is a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity". Standards specifying lighting requirements mainly cover the physical aspects of health and wellbeing, but do not always have the same attention for the mental and social wellbeing.

Fortunately, there is a growing awareness among companies that workplace experience has a significant impact on employee engagement, and leading organizations start recognizing that employee engagement is one of the most critical metrics for business success today [5]. Consequently, there is growing attention for the concept dubbed "the great place to work". But what is a great place to work from a lighting perspective? This thesis starts to explore this question by looking at the activities of office workers and how lighting can influence these, using a (semi-)realistic setting.

1.1. Office work

To understand how lighting contributes to creating a great place to work, we first need to define the most important activities of office workers. These activities obviously are quite diverse, ranging from concentrated work to meetings with colleagues and informal conversations. Recent studies [6]-[7] highlight that support for individual focus work is essential for an effective workplace. A lack of support for this activity even results in a reduction in performance on other activities such as collaboration, making the workplace detrimental to performance instead of supportive. Individual focus work, however, is still quite a broad concept and can span many different types of activities, depending on the role and responsibilities of the individual. Clerical/administrative work, for example, usually requires a low error rate and high speed, benefitting from an environment with low distraction and supporting high concentration. A knowledge worker's job, on the other hand, also includes using specific knowledge to find the best possible solution to a given problem, and as such might benefit also from an environment that stimulates creativity during certain parts of the problem solving process [8–10].

Since the rapid growth of the knowledge economy over the past decades has increased the number of knowledge workers [11], designing their environment to optimize performance is an interesting avenue to investigate further. Thus far, studies into office-work productivity, particularly in lighting research, have largely focused on specific indicators for cognitive task performance such as inhibition (e.g. the Stroop task [12]), speed, concentration (e.g., the d2 test [13]) or working memory (e.g., the digit span tasks or n-back tasks [14]). These performance measures are indicative for part of the knowledge worker's job activities, but do not represent performance of non-routine or insight-based problem solving [15–17].

Many different theories exist on the exact steps an individual employs in the problem-solving process. Two thought processes are often implicated: divergent and convergent thinking. Divergent thinking pertains to a global mindset in the initial stages of the problem-solving process to devise a large number of possible solutions. Following this phase, convergent thinking employs a more local mindset to synthesize and analyze these solutions to come to the best one [18–21]. Interestingly, these processes have been found to be influenced by both positive and negative affect, where divergent thinking benefits from positive affect and convergent thinking from negative affect [22–24]. Additionally, certain environmental parameters such as the presence of windows, light in general, brightness and color [8,25] also influence creativity. Hence, it seems possible to optimize performance in these processes by optimizing the lighting design of an office. Taking a step back from the knowledge workers themselves to the companies that employ them, we see that many companies now see employee engagement as critical to knowledge worker performance [5]. As engagement is thought to be influenced by workplace experience [26], this opens up possibilities to influence knowledge worker performance using lighting.

1.2. The impact of lighting on performance

Light, as it hits the human eye, has been found to exert its effects on performance and well-being via several pathways. They are generally classified in two broad categories: the non-image forming (NIF) and the image forming pathway (IF). The NIF pathway, also called non-visual pathway, and more recently 'ipRGC-influenced pathway' [27], is still an emerging topic of research and has received much attention over the past years since the discovery of the so-called intrinsically photosensitive ganglion cells (or ipRGCs [28,29]). These receptors are reported to be most sensitive to short wavelength light (λ_{max} 450 - 480 nm) and project photic information from the ipRGC's to our biological clock (Suprachiasmatic nucleus – SCN). The light-dark signal serves as our clock's main 'Zeitgeber' and can result in shifting our circadian/daily 24-hour rhythm. However, ipRGCs also project to other regions of the brain, as such potentially affecting mood, alertness, sleep and body temperature [30–32]. The image forming (IF) pathway is primarily responsible for our sense of sight and relies most heavily, though not exclusively, on the well-known rod and cone receptors in our eye. This pathway is typically implicated in visual performance and visual comfort [33–35], but also in the perception of atmosphere, and the related associations we have with a space [36–39].

It should be noted, however, that the divide between IF and NIF pathways is not as clear and clean as the labeling may suggest. There are numerous interactions at the neural, physiological, and behavioral level that sometimes make it hard to uniquely attribute light effects to a specific underlying mechanism. They become even more difficult to disentangle due to correlations and dependencies of different lighting effects in real life spaces.

So, the combination of the IF and NIF pathways supports performance in many different ways. They facilitate visual acuity and visual comfort [33–35], obviously leading to better visual performance. They contribute to the atmosphere and appraisal of a room [36–41], and as such may change our mood [42,43], which in turn may affect our performance [44,45]. Finally, they may affect our sleep [46] (which also changes our mood and performance) and even may have a more acute effect on subjective alertness (although not all studies come to the same conclusion, concerning the latter aspect [32,47]).

1.3. Theory versus practice

Although in theory the lighting toolkit of the designer is the same as that of a researcher, in practice the designer has to adhere to many limiting conditions, for example to ensure that products and designs meet the requirements set out by workplace lighting guidelines (e.g., EN12464-1 [48] or IES RP1-20 [49]) and comply with energy consumption standards (e.g. ANSI/ASHRAE/IES Standard 90.1 [50]) or 3rd party certifications such as LEED and BREEAM. In addition, lighting designers are limited by economic conditions related to the budget, long-term maintenance plans, and preferences of the client. Finally, there appears to be a general lack of knowledge, or perhaps interest in the impact lighting can have on the appearance of spaces and on employees. Therefore, designers usually have no other option than to rely on standard archetypes of luminaires used in offices (e.g., recessed, surface mounted or suspended luminaires), and can employ accent lighting only if budget allows. These standard luminaire types are typically designed as 'jacks of all trades'. They illuminate the horizontal work plane (influencing visual performance), the vertical surfaces in the space (influencing the appearance of the space), and deliver light exposure to the eye, all from a single luminaire, but it is difficult to create various atmospheres in the room using only these luminaires.

Providing designers with more degrees of freedom with respect to how to illuminate a space, would, of course, enable them to improve their designs. However, in order to be able to do so, knowledge on the impact of light on the different surfaces of a room and their interactions is needed. In contrast, researchers are trained to disentangle effects of various lighting and room related variables on dependent variables measuring performance and well-being. However, in the particular case of understanding the impact of light, as it illuminates various parts of a workspace, the inevitable correlations and interactions between the different variables make the puzzle quite complex, even apart from the question which neural pathways are involved in the effects of these variables on human performance and well-being (see Figure 1). This conundrum was already presented in the 1950's by for example J.M. Waldram who wrote "*Eventually designers will have to take all these features into account, balancing their various claims and combining them into a single harmonious and efficient design.*" [40, p96] Although, over the past decades much work has been done to further this cause, more work is still needed as many questions remain still unanswered due to the complexity of the visual environment and the complexity of its impact.

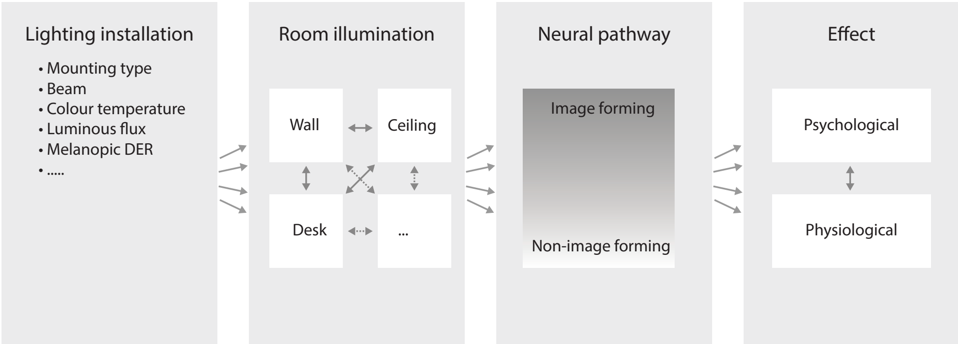

Figure 1.1: schematic overview indicating all steps from lighting installation to effect.

It is, therefore, imperative – for light designers, but also for researchers – to look at light from a holistic perspective, which is colloquially known as 'human centric lighting', and officially defined by ISO/CIE as 'integrative lighting'. This holistic perspective highlights the need to perform research not only in lab settings with well-controlled simple stimuli, but also in more realistic, application-based settings that consider all the interactions between surfaces, interactions between pathways and interactions between effects. Doing so, topics such as atmosphere, glare and comfort can be evaluated in concert with topics such as alertness and cognitive performance to come to an integrative solution.

1.4. Objectives and outline

Given the growth of the knowledge economy and consequently knowledge work on one side, and the rapidly accumulating scientific knowledge regarding the effects of light on our performance and well-being on the other side, this thesis sets out to investigate how lighting can be used to enhance the workplace experience and performance of knowledge workers. Since lighting installations in practice influence both the IF and NIF pathways simultaneously, and consequently multiple aspects related to performance and wellbeing, it is essential to investigate the above in a realistic office setting while still providing the level of control needed to be able to draw reproducible conclusions. To do this, we started with two studies in a realistic, multi-occupant, mock-up office environment, in which we evaluated two different lighting design parameters: wall luminance and desk/eye illuminance. In practice, these parameters are often highly correlated (as they are both the result of the same general lighting installation), but in our experiments we separated them as much as possible.

We started by varying only the wall luminance to change the appearance of the space in both a positive and negative sense by influencing brightness, while we minimized the effect of light on visual acuity by keeping task illuminance constant and minimized any ipRGC-influenced effect of light on sleep or alertness by minimizing the differences in illuminance on the eyes of the participants. To come to a holistic overview of the resulting effects, a wide array of dependent variables was employed covering room appraisal (which included a brightness assessment), subjective alertness, ego depletion, emotional state and several performance tasks covering both problem solving and executive functioning. This experiment is described in Chapter 2.

Next, we repeated this experiment, but this time kept the wall luminance constant and only varied the task illuminance and with it, the illuminance on the eyes of the participants as these two parameters could not be separated. This allowed us to compare the effects of wall luminance to the effects of task/eye illuminance in the context of knowledge worker performance and room appearance (Chapter 3).

In the third study, we selected the ceiling as the remaining major room surface in offices. As the first two experiments mainly resulted in effects on the attractiveness, brightness, and appearance of the room, we focused on these variables for the third experiment, allowing for shorter testing times and more light settings to be tested. In this experiment, we evaluated the effect of the ratio of direct/indirect lighting, and the effect of the luminance distribution on the ceiling for the indirect lighting (Chapter 4). Interestingly, brightness ratings provided by the participants showed a large potential to predict the attractiveness of the room.

Given that attractiveness appeared to be key in our first experiment and given the relation found between brightness and attractiveness, our final study centered on a meta-analysis of brightness perception of the three experiments (described in Chapters 2, 3 and 4). This meta-analysis (Chapter 5) followed an exploratory approach to investigate to what extent we could model brightness based on characteristics of the luminance distribution in the room. This would provide lighting designers with insights on how to assess brightness as an indication for attractiveness of the space and to be used to further refine their lighting designs in the context of an integrative approach.

Based on these four studies, we reflect on the results in the discussion and revisit the original question: What is a great place to work from a lighting perspective?

CHAPTER 2

Lighting up the office: The effect of wall luminance on room appraisal, office workers' performance, and subjective alertness

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Abstract

Creating the right environment is considered essential in today's office designs to foster collaboration, concentration and creativity. Much, however, is still unknown with regard to how lighting affects the office knowledge worker. In this study, we have explored the effects of a single, carefully isolated lighting design parameter, namely wall luminance, on the appraisal of an office space, the affective state of the occupants, their subjective alertness and their performance on a key knowledge worker task: problem solving. Room appraisal increased significantly with higher wall luminance, both on attractiveness and illumination. No effects were found on the pleasure, arousal or dominance dimensions of emotion ratings by the participants, nor were effects found on the performance of divergent and convergent problem-solving tasks. Unexpectedly, wall luminance did affect the subjective alertness of the participants, as participants were able to maintain their level of subjective alertness in the highest wall luminance condition, whereas subjective alertness decreased significantly over time in the lowest and medium wall luminance conditions. As this effect is commonly found in studies where light exposure on the human eye is manipulated (and often attributed to non-visual effects) the finding from this study provides a first indication that next to the amount of light on the eye, wall luminance and room appearance might also play a role.

2.1. Introduction

Historically, visual performance has been the primary factor in designing appropriate lighting conditions in offices (EN12464-1:2002). Over the past decade, however, knowledge concerning the effects of the luminous environment on the emotional state, health and wellbeing of office workers has increased substantially. Consequently, this knowledge is finding its way into modern design practices and is taken into account next to visual performance indicators. Many questions, however, still exist within the design community with regard to the exact mechanisms behind the effects of light that are relevant in the workplace.

The effect of lighting on the office worker can be roughly divided into two categories: effects originating from the visual (image forming) pathway, and those originating from the non-image forming pathway [51,52]. The visual pathway refers to signals generated by light falling onto the retina that travel to the visual cortex and enable the brain to translate the retinal pattern of light into images, hence the name 'image forming'. This sensory input forms the basis of our sight, and ensures we can evaluate the environment in a relatively objective manner (e.g., are objects present yes/no). However, it also provides us with environmental cues that can trigger a host of other, more subjective psychological mechanisms. These include affective responses such as appraisals of the lighting or the physical space, changes in mood and motivation, and cognitive associations with the environment [36,53,54].

The non-image forming pathway, on the other hand, has started to receive much more attention since the discovery of the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs) as a third class of photoreceptors in the human retina, next to rods and cones, over 15 years ago [28,29]. These ganglion cells were found to express the photopigment melanopsin and are reported to be most sensitive to short wavelength light (the blue part of the spectrum, 460 nm to 500 nm). They play a crucial role in several non-visual responses, such as circadian phase shifting, melatonin suppression and pupillary responses to light [55–58]. Along with these more physiological effects, the acute effects of light exposure on alertness have also received increasing attention in several studies [47,59–61]. Both the visual and non-visual pathways have received significant attention from researchers over the past decade. A wealth of studies can be found on both acute and circadian effects of light via the non-image forming pathway. Next to this, studies pertaining to the image forming pathway too have been numerous, although the majority of these have focused on aspects relating to visual performance. Yet, the psychological literature on light – albeit relatively scarce - suggests that there may be additional ways through which the visual pathway impacts employees' effectiveness and wellbeing [52]. These effects appear to be not directly linked to the physiological responses of our body to light, but rather originate from a more psychological appraisal of other characteristics of the luminous environment (e.g., perceived brightness of the room or luminous contrast). As these psychological mechanisms have not been studied as extensively, the current study explores whether such effects can be established without confounding them with the effects of visual performance or alerting and entraining effects induced through the non-visual pathways. In particular, we focus on the effects of wall luminance on the performance of office workers while controlling for illuminance levels on the eye and on the desk.

2.1.1. The influence of the lit environment on office workers

Lighting is one of the few environmental parameters that can have an instant effect on the perception and appraisal of a space. By influencing elements such as the intensity, directionality and the overall luminous balance (balance between the different surfaces of the space), appearances can be changed drastically. This, for example, can have an impact on one's impression and evaluation of the space. Spaces may appear pleasant in one setting, but at the flick of a switch (figuratively) turn to unpleasant [37]. Similarly, the experience of the same room can be altered from cozy to lively, tense or detached by changing the room's illumination [38]. Moreover, the effects of lighting are not limited to appraisal and atmosphere perception, as studies have indicated that different lighting conditions can also trigger changes in mood and emotional state [36,39,62,63], which, depending on context, may lead to changes in behavior.

Studies have shown that altering the (lit) atmosphere of a space can change social behavior in both positive and negative ways. For instance, Page and Moss (1976) found that participants were more prone to aggression in darker environments. They hypothesized that darkness acted as a disinhibitor as a result of either anonymity, the perceived distance between victim and aggressor, or conditioned effects. In contrast, a study by Baron, Rea and Daniels [65] found that dimly lit environments could increase positive judgements of others. This finding was proposed to originate from an increase in positive affect induced by the environment, although no changes in affect itself were found. Similarly, Steidle and colleagues demonstrated how cooperation and creativity became more likely in dim conditions, as a result of grounded and embodied cognitions [25,66]. As these examples indicate, multiple psychological mechanisms (self-awareness, affect, cognitive associations) may emerge as a result of the same visual stimulus (e.g., dimly lit environments) depending on the context. Moreover, they may even result in opposing effects (e.g., judging somebody more favorably versus more harshly).

Next to these more generic studies, the psychological effects of light have also received attention in the more specific context of office work. The most extensive research in this field is the work of Veitch and colleagues (e.g. [54]), who demonstrated that lighting may influence office employees' work engagement via lighting appraisal, which may have an effect on employees' effectiveness [67,68]. As lighting appraisal can be influenced in several different ways within a lighting design, this still leaves open many avenues. For example, the level of contrast and/or uniformity can alter the visual interestingness of a space [69]. Also, studies have shown that appraisal can be strongly improved by increasing the perceived brightness of a space, for example by influencing the illuminance of the different surfaces [70], or by changing the color temperature of the light [71]. Brightness, it seems, is a recurring topic when discussing the appraisal of spaces.

As brightness is mainly determined by what we see in our field of view, one of the major contributors to the perceived brightness of a room is the illumination of the walls and ceiling [70,72]. Although recognized by lighting designers and lighting industry, the illumination of walls and ceiling was not considered at all in European lighting standards prior to the introduction of the 2011 version of the European indoor workplace lighting standard (EN12464-1:2002; EN12464-1:2011), the single focus being on the horizontal work plane. In practice, however, horizontal illuminance and wall and ceiling (il)luminance are quite often interlinked as both are heavily influenced by the same general lighting installation (light intended to light the task surface also reaches the walls and ceiling). As such, brightness in spaces typically depends on the achieved horizontal illuminance instead of being the result of a conscious design choice. This does, however, lead to an essential implication for studies in the field of the effects of lighting on individuals. Due to these interdependencies, the risk of confounding the effects of for example changing the horizontal illuminance with the effects caused by the simultaneous increase in brightness of the overall environment is quite high. As such it is essential to either control for or monitor both these effects in research.

2.1.2. Knowledge work

A complicating factor in studying the effects of lighting on the office worker is the fact that work in offices has become highly dynamic. In the past, the majority of office work revolved around manual and administrative tasks with clearly defined activities. Deriving performance measures from these tasks was fairly easy and straightforward (e.g. number of pages typed or documents processed). Since then, the 'knowledge economy' has seen a vast growth [11] resulting in offices being increasingly occupied by knowledge workers, involved in solving complex problems, with a stronger focus on the quality of the solutions rather than on their quantity. In the context of studies regarding office worker performance, this implies that in addition to the classical laboratory tasks aimed at measuring performance (e.g., visual performance and 'simple' reaction time tasks) additional performance indicators are needed to measure this 'new' type of working. This also suggests that psychological effects of lighting such as appraisal and their effects on behavior may play a much bigger role than they used to do in the traditional office.

Knowledge work as a concept is rather broad and may pertain to many different organizational roles, all with their own characteristics and activities. However, amongst all of them, the so called 'non-routine or insight problem solving' (often related to creativity) is seen as a core activity [15–17]. Although there are several theories detailing the steps of solving a problem from a psychological perspective, at least two different thought processes, both closely related to creativity, have been found to consistently underlie problem solving performance: divergent and convergent thinking [18,19]. Divergent thinking is employed during the initial stages of problem solving to produce a wide range of possible solutions. It is supported by a global information processing mode in which information is processed in a holistic manner. In the consecutive phase, convergent thinking serves to synthesize and analyze these ideas in order to generate a solution. This process is positively influenced by a local processing mode, focusing on details [20,21].

Creativity is often considered as an individual's trait and training based skill (within the context of problem solving). However, recent studies have shown that in addition to person characteristics contextual factors may also play an important role, as suggested by studies on the effects of environmental parameters such as the presence of windows, light, brightness and color [8,25], and by studies on affective processes [73–75]. Similarly, performance on convergent and divergent thinking and information processing was found to be linked to affective processes. For example, divergent thinking has been found to be facilitated by positive affect

[22,24,65]. Positive affect, according to recent accounts, broadens the mind, which is beneficial for divergent thinking [20,21,23], whereas negative affect has been shown to induce a more narrow scope of attention enhancing convergent thinking [23]. Consequently, both positive and negative affect potentially play a significant role in the performance of knowledge workers.

To conclude, perceived room brightness influences room appraisal and perceived atmosphere. These, in turn, may influence convergent and divergent thinking - processes that drive creativity and problem solving, and hence important components of today's knowledge working community - via the affective and motivational responses to light as described by Knez (1995), Küller et al. (2006), Veitch et al. (2013) [36,54,62], or via the associative mechanisms as described by Steidle and Werth (2013) [25].

2.1.3. Study description

The aim of this study was to test the hypothesis that an increase in wall luminance results in a more positive room appraisal, which in turn leads to a more positive affective state and to a higher performance on divergent thinking. Conversely, a decrease in wall luminance was expected to result in a more negative room appraisal, a more negative affective state and a higher performance on convergent thinking tasks. In order to separate lighting effects on visual appraisal and affect as much as possible from visual performance and non-image forming effects, wall luminance was manipulated on three levels while keeping horizontal illuminance on the work plane stable and keeping the differences in vertical illuminance at the eye as small as possible. A varied set of dependent measures was used to explore effects of wall luminance on room appraisal, mood, alertness, ego depletion, divergent and convergent thinking as well as on inhibitory control.

2.2. Method

2.2.1. Participants

Forty individuals were recruited from a student population to take part in this experiment. As compensation for time, effort and travel, the participants received a modest monetary reward per attended session. The study was approved by an ethics board and conducted in accordance with the Helsinki Declaration. Selection criteria included normal or corrected to normal vision and being a native Dutch speaker. In order to ensure normal color vision (essential for the Stroop task), the Ishihara color vision test (concise edition) was performed before the start of the first session.

One participant was excluded based on the score on the Ishihara test and the data from two additional participants were excluded from the analysis because they missed one of the scheduled session(s). This resulted in a total of 37 participants whose data were included in the data analysis. The sample consisted of 23 male and 14 female participants, with ages ranging from 18 to 29 years (mean age 20.59, SD 2.49).

2.2.2. Settings

To simulate an office environment, a space of 7.2 x 7.2 x 3.0 m (length x width x height) was prepared and outfitted with standard office interior elements such as desks, dividers, chairs, a plant and storage cabinets based on a symmetrical setup (see Figure 2.1). Daylight contribution was eliminated using opaque screens and access to the corridor was blocked using a light grey curtain. As the wall luminance was the primary independent variable, the walls were painted in a neutral white color (reflection coefficient 90 %) and were kept bare.

Figure 2.1: Layout and impression of experimental setup - Luminaire type A: General lighting luminaires, Luminaire type B: Spots

Four work stations (desk, chair and a PC setup consisting of a 22 in. display, keyboard and mouse) were grouped in the center of the space. Consistent with an 'open office plan' design, the participants were sitting opposite to each other, separated by a divider with a height of 40 cm above the desk. A fifth desk was added at the head of the group of desks to facilitate the test leader.

To be able to control the wall luminance separately from horizontal task illuminance and vertical illuminance on the eye, two separate lighting installations were employed. The general lighting, designed to achieve a uniformly lit horizontal task illuminance (targets according to EN12464-1 E_{avg} : 500 lx, U_o > 0.6), was created by six standard 600 x 600 mm, low glare LED-based office luminaires with a (luminaire) luminous flux of 3400 lm each (Philips PowerBalance, 4000 K, R_a > 80, R_{UG} < 16, floorplan type A), with a center on center spacing of 1800 x 1800 mm. The wall luminance was controlled by 2 lines (one on each side of the space) of 5 semi-recessed LED spots per line with a center on center spacing of 1200 mm. Each LED spot was outfitted with a wide beam reflector, had a maximum (luminaire) luminous flux of roughly 2300 lm, and was mounted at approximately 900 mm from the wall (Philips StyliD, 4000 K, R_a > 80, floorplan type B).

Using the combination of these two systems, three different lighting conditions were programmed. The appropriate condition was set before the participants arrived. In all three conditions the horizontal illuminance on the desk was set to roughly 500 lx (see Table 2.1 for exact values); uniformity requirements (as indicated in EN12464-1:2011) were verified based on lighting simulations using lighting simulation software (Dialux). The wall luminance in the three conditions was measured using a calibrated Technoteam LMK 5 Color luminance camera (HDR), placed at a height of 1.2 m (indicated as sitting height in EN12464-1:2011), positioned at the individual sitting location of the participants (i.e. measured in 4 locations). The wall luminance was defined as the average wall luminance of the visible part of the wall as seen from the participant's point of view. Next to this, luminance values were determined for the 40° band as described by Loe, Mansfield & Rowloands [69] and recommended in CIE 213:2014 protocols for describing lighting [76]. Additionally, originating from the same study, the logarithm of the maximum to the minimum luminance (LogMM) on the wall was added as an indicator for visual interestingness.

Three different wall luminance settings were used in the experiment. The lowest condition with an averaged wall luminance of 12 cd/m^2 was set to represent an installation with a low perceived brightness while still complying to the illuminance requirements for walls as stated in the European standards for lighting workplaces (EN12464-1: 2011). To achieve this level, the spots were turned off completely. The middle condition (with an average wall luminance of 36 cd/m^2) was set to target preferred lighting conditions such as reported in studies on preferred luminance in office environments [69,77]. The highest wall luminance was set to 72 cd/m^2 and was selected to create a substantially brighter, yet still comfortably illuminated wall.

Table 2.1: Overview of lighting conditions – as used in publication – based on a single seating position. See Appendix 1-Table A1-2 for a more detailed overview of average luminances of space elements based on all 4 seating positions.

wall condition	$L_{avg,wall}$ [(1)] [cd/m²]	$L_{avg,ceiling}$ [(2)] [cd/m²]	$L_{avg,divider}$ [cd/m²]	$L_{avg,screen}$ [cd/m²]	$L_{avg,desk}$ [cd/m²]	$E_{avg,desk}$ [lx]	$E_{v,eye}$ [lx]	$L_{avg\ 40°\ band}$ [cd/m²]	*LogMM* wall
Low luminance	12	21	20	69	95	514	206	16	1.16
Medium luminance	36	27	22	70	98	529	227	29	1.62
High luminance	72	36	26	72	98	538	254	50	1.83

[1] Facing wall including small sections of the side walls

[2] Visible part of the ceiling, excluding luminaires

Abbreviations: Average wall luminance ($L_{avg,wall}$), Average ceiling luminance ($L_{avg,ceiling}$), Average luminance on divider ($L_{avg,divider}$), Average screen luminance ($L_{avg,screen}$), Average desk luminance ($L_{avg,desk}$), Average horizontal illuminance on the desk ($E_{avg,desk}$), Vertical illuminance at the eye position in viewing direction ($E_{v,eye}$), Average luminance of the 40° band ($L_{avg\ 40°\ band}$), Logarithm of ratio maximum to minimum luminance ($LogMM_{wall}$)

Inevitably, the increase in wall luminance resulted in a modest increase in vertical illuminance at the eye. However, due to the size of the space, and the separation of the lighting installations, these effects were small. Overall, the increase in vertical illuminance at the eye was 48 lx when comparing the highest to the lowest setting. Based on the spectrum (as measured with a calibrated JETI spectrometer) and the intensity at the eye, an indication of the non-image forming stimulus can be derived applying the CIE S026 methodology. This resulted in a Melanopic Equivalent Daylight Illuminance (Melanopic-EDI) of 116 lx in the lowest setting versus 127 lx in the medium setting and 142 lx in the highest setting (see Appendix 1-Table A1-1 for full overview of the alpha-opic EDIs and Figure A1-1 for a visualization of the spectral power distribution). Additionally, the computer displays increased the vertical illuminance on the eye in each condition by approximately 15 - 20 lx.

2.2.3. Experimental Design

This study followed a within-subject design with three levels of Wall Luminance (i.e., 12, 36 and 72 cd/m^2). Several dependent variables were measured at multiple time points, introducing a second within-subject factor, namely Time. Ten groups of four participants each participated in three sessions, in consecutive weeks in December and January (group composition stayed the same throughout the experiment). The experiment was divided into two blocks of three weeks (each block hosting 5 groups). Each session took place at the same time (15.00 - 16.30 h) and each group had a fixed day of the week. Per session one lighting condition was presented (set prior to participants entering the room). The order of the lighting conditions varied over the 10 groups.

2.2.4. Measures

Both self-report scales and objective measures were employed to assess the impact of Wall Luminance on affective state and performance. Next to this, questionnaires were administered to gather information on the visual and non-visual effects. All questionnaires were administered using the display, keyboard and mouse on the desk, whereas the objective measures were administered using both paper forms and computer screens (light grey background, white text using Arial font).

Self-report measures

Chronotype was assessed using the Morningness Eveningness questionnaire (MEQ; Horne & Östberg [78]), modified by Terman [79] to better suit modern day language. Since chronotype is a trait (and not a dependent variable) it should not change over the course of the study. However, to ensure session consistency, it was nevertheless administered each session. As expected, no statistically significant differences were found between the different sessions. Our sample contained 11 participants with an evening chronotype, 22 with an intermediate chronotype and 3 with a morning chronotype.

Emotional state was assessed using the Pleasure – Arousal – Dominance emotional state model (PAD; Mehrabian [80]). Each assessment consisted of 6 semantic differentials per dimension (PAD-Pleasure, PAD-Arousal, PAD-Dominance) measured on 7-point scales (1 indicating low pleasure/arousal/dominance, 7 indicating high pleasure/arousal/dominance).

Subjective alertness was measured using the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg [81]), with response options ranging from '1: extremely alert' to '9: extremely sleepy – fighting sleep'.

Room appraisal was assessed using a modified version of the room appearance rating system developed by Veitch and Newsham (1998) [82]. For later studies, Veitch further reduced the 27 semantic differential items to a set of 8 items loading on two different dimensions (Attractiveness and Illumination). The Attractiveness dimension (RA-Attractiveness) used the following five differentials (measured on a visual analog scale of 0-1 and averaged over all items): Unattractive – Attractive, Ugly – Beautiful, Unpleasant – Pleasant, Dislike – Like, Somber – Cheerful. The illumination dimension (RA-illumination) was based on 3 differentials: Vague – Distinct, Dim – Bright, Gloomy – Radiant.

Last, ego depletion was assessed as a control variable to identify possible (mental) exhausting effects of the performance tasks, which would otherwise go unnoticed. Ego depletion was assessed using the State Self-Control Capacity Scale consisting of 25 items scored on a 7-point Likert scale (ED; Christian & Ellis, 2011; Ciarocco, Twenge, Muraven, & Tice, 2011 [83,84]). Summation resulted in total scores ranging from 25 (low ego depletion) to 175 (high ego depletion).

Performance measures
Visual acuity (VA) was measured as a control variable using a modified Landolt-C test. The test consisted of a single A4 paper panel with rows of optotypes in decreasing size (ranging from 1.73 to 0.42 arc minutes). The panel was placed on the desk at roughly 70 cm from the eyes of the participant under an angle of 45 degrees (no chin-rest was used). A total of 4 panels with different optotype arrangements was used to prevent learning effects. Visual acuity was determined from the smallest optotype size at which the orientation could still be correctly identified for all optotypes on a row. Because viewing distance was not controlled

and no significant differences between Wall Luminance conditions were found, the results from this task will not be reported here.

Divergent thinking performance was assessed with the Alternate Uses Task (AUT; Benedek, Könen, & Neubauer, 2012; Guilford, Christensen, Merrifield, & Wilson, 1978 [85,86]). Participants were shown two everyday objects on the screen and were given 5 minutes to write down as many possible (realistic) uses for those two objects. Multiple aspects of the answers (flexibility, fluency, elaboration and originality) may be scored, however, some studies suggest that flexibility is the most reliable aspect to measure [87,88], so only flexibility was considered in this study. The scores for the two objects were added for a total score.

Scoring was performed by the lead researcher (rater 1) and additionally an independent rater who was blind to the condition (rater 2). Inter-rater reliability was tested using the intra-class correlation coefficient (ICC). Based on a two-way model testing for consistency an ICC of 0.63 was found which according to the guidelines by Cicchetti is deemed 'good' [89]. For reporting and analysis of the results, the scores of the two raters have been averaged.

Mednick's Remote Associates test was employed to test Convergent thinking (RAT; Akbari Chermahini, Hickendorff, & Hommel, 2012; Mednick, 1968 [90,91]). For this test, the participants were presented with a list of 10 word-problems (on screen) to solve within 5 minutes. Each word-problem consisted of three words, to which a fourth word, associated with the three presented words, needed to be found. The total score is the number of correctly answered items.

As a more 'classical' cognitive performance test a digital Stroop task was also administered next to the divergent and convergent tasks. The participants were presented with 80 trials consisting of congruent and non-congruent stimuli (respectively 25 % and 75 % of the total) using the colors red, green, blue and purple (color name and font color). For each trial they were asked to press the first letter of the presented font color as quickly as possible (no time limit). Response times (RT) and number of errors were recorded. Response times of errors and response times below 200 ms or above 2500 ms (considered as outliers) were excluded from further calculation. For the correct responses the median RTs were calculated, which were then transformed using a reciprocal transformation to improve normality. The transformed median RTs for both the congruent trials and non-congruent trials were analyzed as were the number of errors for the congruent and non-congruent trials. Additionally, the difference between congruent and non-congruent response times was also included in the analysis, since this is also seen as an indicator for response inhibition [92].

2.2.5. Procedure

Each participant was assigned to a group and was given a table number (1 to 4) to ensure the same position for each session. Each session lasted roughly 1.5 hours (see Figure 2.2), including instructions (both verbally and written) and time for questions.

After administering the Visual Acuity test, the participants were asked to put on their headphones (used to draw their attention to the screen at key moments using a subtle sound) and go through a set of practice questions. With exception of the Visual Acuity test, the full experiment was automated using the Psychopy package developed at the University of Nottingham [93].

The participants started with the first block of questionnaires consisting of the chronotype (MEQ), emotional state (PAD1), and subjective alertness questionnaire (KSS1). After this block, they were instructed to wait until the test leader indicated they could continue (to ensure a synchronized start of the performance tasks).

Following the first block of questionnaires, the three performance tasks were executed. To mitigate learning effects for the individual tasks and carry-over effects from one test to the other, each test was performed two times in a row (2 x 5 minutes for the AUT & RAT tasks, 2 x 80 stimuli for the Stroop task). Only the data of the second part of each task was intended for performance analysis (the first part was considered practice). Between two different tasks a questionnaire was administered (room appraisal – RA1 after task 1 and ego depletion- ED after task 2).

After completing the three performance tasks, a second block of questionnaires was administered consisting of the emotional state (PAD2), subjective alertness (KSS2) and room appraisal questionnaires (RA2).

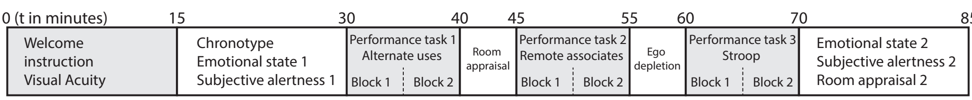

Figure 2.2: Session procedure overview

2.2.6. Statistical analysis

The statistical analyses were performed using the software package R. Pearson's correlations (with Holm corrections for multiple comparisons) per wall luminance condition were analyzed using the psych package. Linear Mixed Models (LMMs) were employed to analyze the main effects using the lme4 package. All p-values derived from the LMMs were based on Satterthwaite approximation for degrees of freedom using the lmerTest package (significance level set at $p < 0.05$). Post hoc analyses were performed using Tukey's honestly significant differences (HSD) from the lsmeans/emmeans package. Finally, the KSS was further analyzed using McNemar's test (base stats package). Next to the values reported in Section 2.3, full results of the Pearson's correlations and LMMs can be found in Appendix 1 – Table A1-6.

2.3. Results

2.3.1. Bivariate correlations

Before testing the effects of the light manipulation, we explored bivariate correlations between the dependent variables. Due to the repeated-measures nature of this study, correlations were computed per wall luminance condition to allow for calculation of p-values. For brevity, only cases where statistically significant correlations were found across all three conditions are discussed here (see Table 2.2, additionally, full correlation matrices are reported in Appendix 1 – Tables A1-3,4,5).

- Room appraisal correlations: RA Attractiveness and RA Illumination correlated significantly on both time points (t1 and t2). This is further investigated in Section 2.3.2.

- Emotional state correlations: the PAD pleasure ratings at t1 and t2 were found to be correlated within each wall luminance condition. The arousal and dominance ratings correlated occasionally, but not consistently across conditions.

- Finally, correlations between different types of dependent variables: PAD arousal at t2 correlated with subjective alertness (KSS) at t2. Additionally, ego depletion and subjective alertness at t2 were found to be correlated.

Table 2.2: Selected Pearson's R correlations (cases where all conditions showed statistically significant results ($p < 0.05$) – Holm corrected)

		Lighting condition		
Variable 1	**Variable 2**	**Low**	**Medium**	**High**
RA Attr1	RA Attr2	0.89	0.88	0.88
RA Attr1	RA Illum1	0.79	0.66	0.75
RA Attr1	RA Illum2	0.78	0.61	0.75
RA Attr2	RA Illum1	0.67	0.68	0.58
RA Attr2	RA Illum2	0.72	0.69	0.75
RA Illum1	RA Illum2	0.90	0.83	0.77
PAD P1	PAD P2	0.69	0.70	0.57
PAD A2	KSS2	-0.64	-0.73	-0.68
ED	KSS2	0.67	0.72	0.58

2.3.2. Room Appraisal – Attractiveness & Illumination

The effects of Wall Luminance on both dimensions of room appraisal (Attractiveness and Illumination) are shown in Figure 2.3. A Linear Mixed Model (LMM) analysis was conducted testing the impact of Wall Luminance, Time and their interaction[1]. The results (of which the means and SD are shown in Table 2.3) showed that participants rated the conditions with a higher Wall Luminance as significantly more attractive ($F(2,72) = 22.7$, $p < 0.001$) and better illuminated ($F(2,72) = 48.9$, $p < 0.001$). No significant effect of Time was found (explaining the high correlation between time points), nor of the interaction between Wall Luminance and Time. As Time was not found to be significant, the results were averaged across this factor for the post hoc tests.

Pairwise post hoc analyses indicated that room appraisal significantly increased from the low to the medium Wall Luminance condition (RA attractiveness: $p < 0.001$, *EMM* $\Delta = 0.11$, $SE = 0.02$; RA illumination: $p < 0.001$, EMM $\Delta = 0.16$, $SE = 0.02$) and from the low to the high Wall Luminance condition (RA attractiveness: $p < 0.001$, *EMM* $\Delta = 0.15$, $SE = 0.02$; RA illumination: $p < 0.001$, *EMM* $\Delta = 0.23$, $SE = 0.02$). When comparing the medium to the high Wall Luminance condition, only the illumination dimension showed a significant increase ($p = 0.02$, *EMM* $\Delta = 0.07$, $SE = 0.02$).

1 This model erroneously omitted the nesting of time per participant in the original paper. The results have been re-analyzed including this nesting, but the overall outcomes did not change – descriptive statistics in the text have been updated.

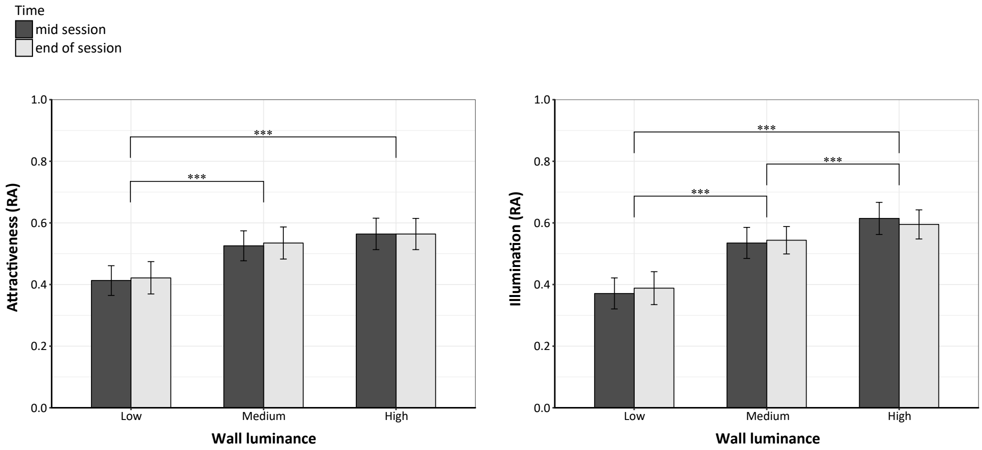

Figure 2.3: Room appraisal dimensions mean scores - whiskers represent the 95 % confidence interval of the mean, *** $p < 0.001$

Table 2.3: Self report measures **-** Mean and SD per level of Wall luminance & internal consistency (Cronbach's Alpha)

		Low		Medium		High		Cronbach's
		Mean	SD	Mean	SD	Mean	SD	Alpha
Room Appraisal (Attractiveness, illumination) Scale: 0-1	RA Attr1	0.41	0.14	0.53	0.15	0.56	0.15	0.91
	RA Attr2	0.42	0.16	0.53	0.16	0.56	0.15	0.92
	RA Illum1	0.37	0.15	0.53	0.15	0.61	0.16	0.77
	RA Illum2	0.39	0.16	0.54	0.13	0.60	0.14	0.77
Emotional State (Pleasure, Arousal, Dominance) Scale: 1-7	PAD P1	5.32	0.74	5.36	0.77	5.29	0.79	0.79
	PAD A1	3.86	0.68	3.95	0.67	4.00	0.72	0.58
	PAD D1	4.68	0.68	4.78	0.76	4.59	0.75	0.72
	PAD P2	4.80	0.87	5.10	0.78	4.99	0.95	0.83
	PAD A2	3.94	0.91	4.01	0.95	4.31	0.84	0.77
	PAD D2	4.51	0.82	4.46	0.84	4.46	0.86	0.82
Subjective alertness	KSS1	3.86	1.64	3.24	1.61	3.51	1.76	---
	KSS2	4.59	2.09	4.16	2.23	3.05	1.70	---
Ego depletion	ED	82.59	23.24	76.92	22.23	73.32	22.88	0.95

2.3.3. Emotional state – PAD

For each of the three emotional state dimensions (pleasure, arousal and dominance) an LMM analysis was conducted to investigate the effects of Wall Luminance, Time and their interaction[2] (see Table 2.3 for mean and SD values).

2 This model erroneously omitted the nesting of time per participant in the original paper. The results have been re-analyzed including this nesting, but the overall outcomes did not change – descriptive statistics in the text have been updated.

For the pleasure dimension, no significant effects were found of Wall Luminance or Wall Luminance x Time. However, a significant decrease in pleasure was found for the Time factor ($F(1,108) = 30.0$, $p < 0.001$, $EMM\ \Delta = 0.36$, $SE = 0.07$). This indicates that performing the experiment had a negative effect on the pleasure of the participants, but that the lighting did not have a significant impact on this.

The analysis for the arousal dimension did not reveal any significant effect for Wall Luminance, Time, or their interaction although the effect of Wall Luminance approached significance ($F(2,72) = 2.53$, $p = 0.09$). The correlations between the arousal dimension and subjective alertness will be reported with the results of the KSS (Section 2.3.6).

Results on dominance were similar to those of the pleasure dimension. A significant decrease in dominance was found for Time ($F(1,108) = 8.91$, $p < 0.01$, $EMM\ \Delta = 0.21$, $SE = 0.07$), whereas no significant effect was found for Wall Luminance, or the interaction between Wall Luminance and Time.

2.3.4. Divergent & Convergent task performance – AUT & RAT

Both the Alternate Uses Task (AUT – flexibility score) and the Remote Associates test (RAT) were analyzed using an LMM. One participant misunderstood the AUT assignment (noted down associations instead of actual uses) and was excluded from this part of the analysis. The results (see Table 2.4 for means and SD values) did not reveal any significant effect of Wall Luminance on the flexibility score ($F(2,70) = 0.37$, $p = 0.69$). The Remote Associates Test (see Table 2.4 for mean and SD values) also did not reveal any significant effect of Wall Luminance on convergent task performance ($F(2,72) = 0.04$, $p = 0.96$), implying that the differences in Wall Luminance did not affect the performance on these tasks.

2.3.5. Stroop task

One additional participant was excluded from the Stroop analyses due to inverting the assignment (provided answers for the stimulus text instead of the stimulus color)

On each of the parameters (median inverted RT on congruent trials and non-congruent trials and the difference between inverted median RTs of non-congruent and congruent trials) a LMM analysis was conducted to test the effect of Wall Luminance. None of the parameters indicated a significant difference, though the inverted RT for the non-congruent trials approached significance ($F(2,70) = 2.71$, $p = 0.074$), suggesting a mild increase in response speed (i.e., a faster responses) with increasing Wall Luminance. However, after adjusting the results for multiple comparisons (Holm corrections), this finding no longer held.

Table 2.4: Performance measures - Means and SD per level of Wall luminance

		Low		Medium		High	
		Mean	SD	Mean	SD	Mean	SD
Alternate uses task – flexibility score	AUT	5.29	2.4	5.04	2.03	5.22	2.10
Remote Associate Task	RAT	4.22	1.78	4.11	1.70	4.16	1.77
Stroop Reaction Time	RT congruent	0.80	0.15	0.82	0.21	0.79	0.14
	RT non-congruent	0.89	0.16	0.90	0.20	0.85	0.15
	RT delta	0.09	0.12	0.08	0.11	0.06	0.11
Stroop Error	Errors congruent	0.25	0.65	0.31	0.58	0.25	0.44
	Errors non-congruent	1.56	1.61	1.42	1.25	1.83	1.54

2

2.3.6. Karolinska Sleepiness Scale (KSS)

Figure 4 shows the effects of Wall Luminance on KSS. The results of the LMM analysis[3] (Wall Luminance, Time and Wall Luminance x Time) on KSS data showed a significant effect of Wall Luminance ($F(2,72) = 5.25$, $p < 0.01$), a significant effect of Time ($F(1,108) = 4.16$, $p = 0.04$), and a significant interaction of Wall Luminance x Time ($F(2,108) = 4.92$, $p = 0.01$). Because of the interaction effect, the simple main effects were analyzed with an LMM for the KSS1 and KSS2 parameters, and with paired t-tests for the effect of time per wall luminance level. The results showed that there was no significant effect of Wall Luminance on the KSS1 parameter ($F(2,72) = 1.95$, $p = 0.15$). As the KSS1 was measured at the start of each session, this implies that the participants entered the room in more or less the same state of sleepiness. However, a significant effect was found for KSS2 ($F(2,72) = 7.99$, $p < 0.001$). Here, the post hoc analyses showed incrementally better alertness (less sleepiness) from low to high and medium to high wall luminance: the difference between low and high Wall Luminance condition was significant (from $M_{low} = 4.59$ to $M_{high} = 3.05$, $p < 0.001$, *EMM* $\Delta = -1.54$, $SE = 0.40$), as was the decrease from the medium to the high Wall Luminance condition (from $M_{medium} = 4.16$ to $M_{high} = 3.05$, $p = 0.02$, *EMM* $\Delta = -1.11$, $SE = 0.40$). The post-hoc tests for the effect of Time within each Wall Luminance condition indicated a significant increase of the sleepiness score over time in the low Wall Luminance condition ($p = 0.03$, *EMM* $\Delta = 0.73$, $SE = 0.34$) and the medium Wall Luminance condition ($p < 0.01$, *EMM* $\Delta = 0.92$, $SE = 0.34$), but not in the high Wall Luminance condition. As such, it appears that participants' alertness was less affected by performing the experiment in the high wall luminance condition than in the other two conditions.

3 This model erroneously omitted the nesting of time per participant in the original paper. The results have been re-analyzed including this nesting. The overall conclusions remain the same, however, time was found to be significant (p = 0.04) in this new model in contrast to 'near significant' (p = 0.07) in the original paper. Descriptive statistics in the text have been updated

However, as the correlation analyses showed a significant correlation (in all conditions) between the second time point of the PAD-arousal dimension and the second time point of KSS, an LMM analysis was performed on the second time point of the KSS data with Wall Luminance as a categorical independent variable and PAD-arousal as continuous covariate. The results showed significant effects of both Wall Luminance ($F(2, 72) = 5.60$, $p < 0.01$) and PAD-arousal ($F(1,106) = 94.65$, $p < 0.001$). The fact that the effect of Wall luminance remained strong suggests that even though PAD arousal and KSS were correlated, emotional state did not mediate the effect of luminance on subjective alertness.

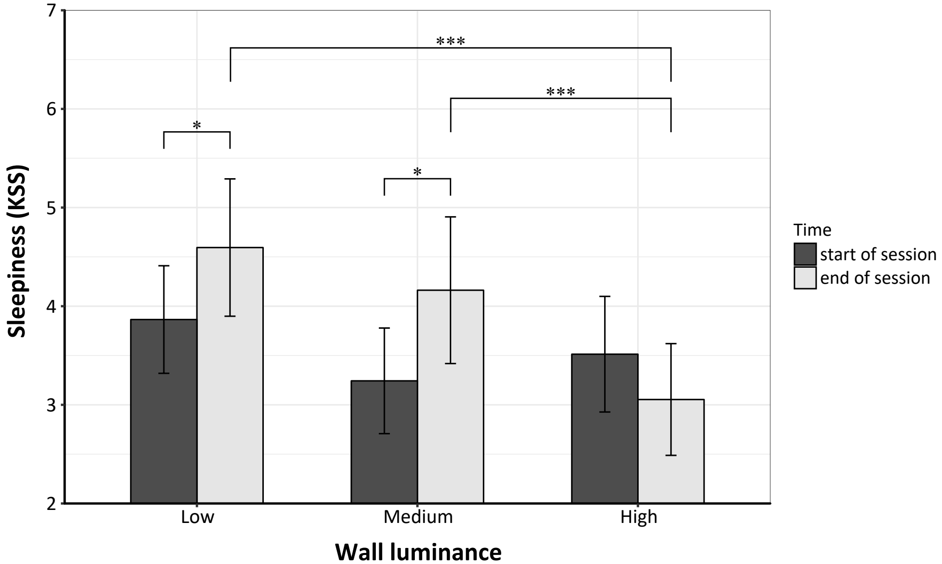

Figure 2.4: Mean KSS scores - whiskers represent the 95 % confidence interval of the mean, * $p < 0.05$, *** $p < 0.001$.

Last, considering the fact that the KSS scale steps do not necessarily correspond to equidistant states of sleepiness, a McNemar test was used to analyze the results. This was done on the basis of state (e.g. sleepy, score 6-9, or alert, score 1-4) using the values at the end of the session. The results indicate that there was a significant difference ($p = 0.02$) between the number of participants who transitioned from alert in the low wall luminance condition, to sleepy in the high wall luminance condition (1 participant) compared to the number of participants who were sleepy in the low wall luminance condition but alert in the high wall luminance condition (10 participants). This further strengthens the finding that the wall luminance condition did in fact influence the subjective alertness in a positive manner.

2.3.7. Ego depletion (ED)

As ego depletion showed a significant correlation with the second time point of the subjective alertness (KSS2), an LMM analysis was performed (Wall Luminance, KSS2). The results showed no effect of Wall Luminance, but did show a significant effect of subjective alertness ($F(2, 104) = 75.00$, $p < 0.001$) on ego depletion.

2.4. Discussion

Although testing the effects of a single independent variable (wall luminance) on the cognitive performance of office workers may sound straightforward in theory, careful manipulation of the actual lighting conditions was necessary to achieve the desired decoupling of horizontal and vertical illumination at the observer position and wall luminance. As this requires a specific lighting installation not common in the field, not many studies have attempted this. As such, our results could be seen as one of the first of its kind and explorative in nature, which is also represented in the multitude of dependent variables taken into account in the test setup.

Using this setup led to some expected, but interestingly, also to several unexpected outcomes. As stated in our hypotheses, we expected the room appraisal to increase significantly with an increase in wall luminance which is clearly supported by our results. However, it was also expected that this increase in room appraisal would be combined with an improved affective state, which we could not confirm from our results. We did not find significant effects on the cognitive performance tasks, yet did find a significant increase in subjective alertness providing a first indication that an increase in wall luminance could have a positive impact on the occupant.

Although interesting in itself, these results lead to a number of questions. First and foremost, what are the possible mechanisms that influenced the subjective alertness of the participants? In numerous studies, effects on alertness have been associated with an increase of illuminance on the eye, in particular in the short wavelength part of the spectrum, linking it to the increased response of the ipRGC's and implicitly linking it to the suppression of melatonin [94–96]. These experiments, however, were often performed during nighttime when melatonin levels are sufficiently high to allow for suppressive effects of light to occur. As melatonin levels are low during daytime, melatonin suppression is a less likely candidate to have caused a change in subjective alertness in our experiment. However, studies such as the one by Smolders et al. [61], have shown that lighting can have alerting effects also during daytime. They suggested two possible mechanisms through which lighting could have induced the alerting effects: first, acute modulation of alertness and mood-related neural pathways through increased light levels on the eye [97,98]; second, beliefs and expectations regarding the effects of bright light. Though every effort was made in our study to keep the illuminance on the eye as constant as possible, small increases in light levels at the eye occurred with higher wall luminance (the difference between the low and high wall luminance conditions was 48 lx at the eye, or 29 lx expressed in melanopic weighted illuminance [99]). Consequently, effects caused by higher illuminance at the eye cannot be completely ruled out. However, a recent analysis of the relationship between changes in subjective alertness as measured with the KSS and (melanopic weighted) illuminance suggests that a much larger change in illuminance is necessary to achieve a similar change in KSS as found in our study (an approximately tenfold increase in melanopic weighted illuminance for ΔKSS = 1.5) [100], making it unlikely that the differences in subjective alertness found in our study were primarily caused by this small change in illuminance at the eye.

An alternative explanation might be that the driving mechanisms are of a more psychological nature, for instance via the hypothesized effect of wall luminance on the emotional state of the participants. The lighting manipulation had a large effect on perceived brightness and attractiveness of the room and as such should have been sufficient to induce a more positive affective state (as also found in Boyce et al. [101]). This, however, was not confirmed by our data as room appraisal increased significantly with wall luminance, but no simultaneous improvement was found on the pleasure or dominance dimensions of the emotional state questionnaire. The arousal dimension suggested a modest yet non-significant increase with wall luminance, which is in line with findings of for instance Smolders et al. (2012) [61]. However, additional analyses indicated that wall luminance had a significant effect on subjective alertness that was independent of arousal, implying that arousal alone cannot fully explain the effects of wall luminance on subjective alertness. As such, it appears there is still a missing ‘link’ in the mechanism chain.

Additional potential psychological mechanisms to explain the effects found on subjective alertness may pertain to associative or motivational mechanisms influenced by the luminous environment. Although no known references between association and subjective alertness were found in literature, brightness has been shown to have cognitive associations with activity, potency and valence [102–104], with detailed cognitive processing (concrete construal) and with self-awareness [105]. Brightness has also been shown to predict room atmosphere, particularly contributing to the liveliness component [106,107]. As such, wall luminance may have affected alertness through associative (meaning-based) or motivation-driven mechanisms. Additional research would be needed to test such mediating processes.

Gaining more insights in the actual mechanism behind the subjective alertness increase might also shed more light on the lack of effects on the cognitive performance tasks. On the one hand, one might expect improvements in cognitive performance with an increase in subjective alertness. On the other hand, as a recent literature review [47] indicates, several studies have found acute effects of light intensity at the eye on subjective alertness, without accompanying improvements on reaction time performance. Our test setup included several cognitive performance tasks, with the Stroop task being the only one which can be classified as an RT-based performance task. It has been established, however, that performance on the Stroop task is not necessarily affected by sleep loss or alertness [108,109]. For the divergent and convergent thinking tasks, a substantial amount of literature is available on the link between affective state and convergent and divergent performance (using the same or similar tests), but little research is available on the link between (subjective) alertness and performance on those tasks, making it difficult to put our findings into context.

Based on our hypothesis, we expected that divergent and convergent thinking would be influenced by changes in affective state. As no effects were found on the affective state, the current results do not invalidate that particular element of the hypothesis, nor do they confirm it. Several factors may have played a role here. First, we drew our sample from a student population, which may not be representative for the knowledge worker population. Second, although the increase in attractiveness was significant, the actual effect was within boundaries of luminance values one can expect in the built environment (especially when considering daylit scenes). As such, our lighting conditions did not represent severe extremes and may not have been strong enough to elicit changes in affective state. The fact that positive lighting appraisals did not translate into affective responses as those reported by Boyce et al. [101] may also partly be explained by differences in test duration. Our time frame was relatively short (1.5 hours) whereas their studies typically lasted for a full day. Considering that associative and motivational effects might play a role, affective responses resulting from a more attractive workspace may only emerge after several hours – or even days, after the novelty and initial rush of being in a new environment subsides.

2.5. Conclusion

The findings of our experiment suggest that an increased wall luminance may have a positive effect on maintaining the level of subjective alertness of office workers. However, uncertainty remains with regard to the underlying mechanism. The results strongly suggest a psychological rather than a biological mechanism, for instance linked to motivational or associative effects. An affective path seems less relevant as no effects of wall luminance on emotional state were found. Additionally, because the differences between the vertical illuminance on the eye in the different lighting conditions were kept relatively small, non-visual effects appear unlikely, although they cannot fully be excluded.

As our findings represent a break from the ‘neuroscientific’ school of thought that effects on subjective alertness are mainly determined by illuminance on the eye, a replication of our findings is essential to exclude a chance, one-off effect (including type 1 errors due to multiple dependent measures). However, if found to be valid, our findings could have a major impact on today’s lighting design requirements and could result in a need for a different way of designing as for example represented in Cuttle (2013) [110], who proposes lighting design criteria related to visual experience of the lit surrounding instead of visibility.

Also, the lack of differences in cognitive performance warrants further investigation. Even though our findings on subjective alertness are highly relevant in today’s practices to enhance the wellbeing of knowledge workers, more insights are needed to understand the impact as they might not result in acute effects, but manifest over time in the form of (reduced) stress or (reduced) sick leave.

To conclude, our study has shown that wall luminance by itself (keeping other lighting design parameters constant) can be a strong influencer of room appraisal. In addition, this appears to affect subjective alertness although the exact mechanism underlying this result is still unclear. Further studies are needed to identify the mechanism and to study potential long-term effects of this finding.

CHAPTER 3

3

Teasing apart office illumination: isolating the effects of task illuminance on office workers.

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Abstract

Task illuminance is one of the most used parameters in office lighting design and is often used as a 'single number criterion' to verify that a lighting design meets the requirements. Although other parameters, such as wall luminance, are often highly correlated with task illuminance, not taking these explicitly into account means critical user criteria such as comfort and satisfaction are left to chance. In this study, we investigated the effect of varying desk illuminance (150 lx to 1500 lx) while keeping wall luminance constant, isolating the effects of illuminance on the desk and eye on office users' overall perception of the space, their mental state and their performance (visual and cognitive). While both visual acuity (paper-based) and perceived brightness increased significantly with higher desk illuminance, the room's attractiveness did not. Even though illuminance at the eye increased considerably with desk illuminance (from 118 lx to 796 lx), only minor effects were found on subjective alertness and cognitive performance. This suggests that focusing on horizontal task illuminance as a design parameter is appropriate in view of visual acuity but has little to no effect on the space's attractiveness, nor on cognitive performance or mental state of the office worker.

3.1. Introduction

While lighting design ideally should focus on creating an environment that satisfies relevant user needs, in practice, lighting installations are quite often specified to simply meet a given set of (numerical) requirements without assessing the impact on the actual user. This practice, sometimes referred to as 'compliance chasing', is characterized by a pass-or-fail approach where the absolute value that results from the calculations is leading (e.g., if the requirement states an average horizontal illuminance of 500 lx is needed, an average of 499 lx would fail the requirement, whereas an average of exactly 500 lx would result in a 'pass'). With this focus on single numeric values, and the traditional focus on the illuminance at the horizontal task surface, many offices today are designed to meet only the required average horizontal illuminance assigned to the space based on the primary task.

These lighting requirements usually do originate from standards or norms that have the user in mind. However, the nuances and additional requirements that these standards also provide (e.g., uniformities, ratios between the different surfaces, wall, ceiling or cylindrical illuminance requirements) are often ignored, despite the fact that several studies have shown that these other parameters too have a clear impact on the appraisal of spaces and the user satisfaction in office environments [54,111,112]. The luminous environment, which is an often recurring topic in literature, has been shown to affect user satisfaction via, for example, wall luminance and room brightness [70,72,113,114]. Although these parameters are part of the latest versions of leading workplace lighting standards such as the EN12464-1:2011 [48] and the IES RP1-12 [115], adoption has been slow [116] and they often are not listed in the design requirements in, for instance, tender documents, which tend to focus on horizontal (task) illuminance requirements only.

The result of a single-requirement design approach is that the overall resulting luminous environment is merely the by-product of the luminaire choice, which is selected mainly to reach the required horizontal illuminance. For example, a more narrow beam tends to result in a higher horizontal illuminance and as such would be perceived as a more economical and sustainable solution (i.e., lower cost and lower energy consumption to reach the same horizontal illuminance). However, the beam shape and width of a luminaire also have a large impact on the illuminance on vertical surfaces such as walls. Choosing a more narrow luminaire often results in lower vertical illuminance which, in turn, is a key component in perceived room brightness [70]. This is further amplified by the introduction of LED light sources, which allow for much more tailored beams. In principle, this opens up many opportunities to improve luminaires for optimal satisfaction of user needs, but also allows luminaires to be optimized for compliance chasing, which can easily result in dark spaces as most of the luminaires' output is utilized to comply with the horizontal illuminance requirements, not to optimize the luminous environment as a whole.

One of the consequences of the impact of the luminaire beam shape on the luminous environment is that causal relationships in studies in which only the horizontal illuminance as the independent variable is reported are quite difficult to interpret, particularly considering the different mechanisms via which lighting can affect the user's performance and well-being. For example, increased user satisfaction with higher horizontal illuminance can be the result of an increased visual performance, as a higher illuminance on the task results in a higher visual acuity through improved contrast [33–35]. In addition, an increased horizontal illuminance quite often goes hand in hand with an increased illuminance on vertical surfaces and/or ceiling (depending on beam shape), potentially resulting in an increase in spatial brightness, which may lead to heightened room appraisal [69,70,113,114]. Moreover, with the increase in horizontal illuminance, illuminance on the eyes tends to increase as well, resulting in a stronger stimulus for the ipRGC's in the eyes [28,29,56]. This in turn has potential effects on (subjective) alertness, mood or task performance and may thereby lead to a higher user satisfaction [47,61].

Given the complexity of the relationship between the luminous environment and the user response, a set of explorative experiments was designed to gain more insight in how different aspects of the luminous environment influence the office worker. The studies focused on separating the effects of illuminance of the walls and that of the task surface, as they are often confounded in office lighting studies [61,111,117]. In the first experiment, reported elsewhere [118], wall illuminance was varied, while keeping illuminance at the desk and the eye constant. It demonstrated a sustaining effect on subjective alertness when using a higher wall luminance.

The experiment described here investigated the effect of different levels of desk illuminance -- and, with it, vertical illuminance at eye position -- while keeping wall luminance constant. A key aspect of both experiments was to employ a broad set of dependent variables, covering room appraisal, well-being and performance on a range of visual and cognitive tasks, to be able to identify possible effects covering both visual and non-visual effects.
Based on the aforementioned literature, our hypotheses were that an

increase in horizontal desk illuminance would lead to improved visual acuity, as illumination of the visual task improved, and to increased alertness due to an increased illuminance on the eye inducing non-visual effects. In contrast, no effect on room appraisal was expected due to the constant wall luminance.

3.2. Method

3.2.1. Participants

Forty-eight individuals were recruited to take part in this experiment. Recruitment took place via an external agency who compensated the participants for their time, effort and travel cost in the form of a modest monetary reward. The study was conducted in accordance with the Helsinki declaration and approved by the internal ethics board. Participants were selected based on the following inclusion criteria: normal or corrected to normal vision, native Dutch speaking, experience with office work, normal color vision (which was tested during the experiment using the Ishihara color vision test, concise edition).

The data from twelve participants were excluded from the analysis because they missed one or more of the scheduled sessions. The remaining 36 participants consisted of 19 female and 17 male participants between 18 and 36 years of age (mean age: 25.3, SD: 4.9) of which 10 evening types, 25 intermediate types and 1 morning type (see 3.2.4)

3.2.2. Settings

A space of 7.2 x 7.2 x 3.0 m (length x width x height) was furnished to resemble an open plan office setting using standard desks, chairs, dividers and storage cabinets in a symmetrical setup (see Figure 2.1). Daylight contribution was excluded using opaque screens. The walls were painted in a neutral white color (reflection coefficient 90 %). Four workstations were grouped in the center of the space with the participants facing the opposing walls. A 40 cm high divider separated the participants sitting opposite each other. Each workstation was outfitted with a 22 in. display, keyboard and mouse to facilitate the questionnaires and cognitive tasks.

Whereas the space and interior were similar to the one as used in de Vries et al. 2018, the lighting installation consisting of six standard 600 x 600 mm, low glare LED-based luminaires (type A in Figure 2.1; Philips PowerBalance, 3400 lm, 4000K, R_a > 80, R_{UG} < 16) was complemented by another 6 identical luminaires (marked with a '+' in Figure 2.1) to increase the upper limit of possible task illuminance levels to > 1500 lx on the desks. Uniformity on the desk with this new installation was estimated using Dialux simulation to be over 0.80 (requirement for uniformity according to EN12464-1:2011 is $U_o \geq 0.60$). The 2 x 5 spots as used on either wall were left unchanged compared to the first experiment [118] (type B in Figure 2.1, Philips StyliD, 2700 lm, 4000K, $R_a > 80$).

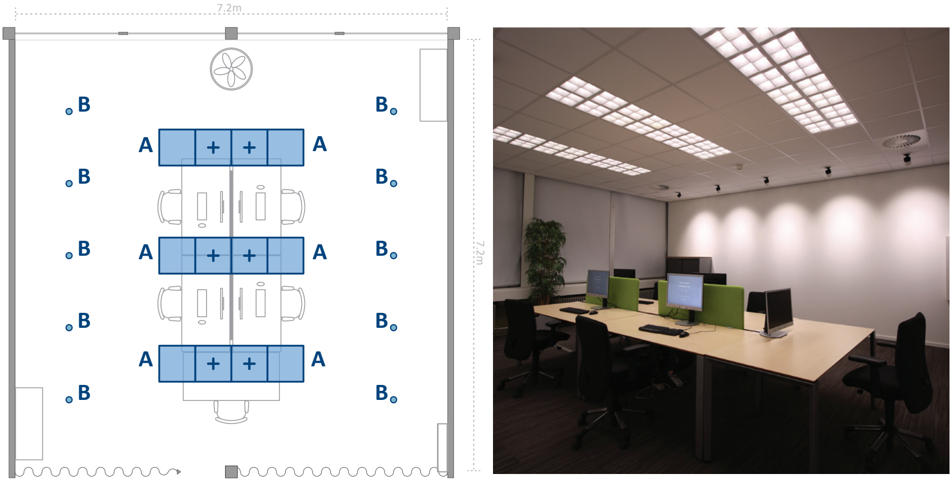

Figure 3.1: Layout and impression of experimental setup - Luminaire type A: General lighting luminaires, '+' indicates the added luminaires of the same type compared to de Vries et al. 2018. Luminaire type B: Spots.

Using this lighting installation, three levels of desk illuminance were set using a calibrated illuminance meter (Konica Minolta CL200) while keeping the wall luminance the same by correcting the output of the spots (measured using a calibrated LMK Color 5 luminance camera).

An overview of the room's lighting characteristics can be found in Table 3.1. Desk illuminance was manipulated at three levels: 150, 500 and 1500 lx. The 500 lx setting was identical to that in our first experiment [118] to allow for comparison of the results. With these settings, the vertical illuminance on the eyes increased from an average of 118 lx in the low desk illuminance condition to 292 lx in the medium desk illuminance condition and 795 lx in the high desk illuminance condition. This translates in a Melanopic Equivalent Daylight Illuminance (Melanopic EDI) of respectively 66, 163 and 442 lx according to CIE S026 [27] (see appendix 2-Table A2-1 for a full overview of the alpha-opic EDI's and figure A2-1 for the SPDs).

Table 3.1: Lighting conditions for each level of Desk Illuminance, mean (and SD) of 4 desks (one measurement per desk) or over the defined surface (e.g. the wall).

Desk illuminance level		Low		Medium		High		Ref [5]
		Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean
L_{desk}	cd/m²	29,9	(0,7)	101,2	(2,8)	308,7	(9,0)	98,0
E_{desk}	lx	158	(0,8)	527	(8,2)	1596	(22,4)	538
$E_{v,eye}$	lx	118,0	(1,6)	291,8	(4,1)	796,3	(13,1)	254
$E_{landoltC}$	lx	156,3	(1,9)	413,3	(4,6)	1160,5	(11,8)	
$L_{wall,ref}$ [1]	cd/m²	76,1	(1,6)	76,9	(1,5)	82,2	(1,3)	72,0
L_{wall} [2]	cd/m²	95,3	(1,2)	94,7	(0,9)	96,8	(0,6)	
$L_{ceiling}$ [3]	cd/m²	21,9	(0,1)	35,9	(0,6)	77,0	(1,7)	36,0
$L_{divider}$	cd/m²	10,7	(0,4)	21,2	(1,3)	52,2	(4,2)	26,0
$L_{display}$ [4]	cd/m²	78,2	(3,2)	78,2	(2,9)	80,7	(3,0)	72,0
$L_{40° band}$	cd/m²	38,7	(0,5)	46,8	(0,8)	71,7	(2,4)	50,0
$LogMM_{wall}$	--	2,61	(0,07)	2,23	(0,08)	1,95	(0,06)	1,83

[1] Wall definition as used in de Vries et al. 2018 – area includes section of side walls

[2] Only backwall

[3] Visible part of the ceiling, excluding luminaires

[4] display set to a representative setting in the experiment (see 3.2.4)

[5] reference values from the '500 lx, high wall luminance' condition from de Vries et al. 2018

Abbreviations: Desk luminance (L_{desk}), Desk illuminance (E_{desk}), Vertical illuminance on the eye in viewing direction ($E_{v,eye}$), Landolt C card illuminance ($E_{landoltC}$), Wall luminance as defined in de Vries et al. 2018 ($L_{wall,ref}$), Wall luminance of visible wall section (L_{wall}), Ceiling luminance ($L_{ceiling}$), Divider luminance ($L_{divider}$), Display luminance($L_{display}$), Luminance of the 40° band ($L_{40° band}$), Logarithm of ratio maximum to minimum luminance ($LogMM_{wall}$)

The fixed wall luminance was selected based on limiting the ratios between desk and wall luminance to prevent extreme contrasts influencing the overall room appraisal. Based on this, the high wall luminance setting (72 cd/m²) of the previous experiment was chosen as this resulted in the least extreme contrast differences between desk and walls in the three desk illuminance levels. The resulting luminance ratios using a wall luminance of 72 cd/m² ranged from 0.4 for the low desk illuminance to 3.8 for the high desk luminance.

3.2.3. Experimental design

This study employed a within-subjects design using three levels of desk illuminance (approximately 150, 500 and 1500 lx – see Table 3.1 for more details). Per session one Desk Illuminance level was presented, every session taking place on a separate day with one week between sessions. Sessions always took place at the same time of day (15:00 – 16:30). Participants were invited in groups; Each group had a fixed composition and was assigned to a specific day of the week. The total test period was divided in three blocks of three weeks (5 groups in the first block, 5 groups in the second block and -- due to several absent participants in the first two blocks -- another 2 groups in a third block). The order of the conditions was randomized over the groups for the original 10 groups. For the additional 2 groups, condition orders were selected to ensure a completely balanced design. As several dependent variables where measured at two time points per session, time of measurement was nested in each session as a second within-subject factor.

3.2.4. Measures

A combination of self-report scales, objective performance measures and appraisal questionnaires was used to analyze the impact of desk illuminance. All questionnaires were administered using the workstations (display, keyboard, mouse) whereas the performance tasks were either fully on paper (Visual acuity), a combination of paper and screen (Alternate uses task, Remote Associates task) or fully on screen (Stroop task, Navon task, on-screen visual performance task). All screen-based elements were presented as white text (Arial font) on a light grey background to prevent high exposure by the screen (see Table 3.1; display luminance, $L_{display}$, was measured using this background with a single, representative question presented in white text).

Self-report scales

The following self-report scales were administered:

- *Chronotype* was evaluated using the Morningness-Eveningness Questionnaire (MEQ [78], modified to fit modern day language [79]). Note that this variable was tested each session for protocol consistency. No significant differences emerged between Desk Illuminance levels.
- *Emotional state* was assessed using the pleasure-arousal-dominance emotional state model (PAD [80]), which was administered using 6 semantic differentials per dimension measured on 7-point scales (1 indicating low pleasure/arousal/dominance, 7 indicating high pleasure/arousal/dominance
- *Subjective alertness* was measured using the Karolinska Sleepiness Scale (KSS [81]) with scores ranging from "1: extremely alert' to "9: extremely sleepy – fighting sleep"
- *Room appraisal* was assessed using a modified version of the room appearance scale developed by Veitch and Newsham [82] using a set of 8 semantic differentials (measured on a visual analog scale of 0 - 1). The semantic differentials are Unattractive – Attractive, Ugly – Beautiful, Unpleasant – Pleasant, Dislike – Like, Sombre – Cheerful, Vague – Distinct, Gloomy – Radiant and Dim – Bright. The original questionnaire used only two dimensions: Attractiveness (based on the first five pairs) and Illumination (based on the last three). However, upon analysis of the consistency of the items within

these two dimensions, we found that the Dim – Bright scale showed a different behavior compared to the other two items in the Illumination dimension and as such this item was analyzed separately (improving Cronbach's alpha for the remaining two items from 0.5 to 0.77). We refer to the scale with the latter two pairs as Distinctiveness/Radiance. This change will be further discussed in the discussion section.

- *Ego depletion* was measured using the State Self-control Capacity Scale (ED [84,119]), which was added as a control variable to monitor possible exhaustive effects of the performance tasks. Possible total score ranged from 25 (low ego depletion) to 175 (high ego depletion)

Objective task performance

The following performance measures were employed:

- *Visual acuity on paper* was measured using a modified Landolt-C test consisting of a single A4 paper panel with rows of optotypes, decreasing in size per row (gap size ranging from 1.73 to 0.42 arc minutes). Visual acuity was estimated based on the last line of optotype sizes for which the orientation could still be accurately identified for all 8 optotypes. No chin rest was used, the panel was roughly 70 cm from the eyes of the participant. Participants were instructed to sit still and not to lean towards the panel. Participants used glasses for the visual acuity task if they habitually wore those during everyday life.
- *Visual acuity on screen* was measured using a tumbling-E test adapted for screen use (at approximately 60 cm distance from the participant). The optotype sizes were defined in number of screen pixels (to accurately display the optotype) in 5, 10, and 15 pixels height and width resulting in gap sizes (i.e., distances between lines) from 1.62 to 6.48 arc minutes. Additionally, the optotypes where shown in several different opacity values (5, 10, 25, 50, 100 %), to increase the difficulty of the task (Michelson contrast ranging from 0.10 for the 5 % opacity to 0.89 for the 100 % opacity setting). Reaction time and error rate were recorded.
- *Divergent thinking performance* was measured using the Alternate uses task (AUT [85,86]) which asks participants to write down as many (realistic) uses of two provided household items as possible in a time span of 5 minutes. Scoring is based on the 'flexibility' of the participant which is represented by the number of different classes of answers the participant comes up with. Scoring was performed by the author and an independent rater who was blind to the experimental condition. Inter-rater reliability was tested using the intra-class correlation coefficient (ICC). Based on a two-way model testing for consistency an ICC of 0.75 was found which, according to the guidelines by Cicchetti, on the border between 'good' and 'excellent' [89]

- *Convergent thinking performance* was measured using the Dutch version of the Remote Associates Task (RAT [90,91]) which presents participants with 10 word-problems where each problem consists of a set of 3 words to which a fourth word, associated with the first three needs to be found. Total number of correct answers in a time span of 5 minutes is recorded.
- *Digital Stroop task* was employed as one of the more classical cognitive performance tasks. The Stroop tasks consists of congruent (25 %) and non-congruent (75 %) stimuli where participants are asked to indicate the presented font color of color names as quickly as possible (no time limit). Response times (RT) are reported. Response times below 200 ms or above 2500 ms were considered as artefacts and excluded from the analysis. Median RTs were calculated and then transformed using a reciprocal transformation to improve normality.
- *Global Local task* was used to determine whether the participants were in a more global or local processing mode. This was measured using a nested letter identification task (Navon task [120]). In this task, a large character (either S or H) is displayed consisting of small characters (either S or H). The participants are asked to identify the small characters by pressing the corresponding key. Response times (RT) are reported. Response times below 200 ms or above 2500 ms were considered as artefacts and excluded from the analysis. Median RTs were calculated and then transformed using a reciprocal transformation to improve normality.

3.2.5. Procedure

Within each group, each participant was assigned to a specific desk to ensure consistency between conditions. Upon entry, the participants were given brief instructions (both in written and verbal form) followed by the color blindness test and a paper-based visual acuity task before starting the session procedure as depicted in Figure 3.2. With exception of the visual acuity task (for which participants were instructed to keep a static position/posture), participants were given no further instructions concerning their posture. The procedure was programmed to run automatically using the Psychopy software package developed at the University of Nottingham [93].

Participants started with a set of questionnaires to determine chronotype (MEQ) and to establish a baseline for emotional state (PAD1) and subjective alertness (KSS1). This was followed by the three cognitive tasks (alternate uses task, remote associates task, Stroop task), each repeated twice (two blocks). The first block of trials was intended to mitigate learning effects, the second one intended for data analysis. The alternate uses task (AUT) and remote associates task (RAT) each consisted of 2 blocks of 5 minutes, whereas the Stroop task (ST) consisted of 1 block of 80 trials, followed by a second block of 112 trials. The three tasks were separated by the room appraisal questionnaire (RA1) between the AUT and RAT and the ego depletion questionnaire (ED) between the RAT and Stroop task. After the third cognitive task, the questionnaires administered at the start of the session were administered again to determine the effects of Desk Illuminance on emotional state (PAD2), subjective alertness (KSS2) and room appraisal (RA2). Last, the global local task (GL) and on-screen visual acuity tasks (VA-Sc) were performed. The total procedure took about 90 min.

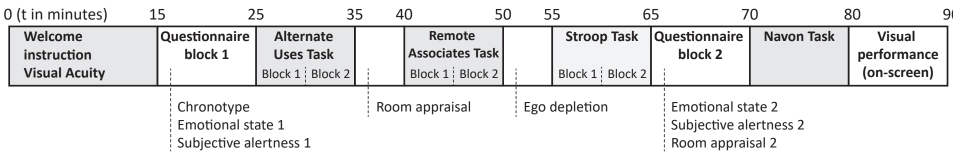

Figure 3.2: Session procedure overview

3.2.6. Statistical analysis

Statistical analyses were performed using the software package R (version 3.5.3 [121]). Due to the presence of the nested factor (time) regular repeated-measures ANOVA analyses were not feasible. As such, Linear mixed models (LMMs) were employed to analyze the main effects using the *lme4* package [122]. All p-values derived from the LMMs were based on Satterthwaite approximation for degrees of freedom using the *lmerTest* package [123] (significance level set at $p < 0.05$). For the parameters which were measured multiple times per session, time was nested in the model under Desk Illuminance. In all cases, the repeated measures aspect was taken into account by including participant ID as a random variable. Post hoc analysis was performed on the LMM models using the *emmeans* package [124] employing Tukey corrections for multiple comparisons and Satterthwaite approximation for degrees of freedom. Finally, the *irr* package [125] was used to determine the intraclass correlation coefficient (ICC). Full results of the LMM models can be found in Appendix 2 – Table A2-2.

3.3. Results

3.3.1. Room appraisal – attractiveness, distinctiveness/radiance, brightness

As mentioned in 3.2.4, we analyzed the room appraisal ratings in three dimensions: attractiveness, distinctiveness/radiance and brightness. Figure 3.3 shows the participants' ratings in the three Desk Illuminance conditions (see Table 3.2 for details). LMM analyses were performed for all three dimensions separately, with Desk Illuminance, Time and their interaction as factors. The results showed a significant effect of Desk illuminance on brightness ($F(1,70) = 30.07$, $p < 0.001$), but not on the attractiveness or the distinctiveness/radiance dimensions (respectively $p = 0.54$ and $p = 0.09$). Post hoc analyses showed that both the medium and high Desk Illuminance conditions were considered significantly brighter compared to the low Desk Illuminance condition (respectively EMM $\Delta = 0.19$, $SE = 0.04$, $p < 0.001$ and $EMM\ \Delta = 0.28$, $SE = 0.04$, $p < 0.001$). The increase in brightness between medium and high Desk Illuminance conditions was near significant ($EMM\ \Delta = 0.09$, $SE = 0.04$, $p = 0.06$).

The effect of Time was significant for both attractiveness (F (1,105) = 9.19, $p < 0.01$) and brightness (F (1,105) = 7.73, $p < 0.01$) – both showed a slight decline over time – but not for the distinctiveness/radiance dimension ($p = 0.11$). There were no interactions between Desk Illuminance and Time on attractiveness, distinctiveness/radiance or brightness (respectively $p = 0.51$, $p = 0.77$, $p = 0.42$).

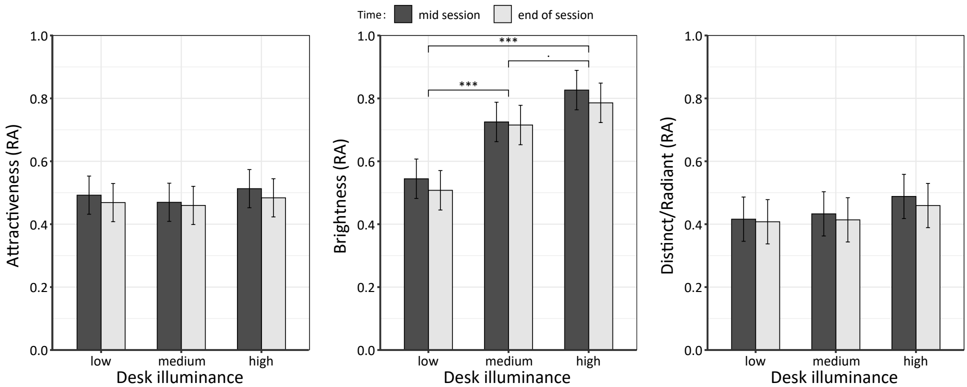

Figure 3.3: Effects of Desk Illuminance and Time of measurement on three dimensions of Room appraisal (EMM), $p < 0.1$, *** $p < 0.001$, significant effects of time not displayed in plot due to absence of interactions with light conditions (see 3.3.1), whiskers represent the 95 % confidence interval of the mean.

Table 3.2: Room Appraisal data overview & Cronbach's alpha

	Desk Illuminance	Low			Medium			High			Cronbach's alpha
Dimension	Time	EMM	SE*	95 % CI	EMM	SE*	95 % CI	EMM	SE*	95 % CI	
Attractiveness	Start	0.49	0.031	[0.43, 0.55]	0.47	0.031	[0.41, 0.53]	0.51	0,031	[0.45, 0.57]	0.90
	End	0.47	0.031	[0.41, 0.53]	0.46	0.031	[0.40, 0.52]	0.48	0,031	[0.42, 0.55]	0.92
Distinctiveness/ Radiance	Start	0.42	0.035	[0.35, 0.49]	0.43	0.035	[0.36, 0.50]	0.49	0,035	[0.42, 0.56]	0.77
	End	0.41	0.035	[0.34, 0.48]	0.41	0.035	[0.34, 0.48]	0.46	0,035	[0.39, 0.53]	0.82
Brightness	Start	0.54	0.032	[0.48, 0.61]	0.73	0.032	[0.66, 0.79]	0.83	0,032	[0.76, 0.89]	--
	End	0.51	0.032	[0.45, 0.57]	0.72	0.032	[0.65, 0.78]	0.79	0,032	[0.72, 0.85]	--

*SE of full model

3.3.2. Emotional state – PAD

LMM analyses were performed for each of the three dimensions of the emotional state questionnaire (pleasure, arousal, dominance, see Table 3.3 for details). For all three dimensions, Desk Illuminance, Time and their interaction were used as predictors. Desk Illuminance did not have a significant effect for any of the dimensions. However, a significant effect of Time was found was for pleasure ($F(1, 105) = 44.13$, $p < 0.001$) and dominance ($F(1, 105) = 20.80$, $p < 0.001$), in both cases reflecting lower ratings at the second measurement.

3.3.3. Subjective alertness – KSS

For subjective alertness, an LMM was set up using Desk Illuminance, Time and their interaction (see Figure 3.4 and Table 3.4 for details). This model revealed that there was a significant effect of Time ($F(1, 105) = 7.35$, $p < 0.01$), but not of Desk Illuminance or their interaction. To further investigate how subjective sleepiness changed over time, the effect of time was analyzed per Desk Illuminance condition using post-hoc testing. The analysis showed that a significant decrease in subjective alertness (increase in sleepiness) during the session only occurred in the low Desk Illuminance condition (*EMM* $\Delta = 0.50$, *SE* = 0.24, $p = 0.042$) but not in the medium and high conditions (medium: *EMM* $\Delta = 0.39$, *SE* = 0.24, $p = 0.11$; high: *EMM* $\Delta = 0.25$, *SE* = 0.24, $p = 0.31$).

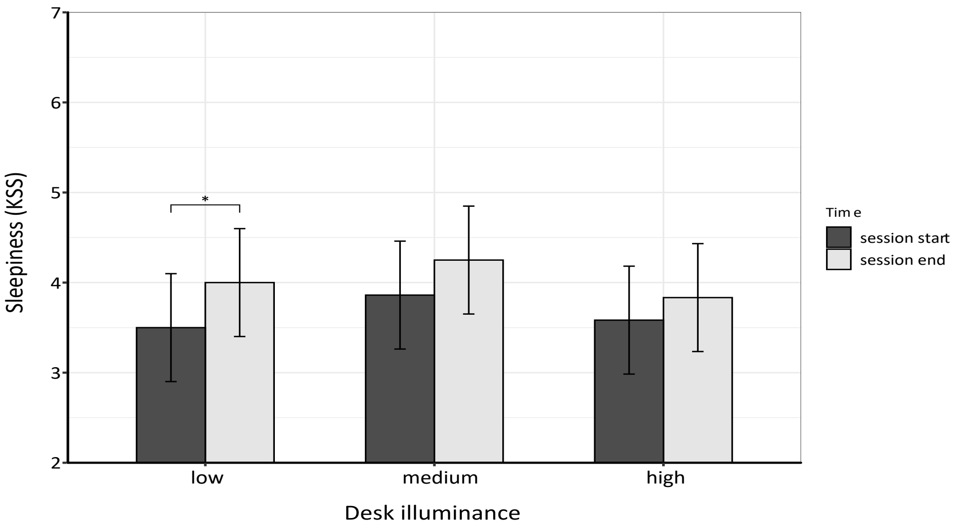

Figure 3.4: Effects of Desk Illuminance and Time of measurement on KSS (EMM). * $p < 0.05$, whiskers represent the 95 % confidence interval of the mean.

Table 3.3: Emotional state data overview & Cronbach's alpha

Desk Illuminance		Low			Medium			High			Cronbach's alpha
Dimension	Time	EMM	SE*	95 % CI	EMM	SE*	95 % CI	EMM	SE*	95 % CI	
Pleasure	Start	5.51	0.135	[5.25, 5.78]	5.45	0.135	[5.19, 5.72]	5.31	0.135	[5.04, 5.58]	0.8
	End	5.04	0.135	[4.77, 5.31]	4.97	0.135	[4.70, 5.24]	4.91	0.135	[4.64, 5.18]	0.88
Arousal	Start	3.92	0.114	[3.69, 4.14]	3.84	0.114	[3.61, 4.06]	3.95	0.114	[3.73, 4.18]	0.47
	End	3.76	0.114	[3.54, 3.99]	3.96	0.114	[3.74, 4.19]	4.04	0.114	[3.81, 4.26]	0.58
Dominance	Start	4.81	0.128	[4.55, 5.06]	4.7	0.128	[4.45, 4.96]	4.81	0.128	[4.56, 5.06]	0.74
	End	4.59	0.128	[4.34, 4.85]	4.47	0.128	[4.22, 4.73]	4.44	0.128	[4.18, 4.69]	0.77

*SE of full model

Table 3.4: Subjective alertness & Ego depletion data overview & Cronbach's alpha

Desk Illuminance		Low			Medium			High			Cronbach's alpha
Parameter	Time	EMM	SE*	95 % CI	EMM	SE*	95 % CI	EMM	SE*	95 % CI	
Subjective alertness	Start	3.50	0.303	[2.90, 4.10]	3.86	0.303	[3.26, 4.46]	3.58	0.303	[2.98, 4.18]	--
	End	4.00	0.303	[3.40, 4.60]	4.25	0.303	[3.65, 4.85]	3.83	0.303	[3.23, 4.43]	--
Ego depletion	--	75.3	3.75	[67.8, 82.8]	70	3.75	[62.5, 77.5]	70.4	3.75	[62.9, 77.8]	0.94

*SE of full model

3.3.4. Ego depletion – ED

Ego depletion was investigated as a function of Desk Illuminance using an LMM, (see Table 3.4 for details). The results showed no significant effects of Desk Illuminance ($F(2, 70) = 1.11$, $p = 0.33$).

3.3.5. Cognitive performance tasks – AUT, RAT, Stroop, Navon

For the alternate uses task (AUT), flexibility was analyzed as a function of Desk Illuminance. However, no significant effects were found (see Table 3.5 for means and SD values). Also, for the remote associates task (RAT) the same model was employed with the same result: no significant effects of the Desk Illuminance. For the Stroop and Navon task, the outcome was analyzed based on the congruent and non-congruent inverted response times, the difference between these two parameters and the total number of errors. However, in none of the cases did Desk Illuminance have a significant effect.

3.3.6. Visual acuity tasks

Visual acuity was tested both on paper (landolt C) and on the computer display (tumbling E). For the paper-based task an LMM analysis was conducted to analyze the effects of Desk Illuminance. This showed a significant effect on visual acuity ($F(2,70) = 13.18$, $p < 0.001$). Post-hoc analyses indicated that visual acuity significantly improved between the low and medium Desk Illuminance conditions ($EMM\ \Delta = -0.10$, $SE = 0.038$, $p = 0.023$), medium and high conditions ($EMM\ \Delta = -0.09$, $SE = 0.038$, $p < 0.046$) and low and high conditions ($EMM\ \Delta = -0.19$, $SE = 0.038$, $p < 0.001$). The LMM analysis on response speed (inverted response time) for screen-based visual acuity with Desk Illuminance, Size (of the optotype), and Opacity (of the optotype) as fixed factors indicated no effect of Desk Illuminance condition ($F(2,385) = 0.04$, $p = 0.96$. The test characteristics (Size and Opacity of the optotypes and their interaction) did impact the response speed, but the statistical results for these factors are not reported in detail as they are not relevant for the study goal.

Table 3.5: Cognitive performance tasks data overview (RT = response time, in seconds)

Desk Illuminance		Low			Medium			High		
Task	**Parameter**	**EMM**	**SE***	**95 % CI**	**EMM**	**SE***	**95 % CI**	**EMM**	**SE***	**95 % CI**
Alternate Uses Task	Flexibility	5.94	0.551	[4.84, 7.05]	6.08	0.551	[4.98, 7.19]	6.21	0.551	[5.10, 7.32]
Remote Associates Task	RAT	4.08	0.343	[4.40, 4.76]	4.03	0.343	[3.35, 4.71]	4.56	0.343	[3.88, 5.24]
Stroop task	Congruent RT	0.79	0.025	[0.75, 0.84]	0.81	0.025	[0.76, 0.86]	0.82	0.025	[0.77, 0.87]
(RT's in seconds)	Non-congruent RT	0.90	0.025	[0.85, 0.95]	0.91	0.025	[0.86, 0.95]	0.91	0.025	[0.86, 0.96]
	RT Delta	0.11	0.013	[0.08, 0.13]	0.1	0.013	[0.07, 0.12]	0.8	0.013	[0.06, 0.11]
	Total errors	2.19	0.351	[1.50, 2.89]	1.86	0.351	[1.16, 2.56]	2.56	0.351	[1.86, 3.25]
Navon task	Congruent RT	0.58	0.013	[0.56, 0.61]	0.59	0.013	[0.57, 0.62]	0.59	0.013	[0.57, 0.62]
(RT's in seconds)	Non-congruent RT	0.66	0.017	[0.63, 0.70]	0.66	0.017	[0.62, 0.69]	0.67	0.017	[0.63, 0.70]
	RT Delta	0.08	0.009	[0.06, 0.10]	0.06	0.009	[0.05, 0.08]	0.07	0.009	[0.06, 0.09]
	Total errors	4.19	0.68	[0.285, 5.54]	3.44	0.68	[2.10, 4.79]	3.97	0.68	[2.63, 5.32]

*SE of full model

3.4. Discussion

We tested the impact of increased desk illuminance in a simulated office setting on visual performance, room appraisal, subjective ratings of alertness, ego depletion, emotional state, and on cognitive performance. Along with desk illuminance, illuminance at the eye also increased substantially, as it would normally, due to the use of luminaires for general illumination and reflectance of the task area. Wall luminance, however, was kept constant in order to prevent the effects of higher illuminance on the desk and on the eye from being confounded with the effects of room appearance and/or brightness. As expected, increased desk illuminance resulted in improved visual acuity on the paper-based task. However, the remaining objective performance measures, and the subjective scales related to performance (i.e., subjective alertness and ego depletion) showed only minimal, if any, effects of the lighting condition. Additionally, while the overall brightness perception of the space did increase with desk illuminance, neither the attractiveness and distinctiveness/radiance dimensions of room appraisal, nor the emotional state did show any effects of the lighting condition.

Our starting hypothesis was that, given the almost seven-fold increase of vertical illumination on the eye, the KSS scores would significantly decrease from the low to the high desk illuminance condition. Although such an effect has been reported in several studies, there is also a large body of research which failed to find alerting effects of higher illumination levels (see Lok et al., 2018 [32]; Souman et al., 2018 [47] for overviews of both positive and negative findings). In the current study, no significant differences in subjective alertness could be established across the employed range of desk illuminance. This was the case despite the fact that our sample was considerably larger than that of most of the studies described in the reviews by Lok et al. and Souman et al., and despite the tenfold increase in desk illuminance (two methodological issues that were noted in these reviews to explain the inconsistent findings in the literature).

In our first study [118], which focused on the effects of wall luminance on the appearance of the space, we found that increasing the wall luminance (with only minimal changes in the illuminance on desk and eyes) resulted in a sustaining effect on subjective alertness. In contrast, subjective alertness was not maintained when wall luminance was too low, with a desk illuminance of 500 lx. This prompted us to investigate, in the current study, the effect of changing desk and eye illuminance on these time dependent effects, with a constant wall luminance. No significant difference in subjective alertness was observed for the medium and high desk illuminances, whereas the low desk illuminance condition resulted in a minor decrease in subjective alertness over time. In other words, subjective alertness was not maintained when desk illuminance was too low, but wall luminance was still high. We should note, however, that this effect was very subtle and not reflected in a significant interaction effect.

It should be noted that in our setup the luminaires that illuminated the desks – and that also were the main contributors to the vertical illuminance measured at eye height - were placed directly over the participants. As such, it is possible that vertical illuminance (measured using standard methods, as an unobstructed measurement of a hemisphere) does not accurately portray the actual illuminance on the eye. Moreover, the spatial distribution of the ipRGC's in the retina is still under discussion (see CIE S 026 for a summary [27]), where current thinking is that some areas in the retina may be more relevant than others. Hence, the vertical illuminance measurement as reported in this study may not be a fully accurate quantification of the stimulus to the non-visual pathway.

As reported above, we found that our desk illuminance manipulation only affected one item on the original brightness dimension of the room appraisal questionnaire. Scores on the brightness item did not correlate highly with the other two items, distinctiveness and radiance. These items did not show significant effects of desk illuminance, nor did the other items, which probed attractiveness of the room. In our previous study we found that wall luminance did affect both brightness (including distinctiveness and radiance) and attractiveness. This latter result matches the results of van Ooyen et al. [70] and Loe et al. [69], who found that vertical surfaces and/or surfaces which are more dominant in the field of view (as in our first study [118]) have a higher effect on preference and appraisal than the horizontal task surface.

We did not find effects of desk illuminance on any of the cognitive performance tasks. This matches our results in the first experiment, which investigated wall luminance [118], but also numerous studies on effects of increased retinal illuminance (see Lok et al., 2018 [32]; Souman et al., 2018 [47]), and corroborates our suspicion that, in the current experiment, increased task illuminance and illuminance at the eye did not enhance cognitive functioning. We should note that, in our study, participants were only exposed to the lighting conditions for 1.5 hours. Hence, we cannot exclude the possibility that (stronger) effects on subjective alertness and cognitive performance may still emerge after longer exposure durations.

In conclusion, the results of our current study demonstrate very few, if any, additional beneficial effects of raising illuminance at the desk. Although this metric may accurately represent needs from a visual acuity perspective, it appears to be unsuitable as a predictor for room appraisal, as we failed to find effects on attractiveness. Moreover, despite a substantial increase in illuminance on the eye, we did not find effects on cognitive performance. These results indicate that focusing only on horizontal task illuminance as the single design parameter could lead to unattractive spaces due to low luminance on walls, which in turn may result in lower attractiveness as shown in de Vries et al. 2018 [118], with little to no benefits for alertness, cognitive performance or well-being of the office worker. A more comprehensive approach of office lighting design, taking all different aspects of the luminous environment into account, is needed. Or, as Peter Boyce recently put it in an editorial, “This approach requires a complete redrafting of lighting recommendations involving new metrics and the abolition of the horizontal working plane.” [126]

CHAPTER 4

Putting the ceiling center stage –
The impact of direct/indirect lighting on room appraisal

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Abstract

Luminaires that employ both a direct and indirect lighting component have the potential to optimally benefit both the visual and non-visual aspects in lighting designs. This type of luminaire, however, still spans a huge range of possible implementations with variations in the ratio of direct/indirect light and in the distribution of the light across the ceiling, all with their respective benefits and downsides. However, the effects of all these variations on for example preference and general appreciation are not well known. In the current study, we investigated the ratio of direct/indirect light and of lighting distribution on the ceiling in an open-plan office setting while keeping work-plane illuminance constant, and measured their impact on room appraisal, atmosphere, and visual comfort. In general, more indirect light and a more uniform ceiling distribution were appreciated, but not for all participants to the same extent. Participants could be classified into two main groups, where in the first group higher perceived brightness corresponded with more positive appraisals and comfort – this group responded well to more indirect light and more uniform distribution – whereas the second group appeared to dislike a bright environment and was less sensitive to ratio and virtually insensitive to uniformity manipulations.

4.1. Introduction

With employee workplace experience and satisfaction being important metrics in the quest for 'a great place to work' [26,127,128], the way the interior design (including its lighting) influences the appearance of a space becomes more and more important. Although often a given (when renting an existing building) or an afterthought at the end of the interior design phase, general lighting plays an important role in how spaces look, how well they are appreciated, and in users' overall workplace satisfaction [112,129,130], including their health and well-being. There are several ways in which lighting can influence occupants, and they can roughly be divided into two categories: visual effects, dealing with what we see and want to see, and non-visual effects (also referred to as non-image forming effects), dealing with how light affects our physiology. The non-visual effects have received increasing attention over the past years as the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) [28,29] (re)opened a research field looking into the exact mechanisms of how light affects our body's physiology both short term (i.e., acute alertness effects – see [32,47] for full overviews), but also more long term (i.e., circadian effects) [55–58]. Lighting optimization for visual and non-visual effects may sometimes be at odds, as one of the key recommendations today is an increased 'melanopic dose' at the eye during daytime [131,132]. The melanopic dose can be raised by increasing light intensity, optimizing the spectrum, or through longer exposure time [27]. However, if not managed carefully, this may lead to negative effects on the visual experience. For example, higher intensities from recessed luminaires increase the risk of discomfort glare from the luminaire or can lead to high contrast, and therefore low comfort vision. Alternately, optimizing the spectrum by using higher color temperatures may lead to a different atmosphere than intended or appreciated in a given culture or for a given task [71,111].

Importantly though, visual and non-visual effects do not have to be in conflict. For example, using the ceiling as a secondary reflector for a luminaire (e.g., by using indirect lighting) can benefit both the visual and non-visual effects. By limiting the luminous flux from the direct light, discomfort glare from the luminaire is reduced, while the total flux (and subsequent human eye exposure) can be increased by adding a large indirect light component that does not add to the glare from the luminaire. An additional benefit is that using the ceiling as a reflector also increases the room brightness and appraisal [70,114] and using combinations of indirect light and direct light have been shown to be preferred over a 'direct light only' solution in several earlier studies [114,133]. More specifically, a study by Houser and colleagues [114] suggested that solutions where the indirect light component had a horizontal work-plane illuminance contribution of 60 % or more were favored over those with a stronger direct light component.

However, by ‘moving’ the flux from the luminaire to the ceiling, also the potential glare source is moved from the luminaire to the ceiling. In the past, the chance of the ceiling becoming a source of glare was relatively small as the majority of office luminaires contained long, diffuse fluorescent tubes to provide the indirect light, resulting in a soft, large pool of light on the ceiling. However, in the case of LED-based luminaires, the indirect component can be anything from a large pool of light to a small, bright spot, creating the risk of overly bright (glary) ceilings.

Although information on glare caused by indirect lighting on ceilings is scarce, some rules of thumb are presented in CIE 147 [134]. This report distinguishes between the effects of uniformly and non-uniformly lit ceilings and indicates that for uniformly lit ceilings, the illuminance contribution from the indirect light to the horizontal work-plane surface (via the ceiling) cannot be more than 1000 lx to comply with the common office glare limit of UGR ≤ 19. For non-uniformly lit ceilings, the report indicates that the maximum allowed contribution (given a certain glare target) depends on the room dimensions, the reflectance of all surfaces and the average luminance of the bright spots on the ceiling. Taking a typical office case as an example, following the CIE guidelines, an average ceiling bright spot luminance of 1000 cd/m^2 would result in a maximum contribution of the indirect light to the horizontal work-plane illuminance of ~700 lx, whereas for an average spot luminance of 1800 cd/m^2 (which is not uncommon for luminaires with a large indirect light component), the maximum contribution to the horizontal work-plane illuminance can only be a mere 70 lx. Although the report clearly indicates that “this approximation does not claim great accuracy”, it does provide an indication of the impact of the type of ceiling illumination on glare.

Next to glare, the overall perception of the space can also change radically when changing the ratio of direct/indirect light in the space and the distribution of the light over the ceiling. This is mediated by changes in the luminous balance, the brightness, the modeling, the uniformity (on different surfaces in the space), and the overall atmosphere. Stokkermans and colleagues [107], for example, found that the combination of perceived uniformity and brightness was able to accurately predict the atmosphere perception using the dimensions defined by Vogels [38]. In their extensive work, Flynn and colleagues [37] used a large set of semantic differentials and identified three possible dimensions which were tentatively labeled “Bright-Dim”, “Uniform-Non-uniform” and “Overhead-Peripheral”. This suggests that in addition to distribution characteristics, location/directionality of the lighting also plays a key role in subjective impressions of a space. Although some general trends can be seen in these results, it is also known that individual differences in preference and atmosphere perception may be quite significant, as shown in several experiments where participants were offered control over light levels [70,77,135,136]. The study by Flynn and colleagues also highlighted this. They concluded that the tested lighting variables did induce consistent and shared impressions in the users, but they also found that subgroups could be identified with regard to whether they used one, two, or all three of the dimensions in their ratings.

Last, the ratio of direct/indirect light has a substantial effect on modeling. Although using only direct lighting tends to result in very efficiently lit horizontal surfaces, it also reduces the illuminance on vertical surfaces, resulting in poor modeling of faces and objects due to harsh shadows. At the opposite end of the spectrum, using only indirect lighting results in a very diffuse lighting with very few shadows. This latter type of installation is described by Boyce as an “almost infallible way to achieve indifferent lighting” [51, p 266] which, although not harming comfort, will also do little to increase the attractiveness of the space. This insight is supported by findings of Veitch et al. [137], who assessed facial appearance in what the authors called a ‘mini-experiment’. The findings of this experiment show that both 100 % direct light and 100 % indirect light caused facial appearance to be judged less favorably compared to a direct/indirect light combination.

Summarizing, combined direct/indirect lighting may offer more flexibility to improve both the non-visual and visual effects of light. Although several studies have investigated the effects of different direct/indirect ratios, they have not taken into account the light distribution on the ceiling. As there are clear suggestions in the literature that this can impact glare, comfort and atmosphere, an experiment was set up to assess the preference of users with regard to different direct/indirect light ratios, in combination with different distributions of the up-light component over the ceiling. Based on the literature discussed above, a number of hypotheses were formulated. First, we expected that both the perceived brightness and attractiveness of the space would increase with an increasing up-light component, given previous findings on the relation between up-light ratios and the average luminance in the visual field. Also, we expected that an increase in ceiling uniformity would decrease the perceived room brightness due to the absence of high luminance peaks. As perceived brightness is also influenced by the ratio of direct/indirect light, we explored the possibility of an interaction effect between ratio and ceiling distribution. Moreover, we explored the effects of both factors on perceived room atmosphere, given the reported relationship between atmosphere and uniformity/brightness. Last, we expected that visual comfort would be influenced by the addition of an indirect component through contrast and glare reduction. For the lower up-light ratios, this is expected to improve comfort for all ceiling distributions, but higher up-light ratios may reduce comfort for non-uniformly lit ceilings, as they may become too bright.

4.2. Method

4.2.1. Participants

Based on a power analysis (G-power3, based on ANOVA repeated measures test with small to medium effect size of f(U) = 0.25) a sample size of 31 participants was suggested. To account for the groups of 4, 32 participants were initially invited, which was later increased to 36 by the external recruitment agency after 2 participants did not show up. These participants (classified as office workers) were selected based on the following inclusion criteria: work at least 20 hours a week in a modern office environment, not more than 50 % of their time working elsewhere or traveling, normal or corrected to normal vision and no known color blindness or eye deficiencies. As indicated, two participants did not show up and an additional two participants were excluded from the analyses based on incorrect use of the scales, resulting in usable data from a total of 32 participants (14 male, 18 female) ranging from 22 to 39 years old (mean 30.9, SD 4.66). Participants received a modest monetary reward (via the agency). The study was approved by the Signify internal ethics board.

4.2.2. Setup and devices

An open-plan office setup was simulated in a space of roughly 8.9 x 5.7 x 2.9 m (length x width x height; see Figure 4.1). A long space was selected to allow for the ceiling to take up a significant part of the visual field (as common in open plan offices).

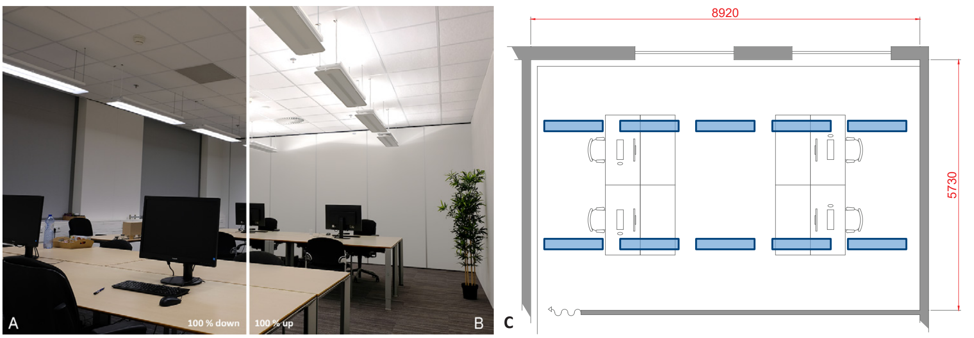

Figure 4.1: Test room shown in a 'split screen' setup and the floorplan. A: 100 % direct lighting; B: 100 % indirect lighting condition. C: floorplan.

Participants were seated at both ‘ends’ of the space, looking in opposite directions into the space. Daylight was excluded using opaque screens. Each participant was seated at a workstation consisting of a regular desk, chair and a PC setup consisting of a 24 in. display, a keyboard and a mouse.

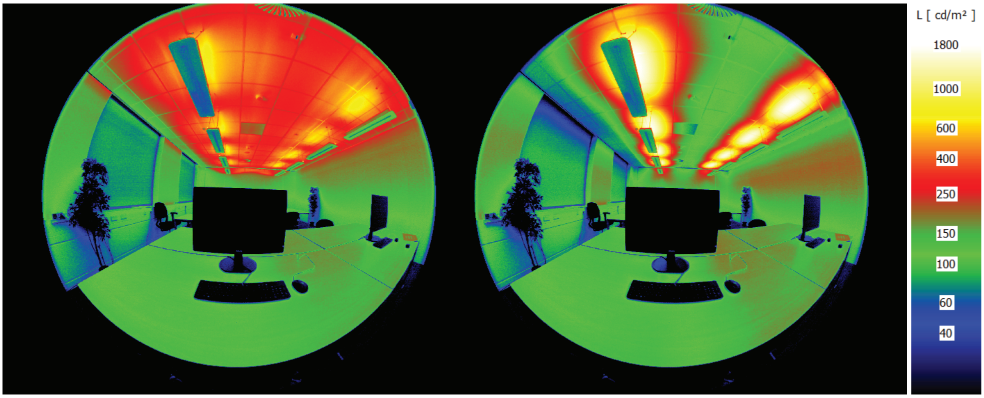

Figure 4.2: Luminance camera images - Left: the image corresponding to the condition of 100 % indirect lighting with a uniform ceiling distribution. Right: the condition of 100 % indirect lighting with a non-uniform ceiling distribution – see Appendix 3, Table A3-3 for a full numerical analysis.

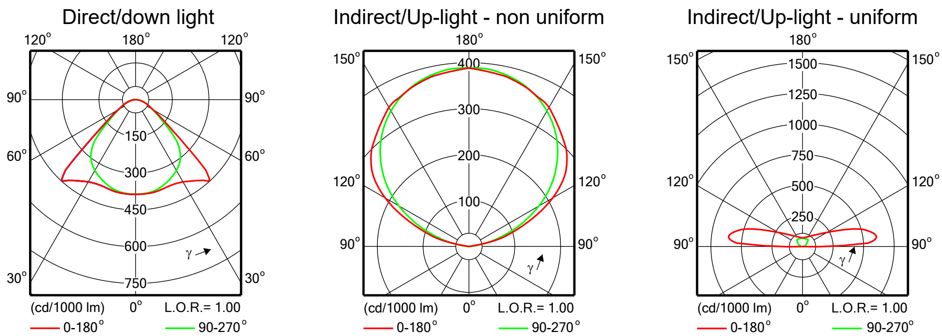

Figure 4.3: Schematic lighting distributions of the direct light and non-uniform and uniform indirect light components

Two rows of five custom-made luminaires were used to light the space with both direct (down) and indirect (up) lighting, suspended 20 cm from the ceiling. The direct light component of the luminaire consisted of a Philips SmartBalance surface mounted LED luminaire, able to provide up to 4000 lm (CCT = 4000 K, R_a ≥ 80). The indirect light component consisted of two custom light engines able to provide up to 8000 lm each (CCT = 4000 K, R_a ≥ 80) of which one was equipped with a wide distribution lens (for a uniform ceiling distribution) and one without any further optics, resulting in a close to Lambertian lighting distribution (for the non-uniform ceiling distribution). See Figure 4.2 for an impression of the resulting luminance distributions on the ceiling and Figure 4.3 for a schematic overview of the lighting distributions. Each component (direct light, indirect light non-uniform and indirect light uniform) could be adjusted individually to create the different settings. All settings were commissioned and characterized using a Technoteam LMK 5 color luminance camera and a Minolta CL-500 illuminance spectrophotometer.

4.2.3. Experimental design

The study followed a within-subject design with 5 levels for lighting distribution Ratio and 3 levels for Ceiling Distribution keeping the horizontal work plane illuminance fixed at approximately 750 lx (averaged across the 4 desks, measured in a single point at the location of the keyboard). Although the task illuminance for offices according to the European standard for indoor workplaces (EN12464-1:2011) is typically set at 500 lx, a target illuminance of 750 lx was selected to stay in line with the overall goal to improve both visual and non-visual effects and to prevent overly high contrasts with the ceiling. The resulting illuminance at eye level (measured in the vertical plane) ranged between 447 – 539 lx (Melanopic-EDI between 266 – 309 lx).

The number of levels for the 2 independent variables were selected to balance the total number of conditions with the required granularity to create visible impact of each variable between the different steps over the full range. As a consequence, the lighting distribution ratios used (expressed as percentages of the total luminous flux) were a set of industry standard ratio's being 100 % direct light (D100-U0), 70 % direct light + 30 % indirect light (D70-U30), 50 % direct light + 50 % indirect light (D50-U50), 30 % direct light + 70 % indirect light (D30-U70) and added to that a setting for 100 % indirect light (D0-U100) to cover the entire range. Note that the total luminaire flux changed for the different settings to keep work-plane illuminance constant.

Ceiling Distribution variations were realized by starting from the wide distribution indirect light component (uniform) and the Lambertian distribution component (non-uniform), to which we added a 50-50 combination of these 2 distributions to provide an indication of the response in between the uniform and non-uniform settings. The full characterization information of all lighting conditions, including luminance and illuminance values, and alpha-opic EDIs is provided in Appendix 3 (Tables A3-1, A3-2, A3-3 and Figure A3-1).

Nine groups of four participants were formed, each group participating in a single session (note that, as described in section 4.2.1, two participants did not show up). Sessions took place on consecutive days (last week of April, first week of May 2019). Each session started at 17.30 h to also enable office workers who worked during the day to join the test. Participants entered and left the test well before sunset (sunset was at ~ 21.00 h). During each session, all 13 conditions were presented (each for 5 minutes) in a randomized order.

4.2.4. Measures

Participants' assessments were collected using a set of 12 semantic differentials, measured on visual analog scales, labeled with a 0 on the left side, and a 1 on the right side with a slider always starting in the mid-point position. Half of the differentials were inverted in the test application, to prevent participants from automatically using the same rating for each setting. For the analysis, the inverted items were restored to their original polarity to get comparable ratings.

The first eight differentials were taken from a modified version of the room appearance rating system by Veitch and Newsham [82] derived from the work by Flynn et al. [37] and Loe et al. [69]. In their modified version, the questionnaire was found to load on two different dimensions: Attractiveness (average of the items Unattractive – Attractive, Ugly – Beautiful, Unpleasant – Pleasant, Dislike – Like, Somber – Cheerful) and Illumination (average of the items Vague – Distinct, Dim – Bright, Gloomy – Radiant). A previous study [138], however, indicated that the brightness semantic differential did not fit in the illumination dimension. To verify if this was also the case in the current study, a test for internal consistency was performed, rendering a satisfactory Cronbach's alpha (i.e., 0.97) for the attractiveness dimension, but not for the illumination dimension (i.e., 0.56). Excluding the brightness semantic differential improved the consistency to an acceptable 0.67. Consequently, the brightness differential was used as a separate dimension, resulting in the following three room appraisals used for the analysis: Attractiveness, Distinct/Radiant and Brightness. As in the original test, for the dimensions with multiple items, the items were averaged to reach a single score per dimension.

Table 4.1: Overview of parameters & semantic differentials employed during the test.

Dependent variables	Semantic differentials
Room appraisal	
Attractiveness	Unattractive – Attractive
	Ugly – Beautiful
	Unpleasant – Pleasant
	Dislike – Like
	Somber – Cheerful
Illumination	Vague – Distinct
	Gloomy – Radiant
Brightness	Dim – Bright
Atmosphere	
Coziness	Cold – Warm
Lively	Monotone – Interesting
Detachment	Homey – Businesslike
Comfort	Uncomfortable – Comfortable

Three additional semantic differential pairs were included to gain a better understanding of how the atmosphere changed. Vogels [38] indicated that atmospheres can be described using four factors: coziness, liveliness, detachment, tenseness. Given that the tenseness differentials were not applicable to office environments (i.e., they described more extreme atmospheres), only coziness, liveliness and detachment were included in the present study, resulting in the following semantic differentials: for coziness: Cold – Warm, for lively: Monotone – Interesting, and for detachment: Homey – Businesslike.

Last, to gain more insight in how comfortable the participants found the different settings, the differential Uncomfortable – Comfortable was added. The final overview of the parameters used in the analysis and the semantic differentials used to measure these parameters is given in Table 4.1.

4.2.5. Procedure

Participants were collected from the entrance of the building and escorted to the test space where they were seated at one of the four positions. The light condition upon entry was the same for all groups (100 % direct light). After reading and signing the informed consent form, they received instructions on the overall test procedure. They then completed a short test run to ensure the procedure was clear.

After this, the test leader switched to the first setting and asked them to start the first sequence on their PC. Each sequence consisted of 2 tasks, of which one used the screen and asked the participants to find the differences between two images shown side-by-side, and one used a combination of screen and paper and asked the participants to write a summary on paper about a short story shown on the screen. The tasks were timed to take respectively 2 and 2.5 minutes and allowed the participants to adapt to the new situation. After this, the 12 semantic differentials were shown on screen (one at a time) in randomized order. Upon completion of the semantic differentials, the participants were prompted to wait until the test leader indicated that they could continue. The test leader was provided with indicator lights (invisible to the participants) to assess if all participants finished the semantic differentials. This sequence was repeated seven times, followed by a short break of 5 minutes (to prevent biasing the results due to potential negative affect caused by fatigue), followed by another 6 sequences to go through all 13 settings (in random order). Participants did not interact with each other during the test, except during the break, and were instructed to not discuss test related aspects.

After all sequences were done, a short informal interview took place to get some first (undocumented) thoughts on the test. Note that the ‘find the differences’ and ‘summary’ tasks were intended to get individuals accustomed to the new settings while working, and not intended to measure performance. As such, performance was not recorded and will not be discussed further.

4.2.6. Statistical analysis

The analyses of the data of the 32 remaining participants were performed in 4 steps. As a first step, to investigate the effect of the factors Ratio (direct/indirect light ratio), Distribution (ceiling luminance distribution) and their interaction on room appraisal, atmosphere and comfort, each dependent variable (DV – see Table 4.1 for an overview of the different DV’s) was analyzed using a linear mixed model (LMM) to test the significance of the individual model elements. To gain a better understanding of the large range of variation in participants’ appraisals that was found in step 1, and the potential correlation between different DVs, we then employed an (unplanned) clustering analysis strategy based on the correlation between DV’s (see Section 4.3.2 for more details) of which the outcome was tested and confirmed by appending the LMM’s from step 1 with the factor Group. In step 3 we performed the initial LMM analyses again, but separately for the two major groups of participants that had emerged in step 2. As a last step, an exploratory analysis investigated if the relationship between attractiveness and brightness could be modeled for our setup. To do this, we performed a linear mixed model analysis using Brightness, Group and their interaction as factors to model Attractiveness (using Participant ID as random factor).

The following software and (sub) packages were used for the above-mentioned steps: The *lme4* package in combination with the *lmerTest* packages was employed to test the linear mixed models (LMM's) using Satterthwaite approximation for degrees of freedom and using an α of 0.05 to test for statistical significance. Post-hoc testing on the models was done using the *emmeans* package employing Tukey corrections for multiple comparisons. Model comparisons were performed using the *performance* package, reporting the R^2-marginal values (fit of only the fixed effects) as an indication of model fit. Last, the hierarchical cluster analysis (employing an agglomerative strategy) was performed using the *amap* package and for step 2 was based on Pearson correlations determined using the *psych* package. Correlations are not tested for significance as they are only intended to describe the relationship of DV's to each other per participant. Where relevant more specific details on the analysis are given when describing the results in Section 4.3.

4.3. Results

The analysis quickly revealed that within the total test population, there were subgroups with markedly distinctive outcomes. The following sections will discuss each step taken to reach the final findings, starting with the overall analysis, followed by identifying/defining the subgroups and a subsequent split analysis taking these subgroups into account. For the sake of brevity and given the impact of the subgroups, the initial overall analysis will only discuss the high-level findings which inspired the exploration of subgroups.

4.3.1. Overall analysis

As a first step, to investigate the effect of the factors Ratio (direct/indirect light ratio), Distribution (ceiling luminance distribution) and their interaction on room appraisal, atmosphere and comfort, each dependent variable (DV) was analyzed using a linear mixed model (LMM). This model included the factors Ratio (4 levels – the D100/U0 level was not included in this factorial model), Distribution (3 levels), their interaction, and participant ID as a random intercept factor. The mean ratings and standard deviations in Table 4.2 highlight that on average, participants rated the space as somewhat bright (with the 100 % direct light scoring lowest) and business like; attractiveness and comfort scored around the middle of the scale; and participants found the space to be somewhat monotone and cold. The results of the LMM analysis are reported in Table 4.3 and showed that Ratio had a significant effect on all DVs (resulting from higher ratings for larger indirect light components), whereas Distribution (and the interaction between Ratio and Distribution) did not show a significant effect on any DV, with the exception of the Distinct-Radiant dimension. This was somewhat unexpected as the mean data (Table 4.2) showed a change in most DVs for the uniform distribution (compared to the other distributions), but only for the higher indirect light ratios.

Furthermore, visual inspection of the data showed a high degree of variability, in particular between different participants for the different DVs. This was confirmed by testing the significance of the random factor in the LMM (see Table 4.3 for an overview and Table A3-4 in Appendix 3 for a full numerical overview of this test). On the other hand, for quite a few of the participants, there appeared to be a correlation between several of the DVs (also see Section 4.3.2). These findings combined could point towards individual differences or potential sub-groups confounding the overall outcome.

4.3.2. Data grouping

To gain a better understanding of the large range of variation and the potential correlation between different DVs, we employed a correlation and clustering analysis strategy. This would allow us to identify potential sub-groups in the population. However, given that the data cannot be considered as independent (because of the within-subject study design) a regular correlation analysis was not appropriate. Instead, we determined the (Pearson) correlation between each of the seven DVs (across all lighting conditions) for each participant to establish a rating pattern for each individual (i.e., which DVs correlated in their data and to what degree). This resulted in a total of 21 DV-pair correlations (i.e., the correlation between brightness & attractiveness, brightness & comfort, brightness & coziness etc.) per participant. Next, a clustering analysis was executed to group participants based on their rating patterns. This was done using hierarchical clustering, where 'distance' was based on correlation between each participant's DV-pair correlations and complete linkage was employed to group participants.

The resulting analysis showed that there were 4 distinct "groups" of participants with similar rating patterns. As Groups 3 and 4 only contained 2 and 3 participants respectively, and Groups 1 and 2 made up 84 % of the total test group (15 and 12 participants, respectively), Groups 3 and 4 were excluded from further analyses to prevent strong bias caused by single participants. To characterize the two remaining groups, Figure 4.4 shows the distribution of the correlations computed per participant per group for each of the DV-pairs highlighting for which correlation pairs the differences were largest.

Table 4.2: Mean and standard deviation (SD) of the total test group of the dependent variables per lighting condition.

Distribution Indirect light	Luminous flux Ratio *	Brightness		Attractiveness		Distinct-Radiant		Comfort		Liveliness		Coziness		Detachment	
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
	D100-U0	0.48	0.25	0.40	0.17	0.43	0.17	0.48	0.18	0.37	0.18	0.38	0.17	0.69	0.19
Non-Uniform	**D70-U30**	0.53	0.19	0.41	0.14	0.39	0.14	0.44	0.16	0.38	0.17	0.42	0.19	0.69	0.17
	D50-U50	0.66	0.21	0.45	0.19	0.47	0.19	0.52	0.20	0.39	0.20	0.44	0.22	0.71	0.22
	D30-U70	0.67	0.20	0.45	0.14	0.44	0.16	0.53	0.18	0.39	0.17	0.39	0.17	0.75	0.13
	D0-U100	0.67	0.16	0.48	0.18	0.48	0.17	0.49	0.19	0.43	0.23	0.44	0.19	0.69	0.20
Mixed	**D70-U30**	0.62	0.20	0.45	0.18	0.46	0.14	0.49	0.18	0.39	0.18	0.44	0.19	0.72	0.16
	D50-U50	0.63	0.17	0.47	0.14	0.46	0.15	0.54	0.14	0.41	0.17	0.43	0.17	0.70	0.15
	D30-U70	0.68	0.17	0.46	0.18	0.51	0.20	0.51	0.21	0.43	0.20	0.40	0.19	0.71	0.18
	D0-U100	0.69	0.16	0.51	0.19	0.53	0.18	0.56	0.20	0.49	0.24	0.48	0.19	0.67	0.22
Uniform	**D70-U30**	0.56	0.19	0.45	0.15	0.46	0.15	0.47	0.18	0.37	0.19	0.41	0.19	0.72	0.17
	D50-U50	0.63	0.18	0.44	0.17	0.45	0.15	0.50	0.19	0.38	0.21	0.39	0.20	0.72	0.19
	D30-U70	0.71	0.17	0.48	0.20	0.53	0.18	0.51	0.24	0.44	0.21	0.45	0.23	0.71	0.19
	D0-U100	0.63	0.17	0.54	0.19	0.55	0.16	0.59	0.18	0.55	0.21	0.50	0.19	0.60	0.23

* Luminous flux ratio is defined as the percentage of luminous flux contained in the downwards (D) and the upwards (U) lighting component

Table 4.3: Overview of results of the Linear Mixed Models per DV as described in 4.3.1; Model fits are provided as an indication of overall model strength.

		Brightness		Attractiveness		Distinct-Radiant		Comfort		Coziness		Liveliness		Detachment	
	df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Ratio	(3,341)	10.60	**<0.001**	5.32	**<0.01**	8.91	**<0.001**	4.92	**<0.01**	2.97	**0.03**	9.18	**<0.001**	3.68	**0.01**
Distribution	(2,341)	0.85	0.43	2.02	0.13	7.39	**<0.001**	1.42	0.24	0.46	0.63	2.16	0.12	0.85	0.43
Ratio * distribution	(6,341)	1.27	0.27	0.79	0.58	1.70	0.12	1.33	0.24	1.20	0.31	1.28	0.27	1.08	0.37
Random effect: participant *			**<0.001**		**<0.001**		**<0.001**		**<0.001**		**<0.001**		**<0.001**		**<0.001**
R^2 conditional / marginal		0.36 / 0.07		0.48 / 0.03		0.50 / 0.07		0.40 / 0.04		0.35 / 0.03		0.41 / 0.06		0.32 / 0.03	

* Full results in Appendix 3, based on likelihood ratio test of model reductions – See table A3-4
Statistical significance ($\alpha < 0.05$) has been highlighted in bold

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Figure 4.4 clearly illustrates that the differences between the two groups are mainly manifest in the scores relating brightness to the remaining DVs (See Appendix 3 Table A3-5 for a numerical overview). With exception of detachment, the participants in group 1 consistently shows a relatively high correlation between brightness and the other DV's, whereas the participants in group two scores substantially lower and with a larger spread. Additionally, DV-pairs not including brightness show much smaller differences between group 1 and 2. This could imply that the grouping is caused by differences in brightness perception, or by differences in the brightness appreciation. To investigate whether brightness perception was indeed a key component in the grouping, we performed a second clustering analysis where distance between participants was based on the pair-wise correlations of their brightness ratings, employing the complete linkage method to group participants.

This analysis showed that roughly 60 % of the participants were in the same group for both analyses. Additionally, we performed a visual assessment of these new groups by replicating the brightness pair plots from Figure 4.4 for these new groups (See Appendix 3 Table A3-6 for a numerical overview). As can be seen by comparing Figure 4.5a (grouping across all DVs) to Figure 4.5b (grouping using only brightness), both groupings result in the same trend with respect to correlations with the brightness DV, but the spread in correlations is considerably larger for the grouping based on brightness only. To test whether this difference was caused by the 5 participants that were not in Group 1 and 2 in the grouping across all DVs (i.e., the aforementioned Groups 3 and 4), we also tested the effect of removing the data of these participants from the visualizations (presented in Figure 4.5c). However, the differences are minor compared to the results of Figure 4.5b (the grouping including these participants).

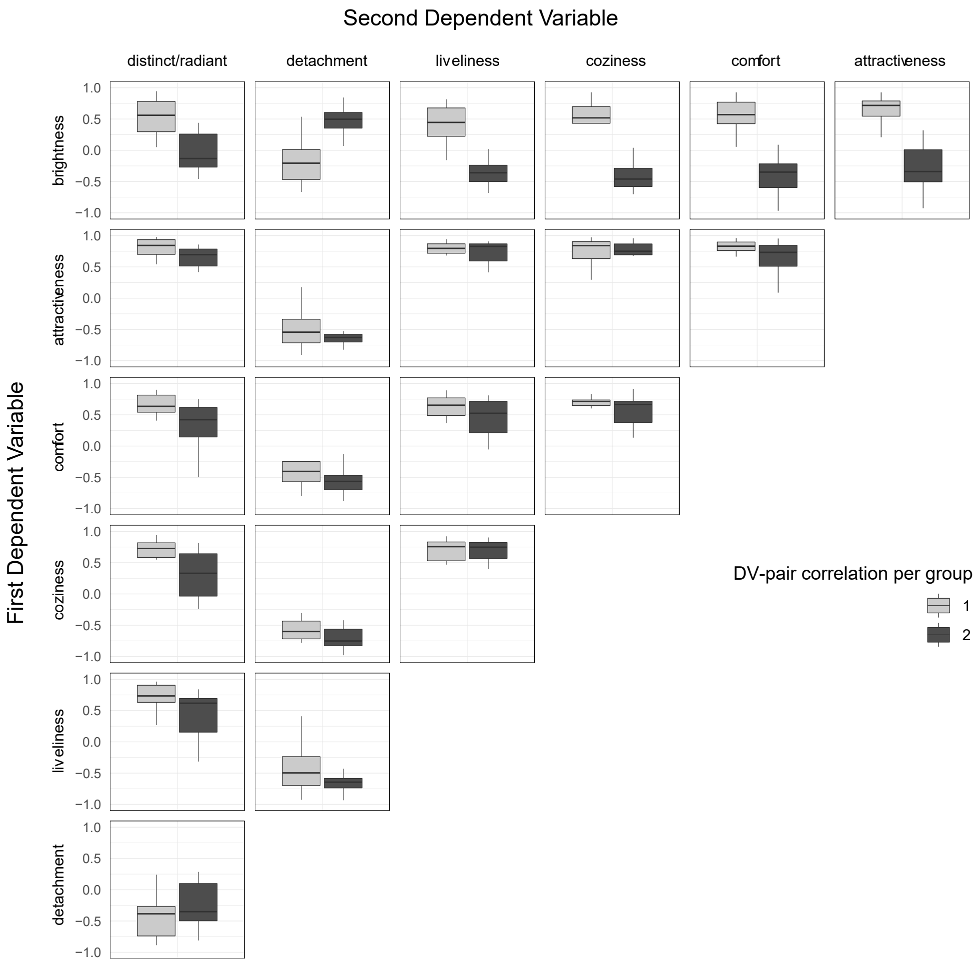

Figure 4.4: Boxplots of the Pearson correlations per DV pair split over group 1 and 2; each boxplot shows the distribution of the Pearson correlations computed per participant in group 1 and 2. Boxplots indicate the median (central line), 25th and 75th percentile (lower and upper hinge) and the smallest and largest value no further than 1.5 * IQR from the hinges (whiskers). See Appendix 3, table A3-5 for a numerical overview.

Concluding, it appears that the distinct groups in the DV-pairs correlation analysis are influenced by the difference in how participants' perceived brightness relates to other assessments, more so than how they rate the brightness perception per se. Considering the large difference in correlations between the two groups for the pairs including brightness, there could be a difference in how they appreciate brightness. Hence, the fact that these two groups are quite distinct warrant a revisit of the analysis of the overall effects.

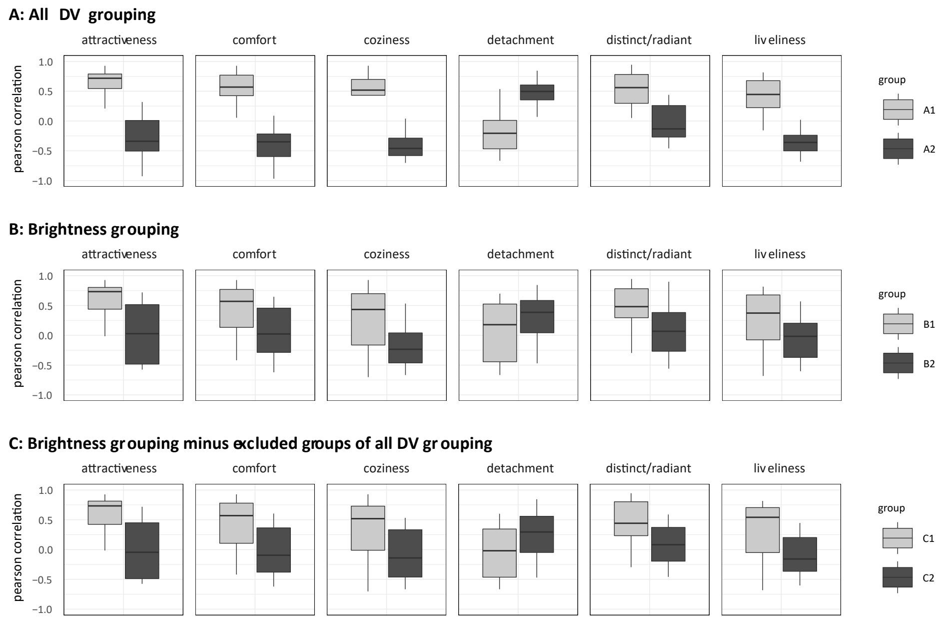

Figure 4.5: Comparison of different grouping methods (A, B, C). Boxplots as in Figure 4.4 but limited to the DV pairs involving brightness. Each boxplot shows the distribution of the Pearson correlations computed per participant in group 1 and 2 for the given DV pairs. See Appendix 3, table A3-6 for a numerical overview.

4.3.3. Overall effects revisited

Based on the findings in Section 4.3.2 we reanalyzed the effects of Ratio and Distribution (and their interaction) on all DVs (see Table 4.4 and Figure 4.6). This was done for Groups 1 and 2 separately as in all DVs (except detachment) interactions occurred between Group and either Ratio or Distribution (see Appendix 3 Table A3-7).

Effect of Ratio

As in the first analysis, the effect of Ratio again emerged in both groups, resulting in a significant effect for the majority of appraisals (see Table 4.4). Especially in Group 1, all DVs, with the exception of Detachment, were significantly affected by the direct/indirect light ratio. For this group, no significant interaction between Ratio and Distribution emerged. Post-hoc analyses on the DVs with a significant main effect of Ratio (averaged over the three Distributions – see Appendix 3, A3-8 for an overview of the full results) consistently showed that the ratios with a dominant indirect light component (i.e., D30-U70 and D0-U100) received higher ratings compared to ratios with a dominant direct light component (i.e., D100-U0 and D70-U30). This implies that for this group, a higher indirect light component is seen as more bright (Estimated marginal mean - *EMM Δ* ranging from 0.15 - 0.28), more attractive (*EMM Δ* ranging from 0.11 - 0.16), more distinct/radiant (*EMM Δ* ranging from 0.10 - 0.14), more comfortable (*EMM Δ* ranging from 0.09 - 0.14), more cozy (*EMM Δ* ranging from 0.13 - 0.15) and more lively (*EMM Δ* ranging from 0.12 - 0.17).

Group 2, however, showed a more varied set of results with respect to Ratio. Also, the analysis showed a significant interaction between Ratio and Distribution for brightness perception. Post-hoc analyses indicated that the effects of Ratio on brightness were only significant in the conditions with a uniform ceiling distribution. Also, in contrast to Group 1, Group 2 rated the setting with 100 % indirect light (i.e., D0-U100) lower on brightness than the D30-U70 condition (*EMM Δ* = 0.19), suggesting that for this group, using only indirect lights leads to a lower rating of brightness. Next to this, although a main effect was found for Ratio on attractiveness in Group 2, no significant effects were found in post-hoc analyses. This is likely to be caused by the correction applied for multiple comparisons. Finally, coziness, liveliness and detachment did all show a single significant effect in the post-hoc analyses . In contrast with brightness, both coziness and detachment showed a significant increase from the D30-U70 to the D0-U100, and liveliness a significant increase from D50-U50 to D0-U100.

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Effect of Distribution

In contrast with the initial analyses, separate analyses per group did reveal effects of Distribution. As already mentioned in section 4.3.3, for Group 2, an interaction occurred between Ratio and Distribution for the brightness dimension. Further post-hoc testing (see Appendix 3, A3-8) showed that the effect of Distribution was limited to the settings with only indirect light (D0-U100). For these, both the non-uniform distribution and the mixed distribution were considered significantly brighter than the uniform distribution. However, as said, this effect was not visible in any of the other DVs for Group 2.

Group 1 did not reveal any interaction between Ratio and Distribution but did show a main effect of Distribution on multiple DVs, being attractiveness, distinct/radiant, comfort, coziness, and liveliness, but interestingly, not on brightness. In Group 1, a uniform ceiling distribution was favored over the non-uniform distribution: it was considered more attractive (*EMM Δ* = 0.07), more distinct/radiant (*EMM Δ* = 0.10), more comfortable (nearly significant with $p = 0.06$ - *EMM Δ* = 0.06), more cozy (*EMM Δ* = 0.07) and more lively (*EMM Δ* = 0.10).

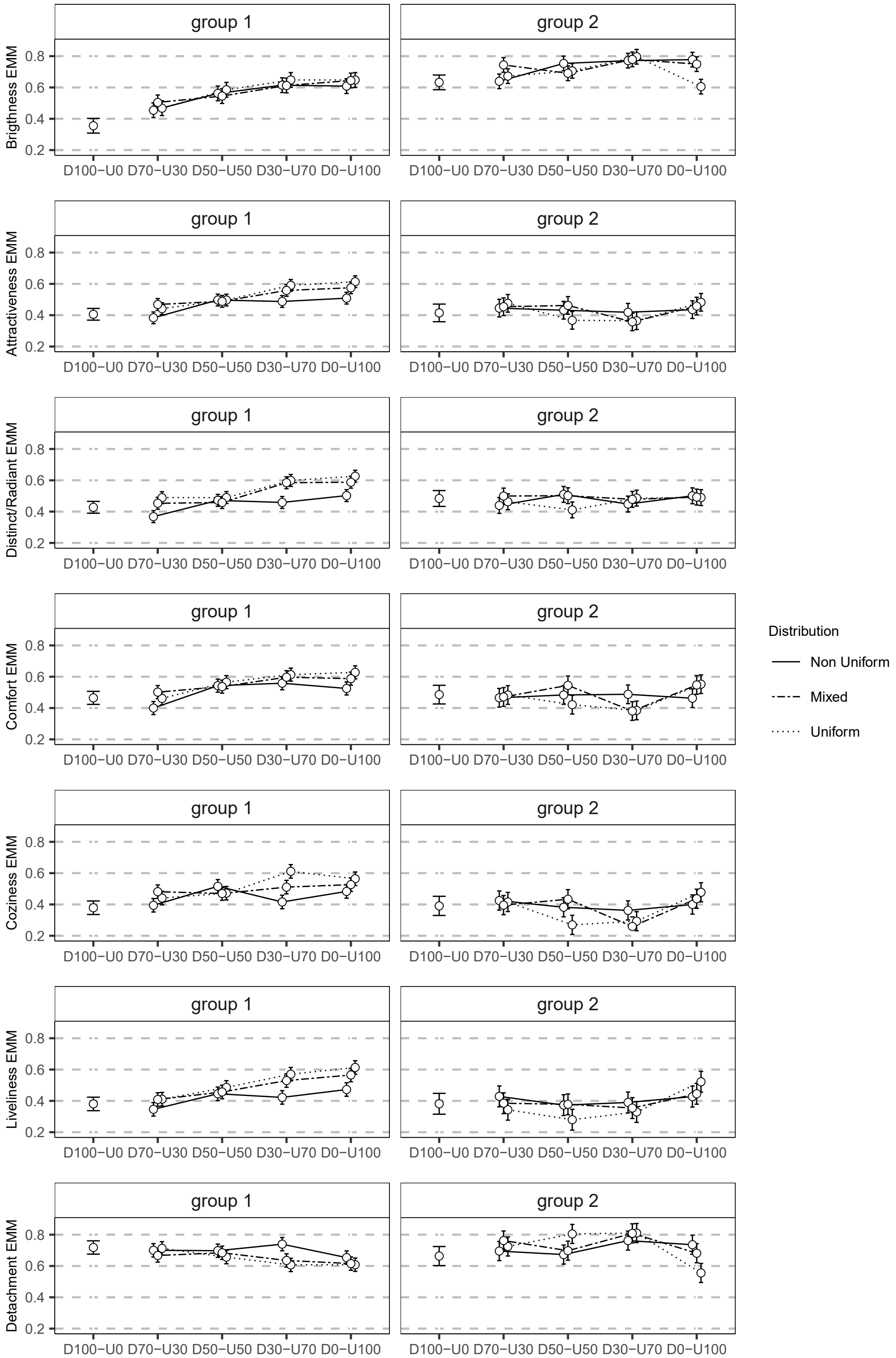

Figure 4.6: Group comparison per DV displaying estimated marginal mean (EMM) – whiskers represent the standard error of the EMM (see Appendix 3, A3-8 for a numerical overview).

Table 4.4: Overview of the test for significance ($p < 0.05$) for the individual factors in the LMM's per DV, split over group 1 and group 2.

		Group 1 (n=15)				Group 2 (n=12)			
		df	*F*	*p*	R^2*	*df*	*F*	*p*	R^2 *
Brightness	Ratio	(3,154)	8.98	**<0.001**	0.27 / 0.12	(3,121)	3.49	**0.02**	0.37 / 0.12
	Distribution	(2,154)	0.42	0.66		(2,121)	1.71	0.18	
	Ratio * Distribution	(6,154)	0.22	0.97		(6,121)	2.30	**0.04**	
Attractiveness	Ratio	(3,154)	10.56	**<0.001**	0.37 / 0.16	(3,121)	2.68	**0.05**	0.53 / 0.04
	Distribution	(2,154)	4.85	**<0.01**		(2,121)	0.09	0.91	
	Ratio * Distribution	(6,154)	0.83	0.55		(6,121)	0.88	0.51	
Distinct-Radiant	Ratio	(3,154)	10.58	**<0.001**	0.37 / 0.20	(3,121)	0.40	0.76	0.57 / 0.03
	Distribution	(2,154)	9.49	**<0.001**		(2,121)	0.86	0.43	
	Ratio * Distribution	(6,154)	1.00	0.43		(6,121)	1.03	0.41	
Comfort	Ratio	(3,154)	9.07	**<0.001**	0.34 / 0.14	(3,121)	2.06	0.11	0.32 / 0.07
	Distribution	(2,154)	3.27	**0.04**		(2,121)	0.25	0.78	
	Ratio * Distribution	(6,154)	0.58	0.74		(6,121)	1.19	0.31	
Coziness	Ratio	(3,154)	2.78	**0.04**	0.26 / 0.11	(3,121)	4.13	**<0.01**	0.39 / 0.09
	Distribution	(2,154)	3.21	**0.04**		(2,121)	0.32	0.73	
	Ratio * Distribution	(6,154)	1.88	0.09		(6,121)	1.42	0.21	
Liveliness	Ratio	(3,154)	9.48	**<0.001**	0.32 / 0.17	(3,121)	3.18	**0.03**	0.42 / 0.06
	Distribution	(2,154)	6.76	**<0.01**		(2,121)	0.48	0.62	
	Ratio * Distribution	(6,154)	0.57	0.76		(6,121)	0.85	0.54	
Detachment	Ratio	(3,154)	1.73	0.16	0.23 / 0.06	(3,121)	3.61	**0.02**	0.37 / 0.10
	Distribution	(2,154)	2.20	0.11		(2,121)	0.18	0.84	
	Ratio * Distribution	(6,154)	0.71	0.64		(6,121)	1.94	0.08	

* R^2 of full model – conditional / marginal

4.3.4. Attractiveness vs Brightness

As an exploratory analysis we investigated if the relationship between attractiveness and brightness could be modeled for our setup, as a higher brightness is often linked to a higher attractiveness in the literature [61,139,140]. Additionally, the brightness item did not appear to be consistent with the remaining two items in the illumination dimension (see Section 4.2.4), and the effect of brightness perception in the grouping appeared sizable. This might hint towards a difference in how brightness (as a perceptual attribute) is rated versus how the more subjectively weighted, psychological attributes such as attractiveness are rated.

To do this, we performed a linear mixed model analysis using Brightness, Group and their interaction as factors to model Attractiveness (using Participant ID as random factor). The results indicated that effects of Brightness, Group and Brightness x Group were all significant (respectively $F(1,336) = 3.94$, $p = 0.05$; $F(1,116) = 57.48$, $p < 0.001$; $F(1,336) = 149.49$, $p < 0.001$). Based on the interaction effect, data for the two groups were analyzed independently in a model with Attractiveness as the DV, Brightness as the fixed factor and Participant ID as random factor. These analyses showed that for both groups, brightness significantly correlated with attractiveness, however in opposite directions. For Group 1, an increase in brightness was linked to an increase in attractiveness ($F(1,185) = 202.87$, $p < 0.001$), whereas for Group 2, an increase in brightness was linked to a decrease in attractiveness ($F(1,149) = 29.93$, $p < 0.001$). To get an estimate of the model strength and relevance of the fixed factor, the marginal R^2-values for both models were assessed. This showed that the model for Group 1 had a marginal R^2 of 0.43, whereas the model for Group 2 had a marginal R^2 of 0.11 (see Figure 4.7 for a visual representation of the model and fit). This seems to imply that brightness had a clear, positive, link with the attractiveness rating for Group 1, whereas this link was negative and less strong (but still significant) for Group 2.

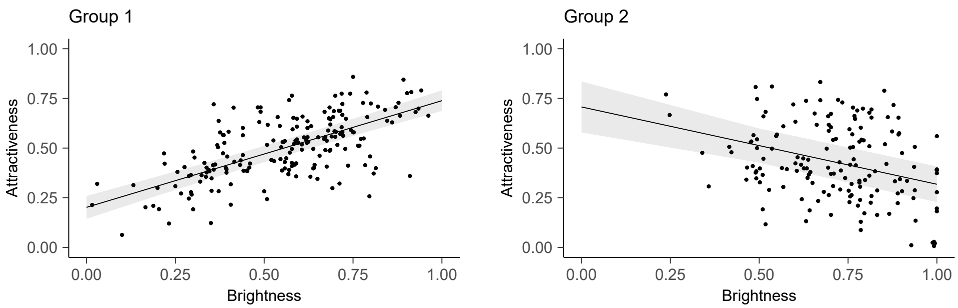

Figure 4.7: Visualization of the relation between Brightness and Attractiveness, where the solid line gives the model fit and the grey band gives the 95 % Confidence Interval, for each of the two groups 1 (left) and 2 (right) of participants separately.

4.4. Discussion

Although past studies have investigated differences in the appraisal of lighting installations with 100 % direct light versus installations with combinations of indirect and direct light, only a few studies have done so in a structured manner over the full range of ratios of direct/indirect light. Moreover, the role of the distribution of the illuminance on the ceiling (resulting from the indirect light) in room appraisal was never investigated. In the current study we tested whether there is a difference in appraisal, atmosphere, and visual comfort for a range of direct/indirect light ratios from fully direct to fully indirect, and three different distributions of the light over the ceiling ranging from quite uniform to non-uniform light, while maintaining a horizontal desk illuminance of approximately 750 lx in all lighting conditions.

The analysis showed a significant effect of the direct/indirect light ratio on appraisal, atmosphere, and comfort, but, surprisingly, the distribution of the light over the ceiling did not affect these attributes, except for the distinct/radiant appraisal. However, a large variation in the ratings was apparent in addition to high correlations between certain DVs. This prompted an investigation into possible sub-groups in our test sample, which revealed two distinct groups of people with different rating patterns across the DVs. The results of the analyses for these two groups separately painted a much more nuanced image, showing effects of both direct/indirect light ratio and light distribution on the ceiling, yet different for each group. Additionally, it also suggested that one group responded more strongly (i.e., showing a much larger variation in their responses) to the different lighting conditions than the other group. These groups also differed in the relationship between brightness and attractiveness. The first group showed a clear positive relationship (i.e., higher perceived brightness was associated with higher attractiveness), whereas the results for the second group hinted towards a more indifferent behavior (slightly negative relationship, with a weak correlation). It has to be noted that the study sample size was determined assuming only 1 group. As such, subdividing the group has impacted the overall power of the analysis of the sub-groups. For easy reference we will label these groups the “brightness appreciative group” and the “indifferent group”, respectively.

As most of the differences between the two groups seemed to be found in the correlation between brightness and the other DVs (see Figure 4.4), we explored also a clustering based only on how participants rated brightness (rather than on their rating pattern across all DVs). Although there appeared to be an overlap between the two sets of clusters (approximately 70 % of participants were in the same group comparing the two analyses), in correlations between brightness and the other DVs, the original clusters were more distinct than when clustering the participants based on their brightness ratings only. This could indicate that the two groups did not only rate the brightness of a given condition differently, but also that either their translation of perceived brightness to appraisal was different or that they took additional perceptual attributes into account for their appraisal.

If we compare our findings with the work of Stokkermans and colleagues [107], we see that they were able to accurately predict perceived atmosphere as a function of perceived brightness and uniformity. This would imply that in our case it is possible that next to differences in perceived brightness, also differences in perceived uniformity influenced room appraisal. Although it is likely that participants perceived uniformity differently between the conditions, we did not measure this directly. As such, any effects of uniformity can only be derived from further analysis of the appraisal ratings in combination with the physical conditions (i.e., the objective uniformity of the ceiling) in the present study. This would, however, be an interesting avenue to investigate further.

Starting with brightness perception, we see that the brightness appreciative group showed an increase in perceived brightness with an increased contribution of indirect lighting, where this increase levels off towards the higher contributions of indirect lighting. The indifferent group showed a more constant brightness rating, almost independently of the indirect light component, with the exception of the 100 % indirect light with the uniform ceiling distribution, which was scored substantially lower in perceived brightness. At the same time, their brightness ratings were substantially higher, on average, than the scores of the brightness appreciative group. Amongst other things, this could imply that their personal reference (i.e., home or work situation) is different. However, the fact that the uniform 100 % indirect light condition was rated significantly less bright by this group, refutes this possible explanation to some extent, as that would have implied identical results also for this condition. Additionally, both our own studies on wall and desk (il)luminance [118,138], but also other studies investigating the impact of different surfaces [69,70] on brightness and preference highlight that, in general, the wall and ceiling illuminances have a larger effect on perceived brightness compared to desk illuminance. This makes it less likely that the above average desk illuminance would be the cause of these differences.

An alternative explanation is that for the indifferent group, the appearance and luminance of the direct light (i.e., the light giving surface of the luminaire) played a large role in their brightness assessment. This could also explain the lower rated brightness of the 100% indirect light with the uniform ceiling distribution of which the luminance peaks on the ceiling were substantially lower compared to the luminance of the luminaire itself. In contrast, the non-uniform and mixed ceiling distributions resulted in luminance peaks on the ceiling comparable to those on the luminaire.

Next, we look at the translation of perceived brightness to appraisals. Earlier, we already concluded that brightness played a large role in the grouping of our participants, and that also the other DVs were related to brightness, especially for the brightness appreciative group. For the indifferent group this is less obvious as the ratings of both brightness and the other DVs across the conditions are quite constant. It is important to note that with the exception of brightness, the remaining DVs are consistently scored lower compared to the brightness appreciate group, implying that for the indifferent group a high brightness could be associated with an overall lower room appraisal score of the space.

While, in general, higher perceived brightness results in more positive appraisals for the brightness appreciative group, there are still important differences between the different DVs. The most notable one is that for the brightness appreciative group, brightness perception seems to have been dominated by the direct/indirect light ratio, whereas the atmosphere ratings (with exception of detachment) and the comfort rating also showed a clear effect of the distribution of the light on the ceiling. This strengthens the earlier findings that next to brightness perception, uniformity too plays a role in atmosphere perception. This matches the work of Stokkermans et al. [107] mentioned earlier, but also for example the work of Loe et al. [69] and Veitch et al. [77] who relate uniformity of the scene to interestingness. However, in those studies, interestingness favored non-uniform scenes, whereas in our study, the more uniform distributions were rated as more positive. Although this cannot be concluded based on this study alone, it is possible that uniformity differences on the ceiling and uniformity differences on for example walls can lead to different associations or meet with different expectations of what these surfaces should look like. Having said that, in our experiment we were not able to fully isolate the effects of the ceiling luminance from that of the wall luminance and we did see a clear increase of luminance for the direct/indirect ratios with a larger indirect component. However, as the walls were mainly influenced by the (Lambertian) reflection of the indirect light via the ceiling, the impact of the different lighting conditions on the distribution/uniformity of the wall luminance was limited. This topic, however, would require a more in-depth analysis of for example, physical luminance and uniformity differences and their appraisals for different contexts and different lighting manipulations.

4.5. Conclusion

The current study revealed that both the ratio of direct/indirect light and the lighting distribution on the ceiling impact room appraisal, atmosphere perception and visual comfort in open plan offices. However, key in delineating these effects is taking into account individual differences. In the initial analysis, only the ratio of direct/indirect light showed a statistically significant effect on perceived brightness, room appraisal, atmosphere perception and visual comfort. After grouping participants based on their rating pattern, also the distribution of the light on the ceiling was shown to have a significant effect for roughly half of the participants. The grouping analysis also showed that there is a large variation in how participants rate and appreciate brightness. Where one group showed a clear positive relationship between perceived brightness and, for example, attractiveness, the other group showed a more indifferent behavior. For the former group, next to brightness, also uniformity played a role in their room appraisal.

On the one hand, our results open new avenues to pursue from a perception research perspective, such as investigating the impact of different surfaces on spatial brightness perception and appraisal and further deep dives in the composition of the subgroups. However, on the other hand, this also shows the dilemma lighting designers face when designing open-plan office spaces for a diverse population.

CHAPTER 5

5

From luminance to brightness – a data driven approach to support brightness assessments in open plan offices.

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Abstract

People can instantly distinguish a brighter from a darker environment, but it is still unknown how to estimate brightness from the luminance distribution in complex visual scenes. In this study we performed a meta-analysis of three experiments, in which participants assessed brightness in an open plan office environment. Experiment 1 varied the luminance distribution on the wall, Experiment 2 varied the desk illuminance and Experiment 3 varied the ceiling illumination. Correlating various measures derived from high-resolution luminance images with participants' brightness ratings, we investigated to what extent brightness could be predicted. In particular, we focused on 19 different luminance distribution characteristics calculated over 11 different areas of the visual field. In line with earlier work, participants could be grouped in two categories, one consisting of participants who substantially and consistently varied in their brightness assessments for the different settings, the other consisting of participants who responded more evenly, regardless of the setting. Based on the brightness-responsive group of participants, brightness could be best modeled with the logarithm of the median luminance calculated over a 60° horizontal band in the field of view or with the logarithm of the 95th percentile over the median calculated over the 40° horizontal band, explaining 35 – 40 % of the variance in brightness perception. For both groups combined, these models explained about 15 – 20 % of variance in brightness perception.

5.1. Introduction

Manipulating brightness is one of the key tools in the toolbox of lighting designers and in many studies has been indicated as a determining element for the atmosphere [107,141] or appraisal of a given space [69,70]. It is, however, still unknown how to predict, or at least get an indication of this subjective experience from the objective luminance distribution in complex visual scenes.

Research into brightness perception can be traced all the way back to 1860 with Fechner studying the measurement of sensation [142]. Follow-up studies by Stevens [143], Marsden [144], Haubner [145,146] and Bodmann and La Toison [147] looked into the relationship of luminance and brightness of clearly defined (simple) stimuli or surfaces. One of the major findings in these studies was that the brightness of a given target does not just depend on its luminance, but also on the luminance of the background. Although the background's impact is relatively straightforward for cases where the surrounding is well-defined (most experimental setups used a uniform background), it becomes less obvious for more complex visual scenes. For those scenes, it is unclear which objects/surfaces are relevant for the perception of brightness, how to define the background of those objects, and how to combine the different elements in a space to an overall brightness judgment. This limitation was widely recognized and in a later study, Marsden [148] proposed an extension for the assessment of the brightness of complex scenes. In this model, the brightness of the brightest surface increases with luminance following a power law with an exponent of 0.35, whereas the brightness of the surrounding surfaces follow a power law with an exponent of 0.60, relative to the brightest surface.

Although this was already a big step forward, the applicability of this method to more complex visual scenes remained challenging as several key questions were still unanswered. For example, one of these questions is how to define which surface is brightest, and how to define the boundaries of the surface in question. Are these simply the physical boundaries of the space (e.g., the walls) or does this definition depend on the pattern, shape or distribution of the lighting effect? Next, once the surface is defined, it is unclear how to aggregate the luminance distribution on that particular surface to come to a single luminance value for that surface as used in the model. When considering relatively uniform surfaces (as likely used in the Marsden study), typical measures such as the mean, minimum or maximum luminance are all relatively close to each other. However, for non-uniform surfaces, these values can vary substantially.

In this respect, the work of Loe et al. [69] provides additional insight as they describe both the measurement method and the aggregation of the luminance distribution in detail. In their study, the luminance distribution of scenes was recorded with a relatively high resolution on a grid of 80 x 90 measurements covering an area of 144° x 162°. Next, they aggregated the luminance distribution over different (central) circles (of size 20° and 40°) and horizontal bands (of width 20° and 40°) in the observer's field of view and determined their maximum, minimum, and average luminance values. Using this setup, they identified the 40° band as the most influential in determining 'visual lightness' of the scene, as rated by observers. In contrast to, for example, the Marsden study, this finding demonstrates that in addition to the absolute luminance values and the ratios between different surfaces, also the location within the field of view should be considered in estimating brightness.

Looking at more than just the target was already posited in the 1950's by for example Waldram and Hopkinson [40,149] who advocated to include brightness as a key component in lighting designs. A key element of their suggestions was that judging only absolute luminance values of individual parts of the field of view was not sufficient to predict brightness, but that the entire area needed to be taken into consideration to account for adaptation of the eye. To that end, they developed the concept which they called 'apparent brightness' in which they combined the intended brightness (i.e., the brightness the designer intends to achieve) of different elements to estimate an adaptation level, which in turn could be used to translate the intended brightness of the individual surfaces to a luminance value for that surface to be used in the engineering phase. The estimation of the adaptation level, however, was still based on experience and 'taking a mentally estimated average of the apparent brightness' [150 - p. 116], making this method still somewhat difficult to apply as also recognized by Hopkinson in his proposal to work towards a luminance basis for lighting codes [151]. The unanswered question, however, was what parts of the visual field would be dominant, which brings us back to the study by Loe et al. [69] who tried to quantify this.

An important aspect to consider, however, in the study of Loe et al. is that the 20° and 40° central circles and the 20° and 40° horizontal bands predominantly covered the walls of the room, whereas the contribution of the ceiling - also a significant part of the visual field - was not considered, despite the fact that they did include up-lighters in some of their scenarios. Therefore, the implicit conclusion that wall luminance is dominant in brightness perception may be somewhat premature. Similarly, Van Ooyen et al. [70] identified the wall (in contrast to the desk) as being most influential in determining the room experience. However, this study only investigated direct luminaires and different surface reflectances, and as such did not include variations in ceiling luminance. So, in both of these influential studies, a key surface such as the ceiling, which is obviously part of the 'solution space' for lighting design, was not considered, even though users may also weigh in this surface in their overall brightness assessment. In contrast, studies by Houser et al. [114], Veitch & Newsham [77], and de Vries et al. [118,138,152] report clear contributions of wall, desk and ceiling luminance in brightness assessments.

It is important to acknowledge that not just the lighting, but also the properties of the space being lit impact the perception of brightness. The reflection properties of materials are incorporated (to some extent) in the luminance measurements, but for example, the actual color, texture and glossiness of materials are not. Also the (sense of) spaciousness and depth information is lost in the 2D nature of the luminance recording. Finally, also part of the information on the lighting itself is lost in the luminance value. Fotios et al. [153] for example showed in an extensive review that the Spectral Power Distribution (SPD) affects brightness perception, and that in absence of proper reporting of SPDs no metric can be developed for brightness prediction. Next to this, recent studies have shown that the ipRGC's also affect the assessment of scene brightness [154,155], which might explain (part of) the impact of the SPD overall.

Given all these complications, it is clear that predicting the perception of brightness from luminance images is far from straightforward, and maybe even impossible at a high level of accuracy. Yet, for a designer it is important to estimate the brightness of a design based on the luminance distribution in that design. To that end, we try to further substantiate the research of Loe et al. by performing a data-driven meta-analysis on the results of our three previous studies. This approach explores the utility of a substantial number of different luminance parameters and the relevance of a substantial number of different zones for predicting brightness perception.

The analysis was performed on the data from three of our previous studies [118,138,152], in which participants assessed brightness for multiple light distributions, involving multiple surfaces, designed in a realistic office environment. All lighting conditions were also physically characterized with high resolution luminance images taken from each participant's desk position. These combined data gave us the opportunity to not only replicate the work of Loe et al. [69], but to also extend it, investigating more aggregation areas (some also including the ceiling), more light distribution characteristics, for a larger sample, and starting from higher accuracy luminance images. Importantly, data were collected in a highly realistic office space and each of the studies varied only one luminous parameter (for example only wall luminance) while keeping the rest of the luminous environment as constant as possible. This creates a diverse dataset in which the correlations between the luminance of different surfaces are relatively low (e.g., the desk luminance does not depend on the wall luminance).

5.2. Methodology

5.2.1. Description of the dataset

The data of three earlier experiments, each performed in a comparable office-like setting, were combined [118,138,152]. All studies probed the same set of room appraisal semantic differentials (modified from [82]), one of which directly queried perceived brightness. Participants assessed brightness on a visual analog scale from dim (0) to bright (1) (see Appendix 4 – A4-1 for histograms per condition). For each experiment, luminance images from each desk position (taken at eye height of a sitting individual) and for each lighting condition were taken. The light manipulations over the three experiments were quite different, creating a diverse dataset and reducing the risk of biasing the model with a too limited set of stimuli. Figure 5.1 provides an overview of several of the selected experimental conditions to provide an indication of the range of stimuli (see Table 5.2 and Appendix 4, Table A4-2, A4-3 and A4-4 for a numerical overview).

The first experiment, described in de Vries et al. 2018 [118], varied the luminance on the wall opposite to the participants at three different levels (i.e., average luminance of 12, 36 and 72 cd/m^2) while maintaining a fixed illuminance at the desks (i.e., 500 lx), eyes (i.e., 206-254 lx), and a fixed luminance at the ceiling (21-36 cd/m^2). This experiment followed a within-subject study design, in which participants stayed in the room for roughly 1.5 hours per session, with successive sessions 1 week apart, and evaluated one lighting condition per session. For more details on method and procedure, we refer to [118]. For this experiment, data of 37 participants were available, with luminance values derived from 12 luminance images (i.e., 4 desk positions, 3 conditions). This experiment will be referred to as the wall-luminance experiment.

The second experiment, described in de Vries et al. 2020 [138], simultaneously varied illuminance at the eye (118 – 796 lx, measured in the vertical plane) and on the desk (158 – 1596 lx measured in the horizontal plane) in three steps, while maintaining a fixed average wall luminance (between 76-80 cd/m^2) and allowing relatively small ceiling luminance variations (22 – 77 cd/m^2). This study was performed with an identical setup as the wall luminance experiment, and yielded data of 34 participants, with luminance values derived from 12 luminance images (i.e., 4 desk positions, 3 conditions). For more details on method and procedure, we refer to [138]. This experiment will be referred to as the desk-illuminance experiment.

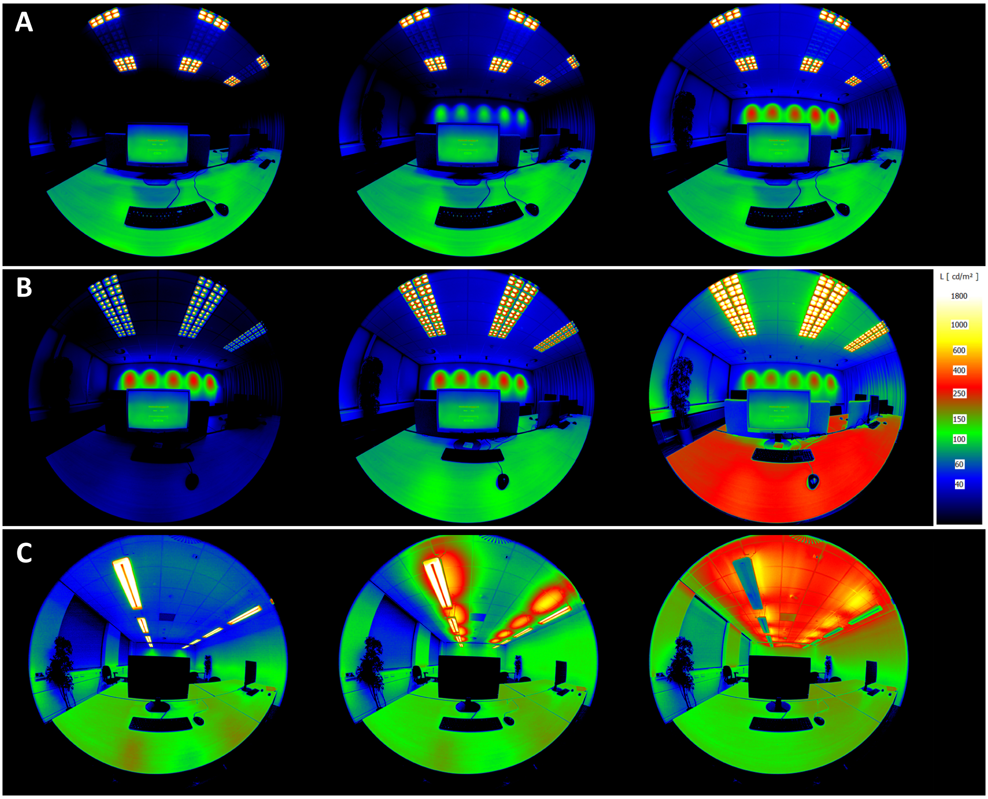

Figure 5.1: Selection from the total set of Luminance images used. A: Wall-luminance experiment with low – mid – high wall luminance (fixed desk illuminance), B: Desk-illuminance experiment with low – mid – high desk illuminance (fixed wall luminance), C: Direct/Indirect-light experiment with left: Direct only, middle: 50 % direct + 50 % indirect (non-uniform ceiling distribution), right: Indirect only (uniform ceiling distribution) – note, display was measured separately and added to the luminance image in post-processing.

The third experiment, described in de Vries et al. 2021 [152], varied the ratio of direct/indirect light of suspended luminaires in 5 steps and varied the distribution of the indirect light component in 3 steps, resulting in a total of 13 different conditions. Desk illuminance was fixed at 750 lx, and average wall luminance varied between 58 and 176 cd/m^2, while ceiling luminance was manipulated between 58 – 362 cd/m^2. This study was also set up as a within-subject experiment, but participants were presented with the 13 stimuli in random order in a single session (with 5 minutes of accommodation in between settings). For more details on method and procedure, we refer to [152]. From this study, data of 32 participants were available, with luminance values derived from 52 luminance images (i.e., 4 desk positions, 13 conditions). This experiment will be referred to as the direct/ indirect-light experiment.

5.2.2. Brightness grouping

The analysis of the direct/indirect-light experiment highlighted two distinctly different subgroups with regards to how participants rated brightness: one group responded strongly to the different lighting conditions, while the other group was more indifferent to the related luminance changes [152]. To check the general validity of such a division of participants, the brightness data of all three experiments were analyzed for similar grouping patterns. This was done using a hierarchical clustering per experiment. As all three experiments used a within-subject setup, distance between clusters was based on the correlation between participants and the grouping based on complete linkage.

These analyses revealed that also in the wall-luminance and desk-illuminance experiments the participants could be subdivided in two or three groups, of which the largest group of participants could be classified as brightness responsive (i.e., with clear differences in brightness scores between the different lighting conditions), and of which the other one or two smaller groups (11 out of 37 in the wall-luminance experiment; 6 out of 34 in the desk-illuminance experiment) consisted of participants who were less responsive with their brightness scores to variations in lighting conditions. In the up/down-light experiment, the division between the two groups was more equal in size (15 responsive vs 17 indifferent) than in these earlier two studies. Separate Linear Mixed Model (LMM) analyses were then performed on the brightness ratings per study, using the factors Lighting Condition, Group, and their interaction, and allowing random intercepts for different participants. For all three experiments, the interaction between Lighting Condition and Group was significant. We therefore chose to study the groups both separately and together in the current analyses.

Table 5.1: Overview of groups and significance of Lighting Condition * Group interaction

Experiment	Brightness responsive	Brightness indifferent	LMM results of interaction Lighting condition * Group		
			F	*df*	*p*
1. Wall luminance	n= 26	n = 11	11.76	(4,68)	< 0.001
2. Desk illuminance	n = 28	n = 6	10.63	(4,62)	< 0.001
3. Direct/Indirect-light ratio	n = 15	n = 17	5.02	(12,360)	< 0.001

5.2.3. Independent variables – luminance distribution and assessment area

We consider two aspects -- size and shape of the visual field involved, and specific characteristics to summarize the luminance distribution -- as independent variables in our analysis.

Assessment area

All luminance images were created using a luminance camera with a circular fish-eye lens (LMK Color 5 with an image resolution of 2448 x 2052 pixels). From these images (see example in Figure 5.2) an almost infinite number of possible areas can be selected to represent the visual field. As a start, we selected a set of areas existing of central circles and horizontal bands of different sizes. The first set of areas consisted of central circles with an angular subtense of 20° and 40° in diameter, as used by Loe et al. [69], to which we added larger circles of 60°, 80°, 100°, 120°, 140° and 160° in diameter (Figure 5.2 – left). The second set of areas was formed by horizontal bands with a width of 20° and 40°, as used by Loe et al., extended with a 60° band (Figure 5.2 – right).

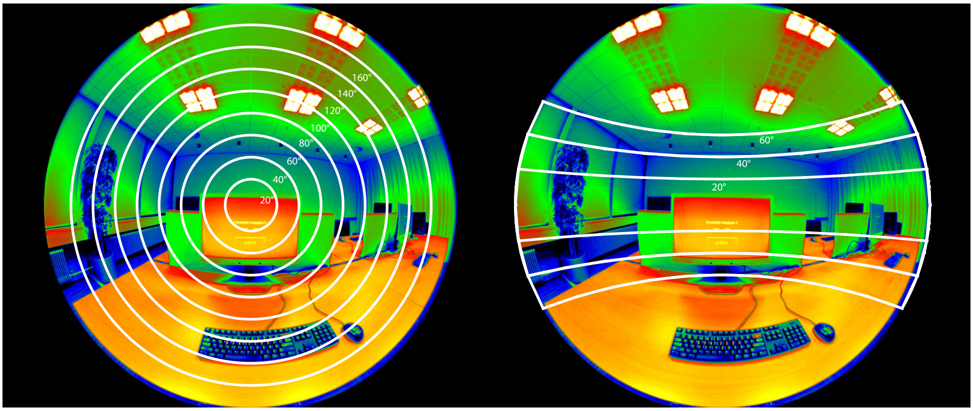

Figure 5.2: Visualization of the areas used to extract the luminance distribution characteristics

Luminance distribution characteristics

Similar to the infinite number of areas that can be selected from luminance images, there is an infinite number of ways to characterize the luminance distribution of such areas. The parameters investigated by Loe et al. [69] were the mean, minimum and maximum luminance over the different assessment areas. Additionally, they investigated the logarithm of the mean and the logarithm of the ratio maximum to minimum luminance. We extended this set with, on the one hand, characteristics based on absolute levels that describe the central tendency of the luminance (mean, median) or the extremes of the area (such as the minimum or maximum luminance), and on the other hand, luminance ratios within the area under consideration, reminiscent of the earlier work on brightness quantification taking into account both the lowest and highest luminance compared to the overall luminance.

In line with recommendations by Loe et al. [69], we extended the characteristics list with percentile values at both the maximum (90th and 95th percentile: L_{90},L_{95}) and minimum (5th and 10th percentile: L_{05}, L_{10}) side of the luminance distribution. These percentile values should capture the essence of maximally and minimally luminous parts of the scene, but be less sensitive to extremely high or low values of tiny elements, which could be unrepresentative and atypical. We excluded the minimum luminance parameter as used in [3], as in our high-resolution luminance images, there were always one or more pixels with a luminance close to 0 cd/m^2, rendering this criterion irrelevant. In addition to the parameters as provided by Loe et al., we added the median luminance, as the luminance values of a given assessment area could be severely skewed. For the three horizontal bands and for the circles up to a subtense of 100° in diameter) there was a very high correlation (i.e., Pearson's $r > 0.95$) between the mean and the median of all 11 different lighting conditions. For the circles with a subtense of 120°, 140° and 160°, however, the r-coefficient dropped to 0.65. As these larger circles include larger sections of the desk and ceiling (deemed important for the desk-illuminance and direct/indirect-light experiments), it was decided to add the median to the set of characteristics.

Last, several ratio-based characteristics were added to investigate different methods for addressing (non)-uniform luminance distributions in brightness assessment. The first addition was the uniformity parameter as defined by the European standard on workplace lighting design (EN12464-1:2011 - U_o = minimum/ mean). Although this characteristic is typically intended to prevent overly high contrasts in lighting designs, it is also interesting to investigate whether it has any predictive power with respect to brightness assessment. For completeness, we also included the ratio of the minimum to the median. Additionally, as many theories on brightness quantification take into account the ratio between the brightest surface and the surrounding, we also added the ratio of the maximum luminance to the mean luminance and of the maximum luminance to the median luminance. In both cases, following the work from Loe et al. [69] we also included the logarithm of these ratios. Note that, to prevent that non-representative values dominate these ratios, we use L_{05} instead of the minimum luminance and L_{95} instead of the maximum luminance.

Table 5.2 provides – as an indication for the range of stimuli included in this study – an overview of the ranges of the different lighting distribution characteristics per experiment for a single assessment area (i.e., the 60° horizontal band). A full overview of all lighting distribution characteristics for all assessment areas can be found in Appendix 4 – Tables A4-2, A4-3, A4-4.

Table 5.2: Overview of the ranges of the different lighting distribution characteristics for the 60° horizontal band assessment area, per experiment.

Mask: 60° horizontal band		Wall-luminance experiment		Desk-illuminance experiment		Direct/Indirect-light experiment	
Level-based characteristics		min	max	min	max	min	max
Mean	[cd/m²]	27.9	49.9	32.6	91.7	98.9	157.3
Median	[cd/m²]	14.9	34.9	22.4	60.8	63.6	144.0
$\log_{10}$(mean)	[cd/m²]	1.45	1.70	1.51	1.96	2.00	2.20
$\log_{10}$(median)	[cd/m²]	1.17	1.54	1.35	1.78	1.80	2.16
5th percentile (L_{05})	[cd/m²]	4.06	6.83	2.64	13.6	9.76	16.9
10th percentile (L_{10})	[cd/m²]	6.46	13.6	4.68	26.6	19.7	50.9
90th percentile (L_{90})	[cd/m²]	79.1	96.8	79.7	233.5	144.9	273.6
95th percentile (L_{95})	[cd/m²]	88.5	115.1	107.7	272	215.8	364.5
Maximum	[cd/m²]	4430	6742	407.2	9035	1209	7151
Ratio-based characteristics							
L_{05}/mean		0.12	0.15	0.08	0.16	0.09	0.12
L_{05}/median		0.17	0.30	0.12	0.23	0.10	0.17
$\log_{10}(L_{05}$/mean)		-0.91	-0.82	-1.11	-0.81	-1.05	-0.92
$\log_{10}(L_{05}$/median)		-0.76	-0.52	-0.93	-0.63	-1.02	-0.76
L_{95}/mean		2.24	3.18	2.32	3.30	1.70	2.49
L_{95}/median		3.22	6.06	3.35	4.93	1.87	3.78
$\log_{10}(L_{95}$/mean)		0.35	0.50	0.37	0.52	0.23	0.40
$\log_{10}(L_{95}$/median)		0.51	0.78	0.52	0.69	0.27	0.58
L_{95}/L_{05}		16.9	21.8	18.9	42.4	15.4	28.1
$\log_{10}(L_{95}/L_{05})$		1.23	1.34	1.28	1.63	1.19	1.45

5.2.4. Processing and analysis

Image processing & extraction

Luminance images (n = 12+12+52 = 76) were exported to text files and loaded and processed using the Python programming language (Python 3.7.3). The assessment area coordinates were generated using AutoCAD and exported to Python to generate 11 inverted masks (i.e., masking the area outside the designated assessment area). Finally, each mask was applied to each luminance image and all 19 luminance distribution characteristics were extracted for each mask/image combination. All the data (i.e., 76 x 11 x 19 = 15,884 datapoints) were compiled in a single dataset and exported for use in the statistical software package R (version 4.03).

Statistical analysis

The overall analysis aimed at finding which combination of assessment area and luminance distribution characteristic provided the best model fit to the brightness appraisals, collected in the three experiments mentioned in section 2.1. To do this, for each area/characteristic combination (i.e., 11 x 19 = 209 in total) an LMM was setup in R (*lme4* package) modeling brightness to this area/characteristic combination (referred to as Area Characteristic) as a single fixed factor and participant ID as a random intercept. From these models, the significance of the Area Characteristic was determined (*lmerTest* package using Satterthwaite approximation for degrees of freedom) to eliminate models which were clearly not significant. Since this significance testing was only performed as a first filter to eliminate models in which the Area Characteristic was clearly not significant, no correction for multiple testing was applied. Subsequently, the R^2-conditional and R^2-marginal values of the models that were significant, were determined as an indication of model fit (*performance* package). Note that both the conditional fit (i.e., the fit of the full model including both the random and fixed effect) and the marginal fit (i.e., the fit of only the fixed effect) are interesting as they provide an indication of predictive power of the Area Characteristic, but also of the magnitude of the interpersonal differences.

To avoid masking of the relationship between brightness and Area Characteristic for the brightness responsive group with the data from the more indifferent group, the analysis was split in two phases. The first phase used only the brightness responsive group (n = 69) to model the relationship between Area Characteristic and brightness perception. The second phase took the best model fit of the first phase and tested this on the full dataset (i.e., including both the brightness responsive and more indifferent subjects, n = 103).

Finally, the best model fit from the first phase (i.e., with only the responsive group) was subjected to additional analyses to investigate the sensitivity of the model. This included testing the impact/contribution of the different experiments on the overall outcome and testing the sensitivity of the model to the specific percentile values in the ratio-based characteristics (i.e., the impact of using L_{91}, L_{93}, L_{97} or L_{99} instead of L_{95} in the ratio-based characteristics).

5.3. Results

5.3.1. Model fits for brightness-responsive group of all three experiments together

As described in Section 5.2.4, for each of the 209 Area Characteristics (i.e., combination of assessment area and light distribution characteristic, e.g., average luminance of the 80° circular assessment zone) a separate LMM analysis was performed modeling for the responsive group the brightness ratings over all conditions of all three experiments to the Area Characteristic as a fixed (linear) factor and the participant as a random (intercept) factor. Figure 5.3 shows an overview of the outcomes of the LMM analyses, grouped by the luminance distribution characteristic part of the Area Characteristic variable. Only the models for which the Area Characteristic had a significant effect on Brightness are shown. A numerical overview of these data, including all non-significant models can be found in the Appendix 4, Table A4-5.

Level-based Characteristics

The level-based characteristics consisted of the mean, the median, the logarithm of these two, the maximum luminance and the percentile values near the minimum and maximum luminance. In general, the models using the L_{05}, L_{10}, L_{90} and L_{95} characteristics rendered lower R^2 values than the models using the mean and median, independent of the assessment area. Additionally, the models based on the logarithms of the mean (log-mean) and median (log-median) resulted in a better fit (i.e., both higher conditional and marginal R^2 values) than the models based on the common mean and median did. This is in line with the findings by Loe et al. [69] who found substantially lower correlations with visual lightness for the mean than for the log-mean. Next to this, the overview shows that the Area Characteristic based on the log-median, overall, yielded a slightly better model than the log-mean. For both the arithmetic and logarithmic mean and median, larger differences in R^2 between the mean and median based models, both for the common as well as for the logarithmic mean and median.

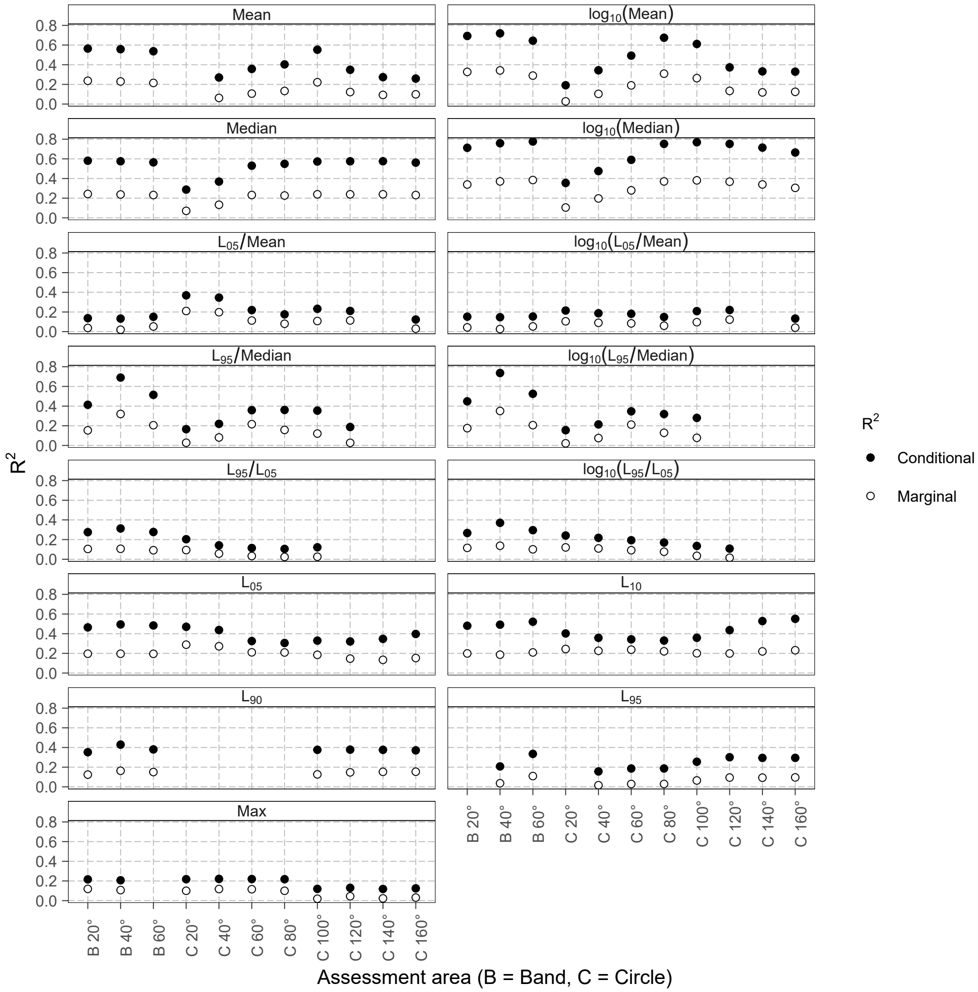

Figure 5.3: Model fit overview showing only models with a significant effect of the Area Characteristic on Brightness

Looking more closely at the combination of assessment area and light distribution characteristic, the best model fit was found when using the log-median on the 60° horizontal band (R^2_{cond} = 0.78, R^2_{marg} = 0.38 – see Figure 5.4). This best result was closely followed by that of the model using the log-mean on the 40° horizontal band (R^2_{cond} = 0.72, R^2_{marg} = 0.34). Both models indicated that a higher overall value of these characteristics resulted in a higher brightness perception (see Figure 5.4). The second-best result matches closely with findings by Loe et al. [69], who found that the best predictor of visual lightness for their data was the log-mean calculated over the 40° horizontal band. However, for our data, taking the median instead of the mean, and using a wider band resulted in a better model fit.

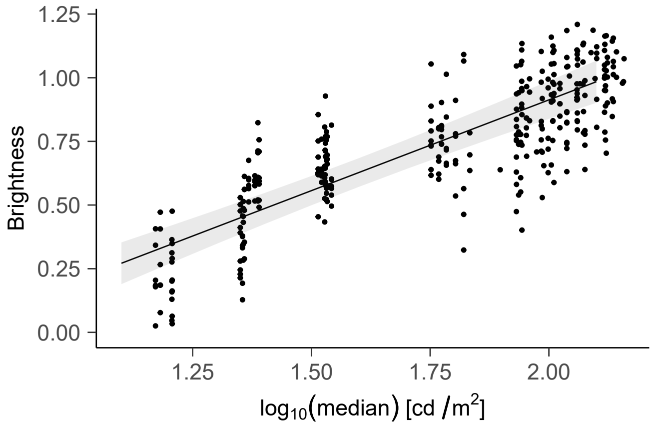

Figure 5.4: Partial regression plot (corrected for random effects) of brightness ratings (all three experiments, all conditions, responsive group) plotted as a function of the log-median characteristic calculated over the 60° horizontal band. The line represents the model fit with 95 % Confidence interval.

Ratio-based characteristics

With the exception of the models based on the L_{95}/median characteristic, models using ratio-based characteristics (i.e., L_{05}/mean, L_{95}/L_{05} and their logarithmic versions) exhibited lower R^2-values than models based on level-based characteristics. This is line with the results of Loe et al. [69], where the characteristic "logarithm of the maximum/minimum" was not highlighted for its power to describe brightness, but instead emerged as a relevant predictor for interestingness.

5

In contrast, the log-L_{95}/median characteristic calculated over the 40° horizontal band did show a substantially higher fit (R^2_{cond} = 0.74, R^2_{marg} = 0.35) with higher ratios being perceived as less bright (as illustrated in Figure 5.5). This model is almost on-par with the model based on the log-median calculated over the 60° horizontal band (R^2_{cond} = 0.78, R^2_{marg} = 0.38) as discussed in Section 5.3.1. However, whereas the log-median showed a good fit consistently for all three horizontal bands (i.e., 20°, 40° and 60°), the log-L_{95}/median characteristic only resulted in a good fit for the 40° horizontal band, and not for the 20° or 60° horizontal bands. Analyzing the original luminance images, we saw that the maximum (and thus the 95th percentile) was significantly higher for the 60° horizontal band than for the 40° horizontal band since the former included two of the luminaires responsible for manipulating the lighting conditions of both the wall-luminance and desk-illuminance experiments, whereas the latter did not. The 20° horizontal band did not include the desk portion of the visual field in the assessment area (which was the main manipulation in one of the experiments), whereas the 40° band did include significant parts of the surrounding desks, thus influencing the 95th percentile. As such, we can conclude that although the model fit for the log(L_{95}/

median) has a higher variability for the different horizontal band sizes than for the log-median characteristic, there is a clear difference in what the different bands assess. Based on this insight, the log-L_{95}/median characteristic calculated over the 40° horizontal band (with lower ratios, i.e., higher uniformity being rated as more bright) is included in the further analyses.

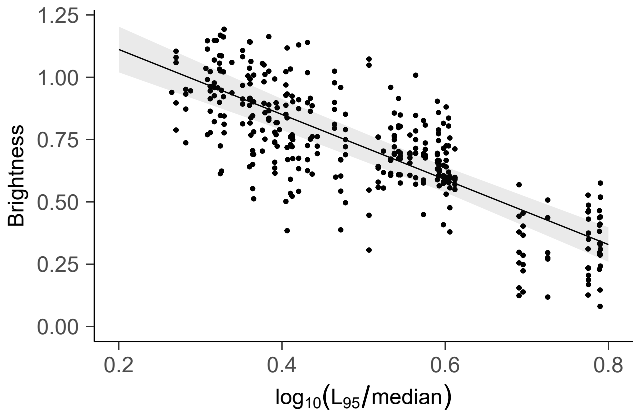

Figure 5.5: Partial regression plot (corrected for random effects) of brightness (all three experiments, all conditions, responsive group) plotted as a function of the Log-L_{95}/median characteristic calculated over the 40° horizontal band. The line represents the model fit with 95 % Confidence interval.

5.3.2. Applying the best models to all participants of all three experiments

To understand the impact of excluding the more brightness-indifferent subjects, we repeated the LMM analyses on the full dataset (n = 103) for the level-based and ratio-based area characteristics that resulted in the best fit as presented in Section 5.3.1. Table 5.3 shows the results of these models and compares them to the findings in Section 5.3.1. As expected, both models fit the full dataset less well than the dataset limited to the brightness-responsive group of participants; however, also for the full dataset both models still explain approximately 50 % of the variance in brightness perception, with both Area Characteristic combinations being significant in predicting brightness.

Table 5.3: Comparison of fitting the best Area Characteristic combinations to brightness (as determined in section 3.1) between the group of brightness-responsive subjects and all subjects (i.e., the full dataset)

Model	Brightness responsive		Full dataset	
	$R^2_{cond.}$	$R^2_{marg.}$	$R^2_{cond.}$	$R^2_{marg.}$
Log-median - 60° band	0.78	0.38	0.52	0.19
Log-L_{95}/median – 40° band	0.74	0.35	0.50	0.17

5.3.3. Exploring model boundaries

The findings presented in Section 5.3.1 indicate that for our dataset brightness can be predicted best using either the logarithm of the median calculated over the 60° horizontal band of the visual field, or the logarithm of the 95th percentile/median ratio calculated over the 40° horizontal band. To better understand the robustness of these two predictors of brightness in complex scenes, two additional analyses were performed: one to investigate the impact of the individual experiments on the general conclusion of best models, and one to investigate the sensitivity of selecting a particular percentile in the L_{95}/median characteristic.

Impact of individual experiments on best model

Although the number of participants in all three experiments were quite similar (n = 37, 34 and 32), the wall-luminance and desk-illuminance experiments only tested 3 conditions each, whereas the direct/indirect light-experiment tested 13 conditions and as such generated over 4 times as many data points. This may lead to a potential risk of skewing the data towards a single experiment. To test this, we took the models that provided the best fit (see Table 5.3) and applied them to the dataset of the wall-luminance and desk-illuminance experiments, on the one hand, and to the dataset of just the direct/indirect light-conditions, on the other hand, including only the brightness-responsive subjects of all three experiments. Table 5.4 and Figure 5.6 present the results and compare them to the results obtained for the same models using the data of all three experiments together, again only for the brightness-responsive subjects (as presented in Section 5.3.1).

In contrast to our expectations, the wall-luminance and desk-illuminance experiments rather than the direct/indirect light-experiment appear to have dominated the overall model fit. This can be inferred from the marginal R^2-values, which are higher for the former than for the latter. On the other hand, all three experiments do appear to complement each other in the full dataset as the conditional R^2-values (i.e., including both the fixed and random elements of the model) are higher for the three experiments together than for the subset of experiments.

Table 5.4: Model fits comparing the combination of all three experiments to either the combination of the wall-luminance and desk-illuminance experiment or to the direct/indirect-light experiment for the best models described in section 3.1.

Area Characteristic	Log(median) – 60° horizontal band		Log(L_{95}/median) – 40° horizontal band	
	$R^2_{cond.}$	$R^2_{marg.}$	$R^2_{cond.}$	$R^2_{marg.}$
All three experiments	0.78	0.38	0.74	0.35
Wall luminance + desk illuminance experiment	0.58	0.45	0.61	0.44
Direct/indirect light experiment	0.39	0.20	0.43	0.18

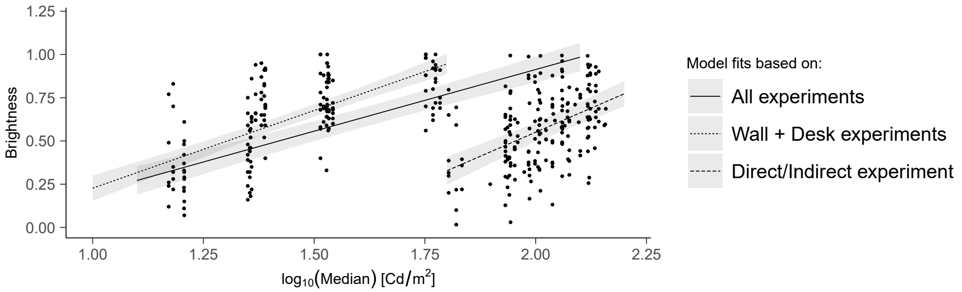

Figure 5.6: Illustration of the model fits, predicting brightness as a function of the logarithm of the median luminance calculated over the 60° horizontal band, for all three experiments together, for the combination of the wall-luminance and desk-illuminance experiment and for the direct/indirect-light experiment.

Percentile sensitivity

For the log-L_{95}/median characteristic, the 95th percentile (L_{95}) was selected instead of the absolute maximum to avoid basing this characteristic on 'single pixel luminance peaks'. However, the 95th percentile was selected quite arbitrarily (for example, the paper by Loe et al. [69] took the 90th percentile value). To investigate the effect of a particular percentile we replaced the L_{95} in the log-L_{95}/median of the 40° horizontal band Area Characteristic by the L_{91}, L_{93}, L_{97} and L_{99} values also calculated using the 40° horizontal band, and modeled brightness based on these four new characteristics for all three experiments together, using the brightness-responsive group. As can be seen in Table 5.5, the different percentiles rendered some variation in both the conditional R^2-values and marginal R^2-values of the corresponding models. However, the results do show a clear optimum around the 93rd to 95th percentile.

Table 5.5: Overview of conditional and marginal R2-values for modeling brightness as a function of different percentiles in the "xx percentile/median" characteristic calculated over the 40° horizontal band.

Parameter (40° band assessment area)	$R^2_{cond.}$	$R^2_{marg.}$
log - 91st percentile / median	0.48	0.19
log - 93rd percentile / median	0.72	0.34
log - 95th percentile / median (reference)	0.74	0.35
log - 97th percentile / median	0.61	0.26
log - 99th percentile / median	0.19	0.03

5.4. Discussion

Using the study performed by Loe et al. [69] as a starting point, we investigated to what extent different luminance distribution characteristics and different assessment areas would be able to provide an estimation of the brightness assessment of participants in three earlier experiments [118,138,152]. We did this by correlating the brightness ratings of 19 lighting conditions against the luminance distribution which was described with 9 level-based characteristics and 10 ratio-based characteristics, each calculated over a total of 11 different areas of the visual field, resulting in a total of 209 possible descriptors of brightness perception. We found that both the logarithm of the median luminance (log-median) calculated over the 60° horizontal band, and the logarithm of the 95th percentile/median ratio (log-L_{95}/median) calculated over the 40° horizontal band best predicted participants' brightness ratings. Although our findings are closely in line with the conclusions of Loe et al. [3], there are also some notable differences. In short, our findings suggest that the log-median luminance outperforms the log-mean luminance as a predictor (which was the best performing predictor in the Loe et al. study) and that a slightly larger assessment area (i.e., a 60° horizontal band rather than the 40° horizontal band as used by Loe et al.) improves the predictions further. In addition, we learned that the ratio-based log-L_{95}/median characteristic exhibits a similar model fit compared to the level-based log-median. A final difference/nuance is that although the conclusions are similar, the goodness of fit for the different models is different. Whereas Loe and colleagues report a 'Correlation coefficient' (no further details provided) of 0.83, our conditional R^2 for the full group is only 0.52 and the marginal R^2 is only 0.19. However, for the brightness responsive group we find R^2-values of 0.78 (conditional) and 0.38 (marginal) respectively, of which the former (conditional) value seems to be more in line with the values found by Loe and colleagues. Looking into the details of their study we find that the 12 participants are all members of the staff of their institution and as such may be more responsive than layman observers. On the other hand, it appears that the 12 members assessed all conditions, making it a repeated-measures experiment, similar to ours, which may imply that the actual correlation in the Loe et al. study (excluding the random/repeated measures effect) is lower (in line with the differences we find between the conditional and marginal R^2). We reflect on our method, findings, and insights in greater detail below.

5.4.1. Data driven approach to brightness prediction in complex scenes

The fact that we had three different experiments, in a similar context, all with similar brightness ratings and all fully described with luminance-based images, presented us with the unique opportunity to investigate relation between luminance and brightness in complex visual scenes using a data-driven approach. In contrast to the study by Loe and colleagues [69], our individual experiments all featured multiple (i.e., 4) observer positions. On the one hand, this led to a lower 'control' over the experimental settings as all observer positions differed slightly, resulting in 76 less defined lighting conditions instead of just 19 highly defined conditions. On the other hand, these multiple observer positions resulted in a richer dataset, as the rooms were not 100 % symmetrical. The latter was further strengthened by the availability of high-resolution luminance images which allowed us to extract the luminance distribution characteristics in great detail for each individual observer. However, this also highlighted certain challenges with regard to using real, high resolution data compared to more coarse and/or simulated data. These challenges especially occurred while extracting the minimum and maximum values: these absolute extremes have a high likelihood of being less relevant as they tend to be isolated pixels in less relevant locations. Looking at the minimum values, for example, these could be found in actual shadow areas (for example under a desk), but could just as well be due to a shadow cast by the wire from one of the PC-keyboards or a PC-mouse. To solve this, we followed the approach set out by Loe et al. [3] by selecting percentile values close to the minimum and maximum which, although not relevant in their study (likely due to their more coarse luminance collection grid), provided a useful solution in our case. Having said that, we used a purely numerical approach, in which, for example, the selection of percentiles is quite arbitrary (more on this in Section 5.4.4). As such, an interesting future approach would be to pre-process the luminance images based on the eyes' ability to resolve details [156] taking into account differences in resolution due to eccentricity. An alternative approach to solving this specific challenge would be to explore the effects of the 'composition' of the image, for example in terms of contrast (as discussed in Amundadottir et al. [157]) or spatial frequencies (e.g. as discussed by Penacchio and Wilkins [158]).

A second refinement compared to the approach by Loe et al. [3] was the use of a larger set of assessment areas including not only the central field of view, but also larger sections of the peripheral view. This choice was made as the (smaller) central assessment areas as used by Loe et al. did not take into account the desk or ceiling of the space. As our experimental manipulations in 2 out of 3 experiments focused on these two zones, we expected that these zones would play a larger role in the overall brightness assessment. Our results, however, showed that whereas the larger (>40°) circles were indeed an improvement over the smaller ones for most of the luminance distribution characteristics used, they did not outperform the characteristics calculated over the 40° and 60° horizontal bands, which only included small sections of the ceiling, but did include some of the adjacent desks. A detailed evaluation of more assessment areas could help in further identifying which areas played the largest role in predicting perceived brightness. However, refining the analysis also might lead to overfitting, rendering outcomes that are only valid for the specific scenes being analyzed.

A final refinement in the approach was the statistical modeling. Where Loe et al. [3] used a relatively straight-forward correlation approach, our dataset featured a within-subject test setup and as such required a more detailed analysis in the form of linear mixed models. Using this approach, random intercepts could be included to correct for the between-subject variation, while still allowing the three different experiments to be considered as one dataset. However, it has to be noted that using this approach, the random intercept also caused the data of the direct/indirect-light experiment to be normalized with the data of the wall-luminance and desk-illuminance experiments. This is visible when comparing Figure 5.4 (corrected for random effects) to Figure 5.6 (uncorrected, showing the effect of the different studies); the slope of the change in brightness assessment with the log(median) of the luminance over the 60° horizontal band is similar for all three experiments, but there is an off-set between the wall-luminance and desk-illuminance experiments, on the one hand, and the direct/indirect-light experiment, on the other hand. An alternative route would have been to add 'experiment' as an independent variable to the LMM. However, as the intent of this study was to look across all three experiments, that route was discarded. Finally, although not further explored in this study, the employed statistical method would also allow for additional predictors to be added to the model. For instance, next to random intercepts, these could also include random slopes to represent individuals not using the full scale or providing more subtle responses. Although these nuances would likely increase the model fits and our knowledge on brightness perception, it would also reduce the general applicability as the outcome becomes highly dependent on individual differences.

5.4.2. Participant grouping

Based on the insight gained in the analysis of the direct/indirect-light experiment [152] that participants could be classified as brightness-responsive and brightness-indifferent, we evaluated the data from the other two experiments and found a similar division in participants. Where one group appeared to respond quite strongly with their brightness assessment to changes in the lighting, the other group appeared to be more indifferent and only showed minor variations in their brightness ratings. As we wanted to prevent that the outcome of the brightness-responsive group would become 'hidden' amongst the data of the brightness-indifferent group, we performed our initial model selection using only the participants who were labelled as brightness-responsive. The models best fitting this brightness-responsive group of participants still resulted in a reasonable fit for all participants, explaining approximately 50 % of variance in brightness perception for the whole group. The difference between the conditional and marginal R^2, however, does highlight that there is still a substantial part of variance explained by individual differences (approximately 30 %). This of course does not come as a surprise as already in the 70's, this effect was shown by Flynn et al. [37] indicating that individual differences played a key role in subjective assessments including brightness. There are, however, few, if any, studies to benchmark these findings against. However, keeping in mind that individual differences can play a large role, a marginal R^2-value of 0.38 for the brightness-responsive group and of 0.18 for the whole group of participants can be considered a substantial effect. At the same time, these R^2-values also indicate that additional characteristics, several of which perhaps not accounted for in the current analysis, play a role in brightness perception. This is also apparent from the spread of the residuals around the fitted regression lines in Figure 5.4 and Figure 5.6.

5.4.3. Level-based characteristics as a predictor for brightness

We tested several level-based characteristics, each providing either an indication of the central tendency (e.g., the mean and median characteristics) or indicating the extremes of the assessment area (such as its minimum or maximum value). The analyses showed that in line with the findings by Loe et al. [69] the logarithm of the mean luminance calculated over the 40° horizontal band performed quite well. However, the logarithm of the median, calculated over the 60° horizontal band performed slightly better (albeit marginally), indicating that the median might provide a slightly better overall description of the luminance level. Histograms of the raw luminance pixel values of the assessment areas used from our experiments showed a skewed distribution, which could explain why the median was a better indicator for describing the central tendency of the luminance than the (arithmetic) mean. Whether this is in general true for complex light scenes needs further investigation. Additionally, the fact that the 60° horizontal band outperformed the 40° horizontal band indicates that taking a slightly larger assessment area could be relevant. It has to be noted here that our three experiments used spaces of a similar size, and thus this conclusion would need to be verified using scenes with substantially different dimensions, preferably both less deep (to benchmark against the findings by Loe et al. [69]) but also deeper as the 40° and 60° horizontal bands would start to include the ceiling more with increasing space depth.

5.4.4. Ratio-based characteristics as a predictor for brightness

The fact that luminous intensity as described in the previous section predicts brightness is quite intuitive; that the uniformity of the luminous distribution would predict brightness equally well is rather unexpected considering it can be seen as independent of the absolute level. Still, according to our analyses, the log-L_{95}/median ratio provided a reasonably well indication of brightness as perceived in complex scenes and rendered similar levels of explained variance. This highlights that the perception of brightness does not only take into account the overall luminance over an area, but also reflects the uniformity of the luminance distribution. This, to some extent does seem to relate to the earlier work of for example Marsden [148] or in a slightly different context the work of Gilchrest et al. [159], who both suggested that the highest luminance in a scene serves as an 'anchor' for the brightness in the entire space. Next to this, in earlier research, Tiller and Veitch [113] also studied brightness in the context of uniformity, but concluded that a lower uniformity had a positive effect on brightness, whereas our data suggest the opposite. Although the overall context in the study of Tiller and Veitch [113] was similar to our wall-luminance and desk-illuminance setup (both used office spaces with recessed luminaires), the range of stimuli used by Tiller and Veitch was limited to either a more diffuse beam or a more tailored beam (resulting in visible scallops on the walls). Additionally, Tiller and Veitch did not quantify the level of uniformity they used, making it difficult to compare their results to ours. A study by Kato and Sekiguchi [160] investigated brightness of a single uniformly lit surface versus multiple equally and uniformly lit surfaces, such that they also indirectly tested uniformity over the field of view. In contrast to the study by Tiller and Veitch, which studied uniformity differences on an individual surface, the results of Kato and Sekiguchi are in line with our findings that a more uniformly lit field of view results in a higher perceived brightness.

Although the overall concept of describing brightness with a ratio-based characteristic of the luminance distribution does seem to have merit, it should be noted that determining this characteristic for a given scene is not without challenges. Our investigation into the sensitivity of this model to the selected percentile (used to determine the ratio) showed that although the 93rd and 95th percentile seemed to perform best, moving to either the 91st or 99th percentile caused a steep drop in model fit. As the 99th percentile is very close to the absolute maximum which shows a value much higher than the 95th percentile (see Table 5.2), it likely characterizes the luminaires instead of the space. The drop in fit of the log-Lxx/median model using the 93rd to the 91st percentile, however, was somewhat unexpected as Table 5.2 shows that the values of the L_{95} and L_{90} characteristics are relatively close together (albeit clearly different). Further investigation of the raw luminance conditions would be needed to further understand this phenomenon. An alternative approach which we also did not explore yet is to model non-linear relationships, which may be particularly relevant for ratio-based measures and might also partially explain inconsistencies in study findings.

5.4.5. Level or ratio-based?

In the previous sections we presented two (competing?) luminance distribution characteristics, both with a relatively high, comparable conditional R^2 fit with brightness ratings and a reasonable marginal R^2 fit (considering that luminance alone will never be able to predict brightness fully), but both with a different concept at its core. The level-based characteristic, the log-median, describes the central tendency of the luminance in a given assessment area whereas the ratio-based characteristic, the log-L_{95}/median, describes a contrast of the (close to) highest value to the central tendency of the luminance. Although it would be a logical step to combine these two characteristics in a single model, the fact that both characteristics employ the median and were found to be highly correlated (Pearson's r = -0.90) means that the value of a model using this combination would be very low. Instead, to investigate which of the two characteristics provides the most accurate prediction of brightness, additional experiments would be needed, in which the log-median and log-L_{95}/median are sufficiently different to avoid high correlation between the two parameters.

5.5. Conclusion

Using a set of clearly defined and documented experiments we showed that we were able to model the brightness rating of participants based on specific luminance characteristics of the different lighting conditions. We found that the logarithm of the median calculated over the 60° horizontal band performed quite well, closely in line with the findings of Loe et al. [69], but adding nuances in the sense that our results highlight the median as a better predictor for brightness in complex scenes than the mean, and the 60° horizontal band as a more representative area than the 40° horizontal band. Next to this, we found that the logarithm of the 95th percentile/median ratio calculated over the 40° horizontal band performed equally well.

Both models provided a pretty good estimation of brightness and seem to confirm and extend the results from other studies. The analyses do, however, suggest that more research is justified and that additional, to date unexplored parameters may also play a role in brightness perception. We should also note that the basis for the current findings has been purely empirical and, ideally, should align with more theoretical approaches: we should be modest enough to acknowledge that we are still quite far from fully understanding brightness perception in complex scenes.

CHAPTER 6

General discussion

Light is known to elicit psychological and physiological effects in building occupants, making it an important topic to consider in the quest for a 'great place to work'. The mechanisms behind these effects of light, however, are in many cases still insufficiently understood. In part this is due to the many overlaps and uncertainties in the full chain from lighting installation to light effect (see Figure 7). For example, a lighting installation in general illuminates multiple surfaces of a space, where the light reflected from these surfaces, reaching the eyes, is processed via the image forming (IF) and non-image forming (NIF) pathways from the eye to the brain/body, thus inducing multiple effects simultaneously. As such, a single lighting installation can result in a host of different effects, both psychological and physiological. This complexity highlights the need for a structured approach to unravel the effects of lighting on occupants. One such approach is to systematically vary the illumination of isolated room surfaces, while keeping that of others constant, in combination deploying a broad selection of dependent variables to capture potential effects, whether IF or NIF based.

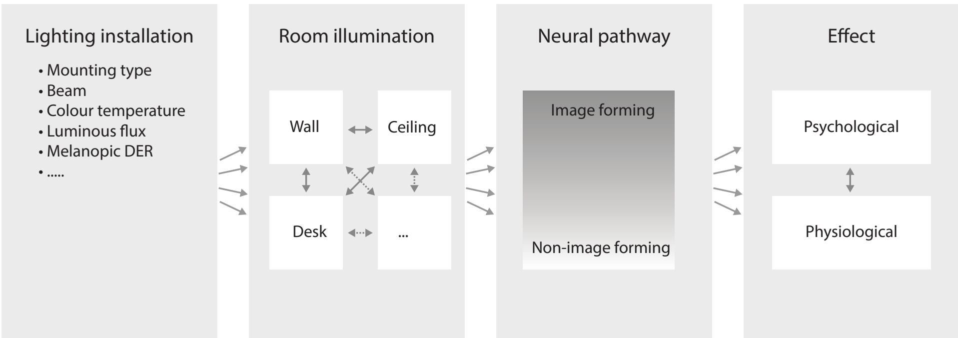

Figure 6.1: Schematic overview indicating all steps from lighting installation to effect – as introduced in Chapter 1

In a series of experiments, we studied the effect of changing the illumination of the wall, the desk/eye, or the ceiling (in Chapters 2, 3 and 4, respectively) on the room appraisal and performance by the participants. In Chapter 5 we performed a meta-analysis using the data from these three experiments to investigate the relationship between the luminance distribution and brightness ratings.

In the current chapter we reflect on the guiding principles of our studies and on the effects (and in some cases the lack thereof) of the lighting interventions. We compare the effects from the different surfaces, and discuss the interindividual differences. Lastly, we briefly look forward and provide directions for future work and share recommendations based on our findings.

6.1. Lighting research from an application perspective

Our application perspective considers the individual space elements (i.e. walls, ceiling, desk) as the surfaces to be manipulated, rather than specific light stimuli designed to activate individual neural pathways – something that is virtually impossible in a realistic setting. As the manipulated surfaces are always part of a larger (realistic) scene, it is the full scene that is ultimately experienced and evaluated by the occupant, which can also result in a diverse set of responses, including psychological and physiological effects. For example, even though our desk illumination manipulation had a clear effect on visual acuity, the illuminated desk is also part of the assessment of the total luminance distribution in the field of view, impacting the appearance and appraisal of the space. By applying this approach in a systematic manner (i.e., manipulating individual, clearly defined space elements, one at a time) it is not the lighting installation which is being evaluated, but the lit environment it can produce. In addition, as the example already highlights, this approach assumes that next to the hypothesized effects linked directly to the illumination of a particular surface, this surface is part of a larger context/scene that can also affect the occupant. Moreover, it tries to capture these effects by using a broad range of dependent variables. Finally, to capture meaningful responses with respect to the attractiveness and atmosphere of a space, it is important that the space looks and feels like a real office, which includes the lighting manipulations discussed earlier, but also a realistic décor and the presence of other occupants.

The application perspective, employed in a controlled setting as used in this thesis, has a lot of potential to uncover psychological and physiological effects as it covers both the effects of the primary stimulus, but also the effects of secondary stimuli caused by light reflected to and from different parts of an environment. As such, it adds knowledge that is often obscured in more fundamental/pure laboratory studies that are less realistic in setup (space size, interior layout, décor, tasks) and tend to be more invasive (chin rests, sensing equipment etc.). At the same time, the controlled mock-up office conditions limit the impact of external factors that one would encounter in (uncontrolled) field experiments.

The caveat of our application approach is that manipulating the (il)luminances of separate surfaces without manipulating that of the adjacent surfaces is essential to isolate the effects of these individual surfaces, but not without challenges. For example, increasing the desk illuminance will almost automatically increase the illuminance on the walls (and vice versa). Although isolating the effects of individual surfaces could be attempted through "extreme" separation (i.e. through the use of self-luminous surfaces such as used by Kirsch and Völker [161] and Kato and Sekiguchi [160] or through the use of projectors as also used by Kirsch and Völker [161]), a certain degree of realism is required to ensure meaningful responses of the occupants with respect to the appraisal and atmosphere of the space. Additionally, such specific/non-realistic installations would also hamper the translation of the research findings to practice. With this in mind, we opted for a more pragmatic approach and combined an installation to illuminate the wall, and one for the general lighting of the space with sufficient distance between the two to isolate the effects of the walls and desk, but close enough to create a coherent, realistic scene. Even though full separation was not possible, controlling the individual parts of the installation allowed us to limit cross-over effects between the different surfaces and installations. In the ceiling experiment (Chapter 4) the lighting installation itself was divided into a direct and indirect section, and as such was able to create a separation between the ceiling and the desk, but not the walls, which were influenced by the indirect component.

To summarize, our ‘controlled application approach’ focusses on realism of the environment, a broad characterization of the stimulus, but also a diverse set of responses that (real) environments can invoke in occupants. Additionally, it uses the lit environment as the main input, not the lighting installation, making translation to lighting designs more practical.

6.2. Effects of the lit environment on performance, emotional state, subjective alertness and room appraisal

What is a great place to work from a lighting perspective? That is the question that was posed at the start of this thesis, realizing that we would only be able to scratch the surface with regards to answering this question. Office duties are varied, and office spaces need to cater to many different types of companies, job roles (from administrative to consultancy to management), and different types of people (age, gender, cultural background, visual ability etc.). Office spaces, therefore, take on many different shapes and sizes. As covering all these different variations would be a life’s work of multiple researchers, we looked at the current trends and selected the open plan office as our domain of interest, with knowledge workers as the selected demographic. In addition, we were interested in the appraisal of the space due to its link with workplace experience which is considered an integral part of the ‘great place to work’ concept [26].

Starting with *task performance*, neither the wall luminance, nor the desk/eye illuminance variations used in our studies had a significant effect on problem-solving related task performance (divergent and convergent thinking), nor on the inhibitory control aspect of executive functioning (measured with the Stroop task in the first two experiments). As highlighted by the literature review of Lok et al. [32], there are several studies investigating the effect of daytime illuminance on executive functioning. Results are described as being mixed with roughly equal numbers of studies finding either a positive, a negative or a non-significant effect of higher daytime illuminance on executive functioning. Although our first two studies investigated two separate aspects of higher daytime illuminance (i.e., higher wall luminance and higher task/eye illuminance), neither found a significant result on the Stroop task, and as such they do not provide further clarity with respect to the mixed nature of the results found by Lok et al. [32].

Next to the executive functioning task, two problem solving tasks were evaluated, testing convergent and divergent thinking performance. These tasks are not often employed in the context of environmental variations. Instead, they are more commonly employed in studies where the primary manipulation target is the mental state or mood of a person, for example through meditation [162], intoxication [163] or focusing on emotionally loaded events [164]. In our case, mood was not targeted directly, but it was hypothesized that it would be influenced indirectly as a consequence of the changes in the lit environment. Although effects of the lit environment on mood were shown in retail studies [42,43], our studies did not find any such effect. As our studies focused on settings close to what one can encounter in actual offices, the differences in the lit environment may not have been sufficiently large to elicit clear shifts in mood, needed to influence divergent or convergent thinking. In future studies, this could be tested using more extreme manipulations of the lit environment. For instance, a substantial reduction in illuminance was shown by Steidle and Werth [25] to improve creative performance. It is, however, questionable whether such lighting manipulations would be suitable in the context of open plan offices as they likely reduce levels below requirements as set by the standards, and do not fit all tasks employed in open plan offices. Additionally, it is important to recognize that the physical environment (of which lighting is but one part) is only one of multiple aspects that are able to influence creativity. For example, Dul, Ceylan & Jaspers [8] found that although the physical work environment can (independently) affect creative performance, the social-organizational work environment and personality traits have a larger effect.

In contrast to the effects of the lit environment on task performance indicators, we did find effects on *subjective alertness*. Subjective assessments of alertness have been shown to correlate well with certain physiological measures of alertness such those derived from EEG measurements [165]. In our case, we found a sustaining effect of wall luminance on subjective alertness. Participants were able to maintain their subjective alertness over time in the high wall luminance condition whereas they became sleepier in the lower wall luminance conditions. In contrast, the desk/eye illuminance experiment only revealed a minor increase in sleepiness over the duration of the experiment in the low desk illuminance condition and did not show any effect at a high desk/eye illuminance. It has to be noted, however, that all three desk illuminance conditions were combined with a high wall luminance, which – as the wall luminance experiment showed – already resulted in a sustaining effect on subjective alertness. Additional research is needed to investigate if there is an interaction (or perhaps compound) effect of wall luminance with desk/eye illuminance on changes in subjective alertness over time. Regardless, the findings from our experiments are relevant in their own right to support creating the 'great place to work' as it highlights that the appearance of the space can have an impact on the alertness of participants, even when only considering short term effects.

The most distinct results we found overall were those on *room appraisal*, which was separated into three dimensions of which attractiveness and brightness were considered most important. Even though all three surface manipulations (i.e., wall, desk/eye, and ceiling illumination) resulted in increased brightness ratings for the room as a whole, only the manipulations on the wall and ceiling resulted in differences in room attractiveness, and showed a high correlation between the attractiveness and brightness ratings. This implies that for some specific (but not all) cases, there is a clear relationship between attractiveness and brightness. The next section will describe this relationship in more detail.

Finally, as with creativity, also here it is important to recognize that light is but one aspect in influencing both subjective alertness and the appearance of the space. In this case, the effect of light is more pronounced, but it is important for future work to consider the relation and perhaps dependency of the effects of lighting on for example the workplace design or the personal context.

6.3. Room appraisal: the effect of illuminating the wall, the desk and the ceiling

Room appearance can be assessed using many different methods, but most commonly the space is assessed with a set of words or word-pairs/semantic differentials describing different elements of appearance. In our case, we employed a concise set of 8 semantic differentials, derived by Veitch from the work of Flynn et al. [166] and Loe et al. [69]. These differentials were suggested to load on two factors: attractiveness and illumination. In the desk and ceiling studies, it was shown that the 'dim-bright' word-pair caused poor internal consistency in the illumination factor. As such, we considered this word pair as an individual factor, labeled brightness, with the remaining items of the illumination factor relabeled to 'radiant-distinct'. Interestingly, this issue did not occur when assessing the wall luminance manipulation.

Starting with room *brightness* we found that both increasing the wall luminance and increasing the ceiling luminance resulted in an increase in brightness when desk illuminance was fixed. When varying desk illuminance (under constant, high wall luminance), the brightness rating of the lowest desk/eye illuminance was already comparable to that of the high wall luminance condition from the first experiment (likely due to the same high wall luminance being used) and increased even more with increasing desk illuminance. This implies that all major surfaces in the field of view have the potential to increase brightness, even to a comparable extent, since the realized brightness differences between the low and high settings in each experiment (i.e., manipulating the wall, desk, or ceiling) resulted in comparable and sizable differences in assessed brightness (maximum difference in EMM Δ between 0.23-0.28). This comparison is complex, however, since it is known that participants use numerical scales in a relative rather than absolute way, which limits the value of comparing scales across experiments. In addition, the question is whether these brightness effects add up when all three manipulations would be combined.

To get a first impression on the latter question, we can use the results of the meta-analysis. This analysis showed that the 40° or 60 ° horizontal band provided the best fit. In contrast to the larger circular assessment areas, the horizontal bands are dominated by the walls, and although the desk and ceiling are a part of these bands, they only cover a small part of the bands. It should also be noted that depending on the room dimensions and the seating position within that room, the areas covered by the ceiling and desk differ. Indeed, with large distances between an observer and the wall in front of them, the ceiling will occupy a larger portion of the 60° horizontal band used by that observer to assess brightness compared to cases where the observer is closer to the wall. But, with the luminance of the walls playing a dominant role in the area used to assess brightness it is unlikely that simply adding brightness components of wall, ceiling and desk gives a realistic overall brightness estimation.

In addition to luminance per se, it was also shown that the luminance distribution over the different surfaces mattered. In the meta-analysis, different ratio-based measures were tested and it was found that the logarithm of the ratio of the 95th percentile (L_{95}) to the median (calculated over the 40° horizontal band) resulted in a high prediction accuracy. In this model, a higher uniformity (i.e. L_{95} and median being closer together) resulted in a higher brightness. This finding has several interesting aspects to consider. The first is that according to this finding, illuminating the wall or ceiling to increase brightness should be done in tandem with an increase of the median of the 40°-60° horizontal band assessment area. Illuminating a certain surface will mainly increase the L_{95}, while the median will likely increase as well, but to a lesser extent, again emphasizing the importance of taking the full space into account when optimizing brightness. Second, as this is a ratio-based luminance characteristic it implies an independence of the absolute level. Even though this was shown in our data set to result in a high predictive value, it is less likely that this can be generalized as a standalone measure considering existing literature/theories such as those described in Section 5.1. For example, the model presented by Marsden [148] does include the ratio between the assessed surface and its background, but as a basis uses the absolute luminance of that surface. Along the same lines, Hopkinson's adaptation-based method (as illustrated by Waldram [150]) assumes a certain adaptation level based on the full field of view, which in turn determines the brightness assessment of the observed luminance in a specific area of the field of view. Based on our findings and previous literature on the impact of uniformity on brightness perception we hypothesize that a combination of a level-based measure (such as the log median) with a ratio-based measure (such as the log L_{95}/median) will provide a more robust method to assess brightness. However, the current data set was not suitable to investigate this combination as the underlying experiments were not set up to vary the absolute level and the ratio independently from each other, resulting in a high correlation between the two. Future studies into this combination, using distinctly different absolute levels and ratios would be needed to provide more insights. In addition, as already discussed in Section 5.4 it is important to realize that the absolute luminance values only provide a part of the solution as also elements such as material properties, spaciousness and light spectrum play a role in brightness assessment.

In contrast to brightness, *attractiveness* showed a more nuanced outcome with respect to the effects of the different surfaces and their luminance distributions. Increases in either wall or ceiling illuminance resulted in increases in attractiveness, but this was not true for increases in desk illuminance. This seems to follow the long history of studies into the impact of light on vertical surfaces on room appraisal such as the work by Waldram [40], Flynn [37], Shepherd et al. [41] and many others. In addition, varying the distribution of the ceiling illumination also resulted in changes in attractiveness, with a more uniform distribution being rated as more attractive. These results seem to imply that brightness and attractiveness are not directly related, although we found relatively high positive correlations between the two in the wall luminance and ceiling illuminance experiments. To better understand this, further investigation is needed to unravel how both brightness and attractiveness are affected by the exact light distribution in an office space.

Finally, to put these results in context, it is important to acknowledge that although a varied set of stimuli was used, the spaces still all resembled open plan offices of a specific size, with lighting interventions that can be described as common to office spaces. As such, range and solution space bias may have occurred. Although on the one hand this is a strength of this study as it makes the outcome highly applicable to a very common type of spaces and lighting installations, it may also be considered as a weakness since our findings are not necessarily generalizable to different office spaces or lighting conditions. To apply these findings outside our solution space, verification in other settings will be needed. Still, placing our results in the context of earlier studies, such as the one from Loe et al. [69] or van Ooyen et al. [70], our findings are consistent with theirs, but provide further refinement to existing theories on the use of luminance in brightness predictions and allow for a better assessment of brightness and attractiveness for open plan offices.

6.4. Interindividual differences

Triggered by the observation that a substantial number of participants in the ceiling illuminance experiment appeared to score consistently high on all measures, we analyzed the difference between participants to identify to what extent people differed in their assessments. This analysis showed that the group of participants (n = 32) could be divided in two sub-groups: one that was responsive to luminance variations with a clear preference for bright environments, and a second one that was more indifferent to the luminance variations we applied and appeared to be less appreciative of bright environments. After reanalyzing the data from the wall luminance and desk/eye illuminance experiments, similar (yet less evenly distributed) sub-groups were found in those studies. Explicitly considering the two sub-groups showed an increase in accuracy for predicting brightness from the luminance distribution in the room.

Interindividual differences are known to have an impact on appearance assessments (as already indicated by Flynn et al. in 1973 [37]). When modeling appearance in terms of brightness or luminance distribution this is typically corrected for by adding a random intercept in the model (in case of within-subject designs). However, this only corrects for the absolute level of the rating, not for the rate of change (i.e., the slope of the model). Because the differences between the two sub-groups were mainly related to their responsiveness to brightness, analyzing these two sub-groups separately introduced differences in slope when modeling appearance or brightness. A more extreme approach would consider to add a random slope for all participants. Although this most probably would result in a better fit in the various models, it might reduce the general applicability of the models in lighting design. Moreover, the two groups were quite distinct and portraying both groups separately provided quite insightful images which would have been less the case if we had accounted for them in individual random slopes. Unfortunately, even though we were able to consistently identify two sub-groups, our data was not suited to provide information on the underlying characteristics of these two sub-groups determining whether a person was 'brightness responsive' or 'brightness indifferent'. This could be based on external or unrecorded personal characteristics. For example, it was unknown how our office setup and lighting manipulations compared to participants' regular place of work, while that might have evoked different responses in terms of whether our experimental office was considered bright or dim. As such, performing qualitative pre- and post-study interviews would be a good addition to future experiment to unearth the underlying characteristics of these two sub-groups.

6.5. Looking forward (implications for research)

The above reflections on the results highlight several topics that need attention from both a research and design perspective. First and foremost, there is a dire need for an integrative approach when considering all possible lighting effects, especially in realistic installations. The wall luminance experiment, for example, highlighted that next to the neuroscience driven notion that an increase in eye exposure may result in an increase in alertness via NIF pathways, also the appearance of the space plays a role in maintaining subjective alertness. This highlights that for future studies it is essential to carefully characterize the spaces used for testing, and to deploy a wide array of dependent variables, recognizing the complexity of the human responses to light.

In addition, not only fundamental research, but also application-based research is needed to further investigate mechanisms that govern the effect of light on humans, such as for example the effect of light on our subjective alertness. Such studies should identify the different triggers that influence subjective alertness and the context in which changes in alertness can occur (e.g., the psychological and physiological condition of the participant prior to being exposed). Next to this, although there is a general belief that improving alertness is positive, more evidence needs to be gathered on the practical relevance of increasing subjective alertness in working environments, especially as the link between subjective alertness and task performance has yet to be consistently demonstrated.

Since brightness is an important characteristic for the subjective assessment of an illuminated environment such as its attractiveness and atmosphere, it is relevant not only for the office context, but also for other applications such as retail, healthcare, education and even in industrial settings. Although our research found a clear link between characteristics of the luminance distribution and assessment area on the one side and brightness on the other, and confirmed and refined the findings of other researchers, it followed a purely empirical approach with known limitations. As this approach can be influenced by range and lighting solution bias, studying this relationship from a theoretical perspective would support the validity of our findings, but would also provide better underpinning for the type of luminous distribution that would work best to support the 'great place to work'.

Last, but not least, is the need to further understand and act upon interindividual differences. In order to support diversity and inclusivity in the workplace it is essential to understand the key characteristics of groups or individuals, which determine their needs for a specific environment. This includes investigating the underlying characteristics of the two subgroups that we identified in our research. In addition to the interindividual differences in brightness perception discussed in the current thesis, Kompier et al. [167] recently reported similarly substantial interindividual variance in visual comfort in response to transitions in illuminance: where transitions to a higher illuminance were considered more comfortable by some, the reverse was found for others. Moreover, such responses appeared to be quite stable for individual participants. Is interindividual variance in visual comfort, brightness perception and perceived attractiveness the result of differences in vision, in preference or in reference? An answer to this question will enable designers and employers to cater better to the needs of their employees. In addition, understanding how we can deal with multiple subgroups, and thus multiple preferences, in the same space is an important topic for further study. Although some work on this has already been done by amongst others Chraibi et al. [168]

who looked at consensus based controls to account for interindividual differences, still much is unknown, especially in light of the (unknown) characteristics of the different subgroups.

6.6. Conclusions and recommendations for lighting practice

This dissertation was given an ambitious title 'lighting up the great place to work'. The question now is, can we, based on our findings, provide recommendations that warrant this title? The open plan office, which was chosen as a subzone of offices in general, is an area in which knowledge workers spend a large part of their time, and thus it should have a beneficial effect on workplace experience and performance. As a basis, the visual performance of course needs to be catered for with a sufficient level of task illuminance. Next to this, our experiments clearly indicate that, considering short term effects, the workplace appearance, as influenced by lighting the walls and ceiling can play in a role in both workplace experience (i.e., in terms of brightness, attractiveness, atmosphere) and via alertness may impact performance as well. Illuminating individual surfaces such as the walls to an average of at least 100 cd/m^2, or using a large indirect component (>70 % of flux from the indirect component) with a uniform ceiling distribution will already greatly improve the workplace from an occupant perspective. However, the best effects will be achieved when considering the most important assessment areas (e.g., the 60° horizontal band) as a whole. This includes designing for the absolute level to improve brightness, but also limiting the differences within this assessment area will support an increased perceived brightness. In practice, as larger open plan offices have many different seating positions, with different viewing directions, adding/overlaying all these 60° horizontal bands likely results in coverage of the full space. This means that in open plan offices, it is important to at least assess/illuminate the full ceiling and all walls to cover the upper half of the visual field. For the lower half of the visual field, there are often other visual obstructions (such as desk dividers or cupboards) which play a large role and as such should also be considered as part of the visual field.

Although we mainly describe short term effects in our recommendations, these can also lead to long term effects. These can range from an increase in engagement through an improved workplace satisfaction, to the workplace experience being a great motivator to go back to the office after the many 'lock-down' periods related to the current COVID-19 pandemic. Finally, although not a part of this research, we of course also need to design for long-term effects such as ensuring proper circadian entrainment. However, maybe one of the most important findings from our research is that the resulting design should always look beyond the intended manipulation (often based on visual performance and physiological effects) and also consider possible ‘side effects’ such as the psychological effects. As these side effects have the potential to overpower the intended effects, considering them from the start will aid in designing the great place to work.

To conclude, lighting can definitely contribute to creating the great place to work, but can only do so by taking a holistic and integrative approach, to cover both the psychological and physiological effects that light can have, in both the long and short term.

6

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Appendices

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Appendices

Appendices

Appendix 1: Supplemental materials - Lighting up the office (Chapter 2)

- Alpha-opic Equivalent Daylight illuminance values and Spectra
- Detailed space characterization
- Dependent variable correlation matrices per condition
- Full result table, Linear mixed models

Appendix 2: Supplemental materials - Teasing apart office illumination (Chapter 3)

- Alpha-opic Equivalent Daylight illuminance values and Spectra
- Full result table, Linear Mixed Models

Appendix 3: Supplemental materials - Putting the ceiling center stage (Chapter 4)

- Lighting condition characterization – illuminance
- Alpha-opic Equivalent Daylight illuminance values and Spectra
- Lighting condition characterization – luminance
- Result table, random effects significance
- Pearson correlation distribution per DV pairs
- Full results table, Linear Mixed Models (Ratio * Distribution * Group)
- Overview of results per dependent variable including post-hoc comparisons

Appendix 4: Supplemental materials - From luminance to brightness (Chapter 5)

- Brightness data histograms
- Range indication for luminance characteristic per assessment area for each experiment
- Model fit overviews per luminance characteristic

Appendix 1: Supplemental materials - Lighting up the office (Chapter 2)

Table A1-1 Alpha-opic Equivalent Daylight Illuminances according to CIE s 026:2018

Wall luminance	Equivalent Daylight Illuminance - eye [lx] *				
	S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
Low	88	176	207	132	116
Medium	107	195	227	145	127
High	127	218	253	162	142

* Averaged over 4 desk seating positions, measured at eye height (1.2 m) facing forward

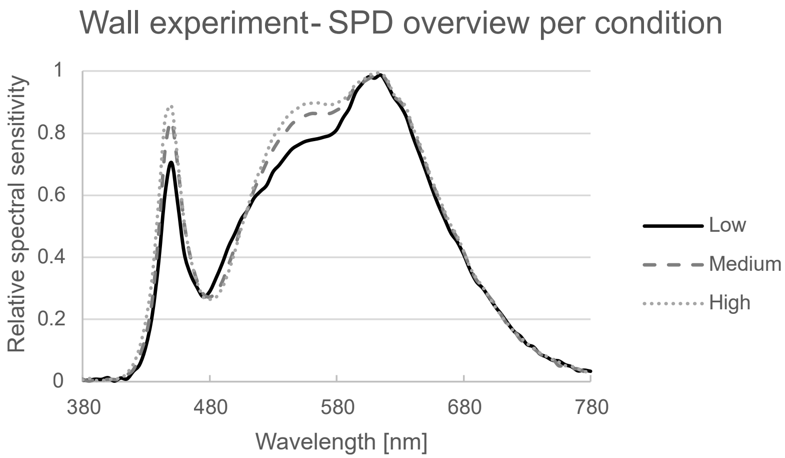

Figure A1-1 Spectral power distribution (relative) per lighting condition as measured on single observer position.

Table A1-2 Characterization of space based on physical space elements and 40° horizontal band. Mean and SD values over 4 desk positions, measured using luminance camera at eye height (1.2m) at each seating position facing forward (0° tilt).

Wall luminance condition		Low luminance		Medium luminance		High luminance	
		Mean	(SD)	Mean	(SD)	Mean	(SD)
Back wall	cd/m2	13.0	(0.1)	47.1	(0.6)	99.7	(1.3)
Ceiling - luminaires excluded	cd/m2	20.3	(0.4)	26.6	(0.5)	35.9	(0.4)
Ceiling - luminaires included	cd/m2	178.6	(14.5)	183.2	(11.5)	179.4	(13.7)
Desk	cd/m2	81.1	(1.9)	83.1	(1.9)	83.5	(1.6)
40° horizontal band	cd/m2	25.6	(0.7)	34.4	(0.9)	47.6	(0.9)

Table A1-3 Low wall luminance condition Pearson's correlation matrix. Holm corrected; raw probabilities are reported below the diagonal and correlations adjusted for multiple comparisons above the diagonal (* $p < 0.05$, ** $p < 0.01$).

	RA Attr1	RA Attr2	RA Illum2	RA Illum2	PAD P1	PAD P2	PAD A1	PAD A2	PAD D1	PAD D2	ED	KSS1	KSS2	MEQ	Stroop NC	RAT	AUT
RA Attr1	--	0.89**	0.79**	0.78**	0.03	0.13	0.29	0.48	0.01	0.10	-0.11	-0.28	-0.18	-0.16	0.20	0.09	-0.48
RA Attr2	0.89**	--	0.67**	0.72**	0.15	0.29	0.19	0.55	0.06	0.26	-0.33	-0.28	-0.42	-0.15	0.12	0.03	-0.30
RA Illum1	0.79**	0.67**	--	0.90**	0.08	0.13	0.27	0.45	0.06	0.09	-0.08	-0.17	-0.11	-0.11	0.06	0.25	-0.39
RA Illum2	0.78**	0.72**	0.90**	--	0.11	0.26	0.30	0.57*	0.09	0.20	-0.23	0.00	-0.20	-0.17	-0.05	0.31	-0.26
PAD P1	0.03	0.15	0.08	0.11	--	0.69**	0.13	0.30	0.56*	0.59*	-0.50	-0.24	-0.38	0.21	-0.21	0.22	0.19
PAD P2	0.13	0.29	0.13	0.26	0.69**	--	0.19	0.53	0.30	0.61**	-0.75**	-0.04	-0.56*	0.37	-0.20	0.31	0.25
PAD A1	0.29	0.19	0.27	0.30	0.13	0.19	--	0.31	0.10	0.07	-0.14	-0.33	-0.17	0.20	-0.03	0.16	-0.23
PAD A2	0.48**	0.55**	0.45**	0.57**	0.30	0.53**	0.31	--	-0.04	0.23	-0.50	-0.15	-0.64**	0.14	-0.08	0.32	0.18
PAD D1	0.01	0.06	0.06	0.09	0.56**	0.30	0.10	-0.04	--	0.54	-0.19	-0.04	-0.04	-0.15	-0.04	0.06	-0.14
PAD D2	0.10	0.26	0.09	0.20	0.59**	0.61**	0.07	0.23	0.54**	--	-0.59*	0.00	-0.38	-0.01	-0.33	0.32	0.04
ED	-0.11	-0.33*	-0.08	-0.23	-0.50**	-0.75**	-0.14	-0.50**	-0.19	-0.59**	--	0.10	0.67**	-0.35	0.34	-0.40	-0.43
KSS1	-0.28	-0.28	-0.17	0.00	-0.24	-0.04	-0.33*	-0.15	-0.04	0.00	0.10	--	0.37	-0.22	-0.18	0.17	0.15
KSS2	-0.18	-0.42**	-0.11	-0.20	-0.38*	-0.56**	-0.17	-0.64**	-0.04	-0.38*	0.67**	0.37*	--	-0.43	0.23	-0.10	-0.35
MEQ	-0.16	-0.15	-0.11	-0.17	0.21	0.37*	0.20	0.14	-0.15	-0.01	-0.35*	-0.22	-0.43**	--	-0.08	-0.08	0.32
Stroop NC	0.20	0.12	0.06	-0.05	-0.21	-0.20	-0.03	-0.08	-0.04	-0.33	0.34*	-0.18	0.23	-0.08	--	-0.22	-0.44
RAT	0.09	0.03	0.25	0.31	0.22	0.31	0.16	0.32	0.06	0.32	-0.40*	0.17	-0.10	-0.08	-0.22	--	0.21
AUT	-0.48**	-0.30	-0.39*	-0.26	0.19	0.25	-0.23	0.18	-0.14	0.04	-0.43**	0.15	-0.35*	0.32	-0.44**	0.21	--

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Table A1-4 Medium wall luminance condition Pearson's correlation matrix. Holm corrected; raw probabilities are reported below the diagonal and correlations adjusted for multiple comparisons above the diagonal (* $p < 0.05$, ** $p < 0.01$).

	RA Attr1	RA Attr2	RA Illum2	RA Illum2	PAD P1	PAD P2	PAD A1	PAD A2	PAD D1	PAD D2	ED	KSS1	KSS2	MEQ	Stroop NC	RAT	AUT
RA Attr1	--	0.88**	0.66**	0.61**	0.05	0.15	0.22	0.00	0.13	0.03	0.16	-0.12	0.24	-0.28	-0.16	-0.19	-0.28
RA Attr2	0.88**	--	0.68**	0.69**	0.10	0.28	0.16	0.11	0.10	0.13	0.14	-0.04	0.19	-0.27	-0.17	-0.19	-0.40
RA Illum1	0.66**	0.68**	--	0.83**	0.34	0.24	0.16	0.05	0.25	0.17	0.24	-0.08	0.17	-0.22	-0.02	-0.34	-0.24
RA Illum2	0.61**	0.69**	0.83**	--	0.32	0.21	0.37	0.08	0.25	0.02	0.05	-0.20	0.06	-0.09	0.04	-0.41	-0.38
PAD P1	0.05	0.10	0.34*	0.32	--	0.70**	0.19	0.00	0.50	0.31	-0.15	-0.22	-0.08	0.32	-0.09	0.00	-0.02
PAD P2	0.15	0.28	0.24	0.21	0.70**	--	0.23	0.22	0.35	0.44	-0.29	-0.14	-0.14	0.25	-0.24	-0.04	0.15
PAD A1	0.22	0.16	0.16	0.37*	0.19	0.23	--	0.24	0.15	0.16	-0.31	-0.48	-0.25	0.26	-0.06	-0.20	-0.08
PAD A2	0.00	0.11	0.05	0.08	0.00	0.22	0.24	--	-0.18	0.36	-0.63**	-0.38	-0.73**	0.24	-0.32	-0.14	0.37
PAD D1	0.13	0.10	0.25	0.25	0.50**	0.35*	0.15	-0.18	--	0.46	-0.10	0.11	0.04	-0.07	-0.22	0.24	0.10
PAD D2	0.03	0.13	0.17	0.02	0.31	0.44**	0.16	0.36*	0.46**	--	-0.24	-0.10	-0.29	0.02	-0.53	0.18	0.36
ED	0.16	0.14	0.24	0.05	-0.15	-0.29	-0.31	-0.63**	-0.10	-0.24	--	0.43	0.72**	-0.56*	0.13	-0.05	-0.41
KSS1	-0.12	-0.04	-0.08	-0.20	-0.22	-0.14	-0.48**	-0.38*	0.11	-0.10	0.43**	--	0.49	-0.37	0.03	0.31	-0.09
KSS2	0.24	0.19	0.17	0.06	-0.08	-0.14	-0.25	-0.73**	0.04	-0.29	0.72**	0.49**	--	-0.51	0.17	-0.01	-0.35
MEQ	-0.28	-0.27	-0.22	-0.09	0.32	0.25	0.26	0.24	-0.07	0.02	-0.56**	-0.37*	-0.51**	--	0.13	-0.04	0.16
Stroop NC	-0.16	-0.17	-0.02	0.04	-0.09	-0.24	-0.06	-0.32	-0.22	-0.53**	0.13	0.03	0.17	0.13	--	-0.32	-0.50
RAT	-0.19	-0.19	-0.34*	-0.41*	0.00	-0.04	-0.20	-0.14	0.24	0.18	-0.05	0.31	-0.01	-0.04	-0.32	--	0.33
AUT	-0.28	-0.40*	-0.24	-0.38*	-0.02	0.15	-0.08	0.37*	0.10	0.36*	-0.41*	-0.09	-0.35*	0.16	-0.50**	0.33*	--

Table A1-5 High wall luminance condition Pearson's correlation matrix. Holm corrected; raw probabilities are reported below the diagonal and correlations adjusted for multiple comparisons above the diagonal (* $p < 0.05$, ** $p < 0.01$).

	RA Attr1	RA Attr2	RA Illum2	RA Illum2	PAD P1	PAD P2	PAD A1	PAD A2	PAD D1	PAD D2	ED	KSS1	KSS2	MEQ	Stroop NC	RAT	AUT
RA Attr1	--	0,88**	0,75**	0,75**	0,15	-0,09	0,02	0,06	0,00	0,00	0,09	0,00	0,06	-0,07	0,06	-0,20	-0,17
RA Attr2	0,88**	--	0,58**	0,75**	0,03	0,04	0,02	0,05	0,07	0,18	0,06	0,08	0,00	-0,09	-0,02	-0,23	-0,10
RA Illum1	0,75**	0,58**	--	0,77**	0,08	-0,22	-0,07	0,10	-0,12	-0,22	0,10	0,12	0,24	0,00	0,13	-0,11	-0,16
RA Illum2	0,75**	0,75**	0,77**	--	0,07	-0,06	-0,03	0,23	-0,10	0,03	0,10	0,01	0,06	-0,12	0,04	-0,19	-0,09
PAD P1	0,15	0,03	0,08	0,07	--	0,57*	0,37	0,44	0,55	0,43	-0,29	-0,42	-0,41	0,15	-0,20	0,21	0,23
PAD P2	-0,09	0,04	-0,22	-0,06	0,57**	--	0,35	0,48	0,47	0,55*	-0,61**	-0,23	-0,56*	0,27	-0,30	0,07	0,46
PAD A1	0,02	0,02	-0,07	-0,03	0,37*	0,35*	--	0,26	0,22	0,15	-0,41	-0,61**	-0,40	0,36	0,01	-0,01	0,21
PAD A2	0,06	0,05	0,10	0,23	0,44**	0,48**	0,26	--	0,20	0,25	-0,52	-0,20	-0,68**	0,10	-0,31	0,24	0,34
PAD D1	0,00	0,07	-0,12	-0,10	0,55**	0,47**	0,22	0,20	--	0,74**	-0,15	-0,11	-0,26	-0,03	-0,36	0,09	0,38
PAD D2	0,00	0,18	-0,22	0,03	0,43**	0,55**	0,15	0,25	0,74**	--	-0,28	-0,16	-0,31	-0,02	-0,39	0,16	0,39
ED	0,09	0,06	0,10	0,10	-0,29	-0,61**	-0,41*	-0,52**	-0,15	-0,28	--	0,10	0,58*	-0,28	0,25	-0,24	-0,49
KSS1	0,00	0,08	0,12	0,01	-0,42**	-0,23	-0,61**	-0,20	-0,11	-0,16	0,10	--	0,32	-0,05	-0,12	-0,09	-0,03
KSS2	0,06	0,00	0,24	0,06	-0,41*	-0,56**	-0,40*	-0,68**	-0,26	-0,31	0,58**	0,32	--	-0,12	0,27	-0,04	-0,22
MEQ	-0,07	-0,09	0,00	-0,12	0,15	0,27	0,36*	0,10	-0,03	-0,02	-0,28	-0,05	-0,12	--	-0,02	-0,13	0,16
Stroop NC	0,06	-0,02	0,13	0,04	-0,20	-0,30	0,01	-0,31	-0,36*	-0,39*	0,25	-0,12	0,27	-0,02	--	-0,30	-0,44
RAT	-0,20	-0,23	-0,11	-0,19	0,21	0,07	-0,01	0,24	0,09	0,16	-0,24	-0,09	-0,04	-0,13	-0,30	--	0,18
AUT	-0,17	-0,10	-0,16	-0,09	0,23	0,46**	0,21	0,34*	0,38*	0,39*	-0,49**	-0,03	-0,22	0,16	-0,44**	0,18	--

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Table A1-6 Result overview Linear Mixed Models

			F	*df*	*p*
Room Appraisal - Attractiveness	RA-Attr	Wall Luminance	46,73	(2,180)	**< 0,001**
		Time	0,21	(1,180)	0,65
		Wall Luminance * Time	0,06	(2,180)	0,95
Room Appraisal - Illumination	RA-Illum	Wall Luminance	95,5	(2,180)	**< 0,001**
		Time	0,03	(1,180)	0,88
		Wall Luminance * Time	0,65	(2,180)	0,52
Emotional State - Pleasure	PAD P	Wall Luminance	1,53	(2,180)	0,22
		Time	21,42	(1,180)	**< 0,001**
		Wall Luminance * Time	1,06	(2,180)	0,35
Emotional State - Arousal	PAD A	Wall Luminance	2,62	(2,180)	0,08
		Time	2,52	(1,180)	0,12
		Wall Luminance * Time	0,75	(2,180)	0,47
Emotional State - Dominance	PAD D	Wall Luminance	0,63	(2,180)	0,53
		Time	7,81	(1,180)	**0,006**
		Wall Luminance * Time	0,62	(2,180)	0,54
Subjective alertness	KSS	Wall Luminance	6,58	(2,180)	**0,002**
		Time	3,45	(1,180)	0,07
		Wall Luminance * Time	4,09	(2,180)	**0,02**
Subjective alertness 2	KSS 2	Wall Luminance	5,60	(2,72)	**0,006**
		PAD-A2	94,65	(1,106)	**< 0,001**
Ego depletion	ED	Wall Luminance	0,82	(2,73)	0,45
		KSS 2	75,00	(1,104)	**< 0,001**
Alternate uses task – flexibility score	AUT	Wall Luminance	0,37	(2,70)	0,69
Remote Associate Task	RAT	Wall Luminance	0,04	(2,72)	0,96
Stroop - Reaction Time [(1)]	RT congruent	Wall Luminance	0,11	(2,70)	1,00
	RT non-congruent	Wall Luminance	2,71	(2,70)	0,37
	RT delta	Wall Luminance	0,13	(2,70)	1,00
Stroop - Errors [(1)]	Errors congruent	Wall Luminance	0,13	(2,70)	1,00
	Errors non-congruent	Wall Luminance	1,23	(2,70)	1,00

[(1)] All stroop p-values corrected for multiple comparisons using Holm correction

Appendix 2: Supplemental materials - Teasing apart office illumination (Chapter 3)

Table A2-1 Alpha-opic Equivalent Daylight Illuminances according to CIE s 026:2018

Desk illuminance	Equivalent Daylight Illuminance - eye [lx] *				
	S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
Low	61	101	117	75	66
Medium	146	250	291	186	163
High	374	681	795	506	442

* Averaged over 4 desk seating positions, measured at eye height (1.2 m) facing forward

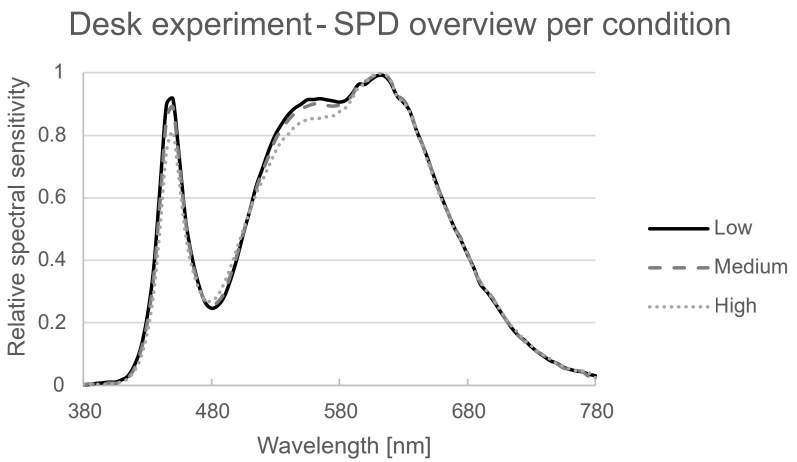

Figure A2-1 Spectral power distribution (relative) per lighting condition as measured on single observer position.

Table A2-2 Full result table, Linear Mixed Models

		df	*F*	*p*
Room appraisal - Attractiveness	Desk Illuminance	(2, 70)	0,61	0,548
	Time	(1, 105)	9,19	0,003
	Desk Illuminance * Time	(2, 105)	0,68	0,509
Room appraisal - Distinctiveness/Radiance	Desk Illuminance	(2, 70)	2,45	0,093
	Time	(1, 105)	2,55	0,112
	Desk Illuminance * Time	(2, 105)	0,26	0,771
Room appraisal - Brightness	Desk Illuminance	(2, 70)	30,07	3,75E-10
	Time	(1, 105)	7,73	0,006
	Desk Illuminance * Time	(2, 105)	0,87	0,424
Emotional state - Pleasure	Desk Illuminance	(2, 70)	1,03	0,361
	Time	(1, 105)	44,13	1,39E-09
	Desk Illuminance * Time	(2, 105)	0,13	0,876
Emotional state - Arousal	Desk Illuminance	(2, 70)	0,75	0,476
	Time	(1, 105)	0,09	0,762
	Desk Illuminance * Time	(2, 105)	2,00	0,140
Emotional state - Dominance	Desk Illuminance	(2, 70)	0,78	0,46
	Time	(1, 105)	20,80	1,38E-05
	Desk Illuminance * Time	(2, 105)	0,73	0,484
Subjective alertness - KSS	Desk Illuminance	(2, 70)	0,69	0,507
	Time	(1, 105)	7,35	0,008
	Desk Illuminance * Time	(2, 105)	0,27	0,766
Ego depletion	Desk Illuminance	(2, 70)	1,11	0,334
Alternate Uses Task - Flexibility	Desk Illuminance	(2, 70)	0,16	0,855
Remote Associates task	Desk Illuminance	(2, 70)	0,84	0,435
Stroop - Congruent RT	Desk Illuminance	(2, 70)	1,16	0,319
Stroop - Non-congruent RT	Desk Illuminance	(2, 70)	0,05	0,947
Stroop - RT Delta	Desk Illuminance	(2, 70)	1,82	0,170
Stroop - Total errors	Desk Illuminance	(2, 70)	1,61	0,208

Navon - Congruent RT (inv.)	Desk Illuminance	(2, 70)	0,23	0,794
Navon - Non-congruent RT (inv.)	Desk Illuminance	(2, 70)	0,12	0,890
Navon - RT Delta (inv.)	Desk Illuminance	(2, 70)	1,35	0,266
Navon - Total errors	Desk Illuminance	(2, 70)	0,48	0,621
Visual acuity - paper	Desk Illuminance	(2, 70)	13,18	1,38E-05
Visual acuity - screen	Desk Illuminance	(2, 385)	0,04	0,96
	Size (of Optotype)	(1, 18092)	2068	2,00E-16
	Opacity (of Optotype)	(1, 18092)	2001	2,00E-16
	Desk Illuminance * Size	(2, 18092)	0,54	0,583
	Desk Illuminance * Opacity	(2, 18092)	0,22	0,801
	Size * Opacity	(1, 18092)	491,9	2,00E-16
	Desk Ill. * Size * Opacity	(2, 18092)	0,09	0,908

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Appendix 3: Supplemental materials - Putting the ceiling center stage (Chapter 4)

Table A3-1 Characterization of lighting conditions – Illuminance; mean and SD values represent the mean and SD across the 4 desks.

Setting #		1	2	3	4	5	6	7	8	9	10	11	12	13
Flux Down [%]		**100**	**70**	**50**	**30**	**0**	**70**	**50**	**30**	**0**	**70**	**50**	**30**	**0**
Flux Up [%]		**0**	**30**	**50**	**70**	**100**	**30**	**50**	**70**	**100**	**30**	**50**	**70**	**100**
Distribution indirect		**--**	**Uniform**	**Uniform**	**Uniform**	**Uniform**	**Non Uniform**	**Non Uniform**	**Non Uniform**	**Non Uniform**	**Mixed**	**Mixed**	**Mixed**	**Mixed**
Horizontal illuminance [lx]	mean	763	759	760	760	772	754	757	766	783	757	768	759	784
	SD	17	16	17	18	21	17	18	19	23	17	18	18	22
Vertical illuminance [lx]	mean	447	458	472	488	528	457	472	494	539	459	478	488	538
	SD	5	5	6	7	10	6	8	10	15	6	7	9	13
Ratio ver/hor		59 %	60 %	62 %	64 %	68 %	61 %	62 %	64 %	69 %	61 %	62 %	64 %	69 %
Mel-DER* eye	mean	0,596	0,592	0,590	0,586	0,581	0,590	0,587	0,582	0,574	0,591	0,588	0,584	0,577
	SD	0,003	0,002	0,002	0,001	0,001	0,002	0,002	0,001	0,001	0,002	0,002	0,001	0,001
Mel-EDI [lx]**	mean	266	272	279	286	306	270	277	287	309	271	281	285	310

*Mel-DER = Melanopic Daylight (D65) Efficacy Ratio (according to CIE S 026:2018)
**Mel-EDI = Melanopic Equivalent Daylight (D65) Illuminance (according to CIE s 026:2018)

Table A3-2 Alpha-opic Equivalent Daylight Illuminances according to CIE s 026:2018

Setting #	Flux down [%]	Flux up [%]	Distribution indirect	Equivalent Daylight Illuminance - eye [lx] * S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
1	100	0	--	244	385	449	296	267
2	70	30	Uniform	249	394	460	302	271
3	50	50	Uniform	256	406	474	310	279
4	30	70	Uniform	263	419	490	320	286
5	0	100	Uniform	283	453	530	344	307
6	70	30	Non Uniform	247	392	459	300	270
7	50	50	Non Uniform	254	405	474	309	277
8	30	70	Non Uniform	210	337	394	256	229
9	0	100	Non Uniform	284	461	541	348	309
10	70	30	Mixed	248	394	461	302	271
11	50	50	Mixed	258	410	480	314	281
12	30	70	Mixed	262	419	490	319	285
13	0	100	Mixed	285	461	540	349	310

* Averaged over 4 desk seating positions, measured at eye height (1.2 m) facing forward

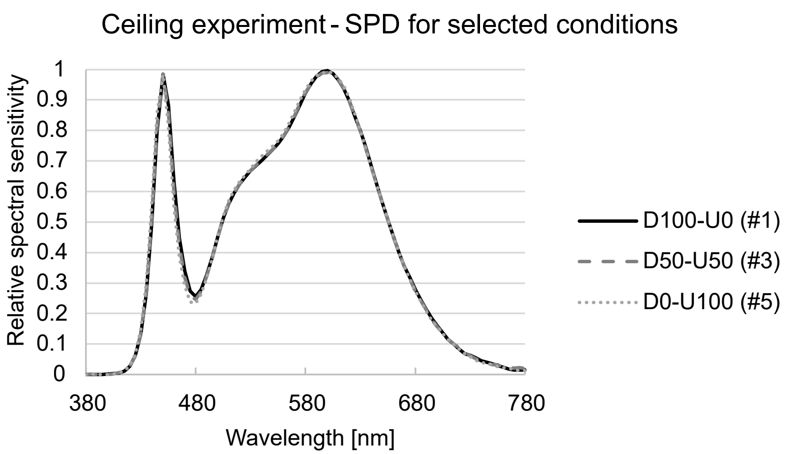


Figure A3-1 Spectral power distribution (relative) for selected representative lighting conditions as measured on single observer position. All spectra shown are for the uniform indirect distribution (same source used for the other distributions).

A

Table A3-3: Characterization of lighting conditions - Luminance

Setting #	Flux Down [%]	Flux Up [%]	Distr.	Ceiling [cd/m²]						Desk 1 [cd/m²]						40° band [cd/m²]					
				Mean	Min	Max	min/ avg	max/ avg	LogMM	Mean	Min	Max	min/ avg	max/ avg	LogMM	Mean	Min	Max	min/ avg	max/ avg	LogMM
1	100	0	--	58	19	85	0,32	1,47	0,66	140	17	199	0,12	1,42	1,06	78	8	207	0,11	2,67	1,40
2	70	30	Uni	112	31	218	0,28	1,94	0,84	137	19	187	0,14	1,36	1,00	87	8	203	0,09	2,34	1,39
3	50	50	Uni	171	50	344	0,29	2,01	0,84	140	23	188	0,16	1,35	0,92	101	11	317	0,11	3,13	1,47
4	30	70	Uni	226	62	493	0,28	2,18	0,90	135	20	179	0,15	1,32	0,96	114	11	452	0,09	3,97	1,62
5	0	100	Uni	357	92	782	0,26	2,19	0,93	138	27	184	0,20	1,34	0,83	144	11	734	0,08	5,11	1,83
6	70	30	Non-Uni	118	27	463	0,23	3,94	1,24	138	15	191	0,11	1,39	1,12	91	9	392	0,10	4,32	1,62
7	50	50	Non-Uni	161	32	760	0,20	4,71	1,37	135	21	189	0,15	1,40	0,96	103	10	692	0,10	6,72	1,82
8	30	70	Non-Uni	224	36	1183	0,16	5,29	1,51	137	26	183	0,19	1,33	0,84	116	8	966	0,07	8,34	2,06
9	0	100	Non-Uni	357	48	1871	0,13	5,25	1,59	141	29	195	0,20	1,39	0,83	152	9	1688	0,06	11,13	2,26
10	70	30	Mix	116	34	327	0,29	2,81	0,98	137	19	187	0,13	1,36	1,00	91	9	318	0,10	3,49	1,54
11	50	50	Mix	162	44	543	0,27	3,34	1,09	135	20	185	0,15	1,36	0,96	103	8	508	0,08	4,95	1,80
12	30	70	Mix	229	54	820	0,24	3,59	1,18	138	24	184	0,17	1,33	0,89	119	8	755	0,07	6,35	1,95
13	0	100	Mix	362	75	1335	0,21	3,69	1,25	143	27	192	0,19	1,35	0,85	148	8	1113	0,06	7,52	2,12

Setting #	Flux Down [%]	Flux Up [%]	Distr.	Wall Front [cd/m²]						Wall Left - Window side [cd/m²]						Wall Right - Separation wall [cd/m²]					
				Mean	Min	Max	min/ avg	max/ avg	LogMM	Mean	Min	Max	min/ avg	max/ avg	LogMM	Mean	Min	Max	min/ avg	max/ avg	LogMM
1	100	0	--	58	21	130	0,36	2,23	0,79	56	4	149	0,07	2,67	1,61	79	30	133	0,38	1,68	0,64
2	70	30	Uni	75	27	126	0,37	1,67	0,66	64	5	141	0,07	2,22	1,47	92	46	130	0,50	1,41	0,45
3	50	50	Uni	100	43	185	0,43	1,84	0,63	75	6	156	0,08	2,07	1,41	109	69	165	0,63	1,52	0,38
4	30	70	Uni	125	60	279	0,48	2,23	0,67	83	7	178	0,08	2,14	1,42	125	79	226	0,63	1,80	0,46
5	0	100	Uni	176	83	443	0,47	2,52	0,73	108	6	285	0,05	2,64	1,68	163	77	383	0,47	2,35	0,70
6	70	30	Non-Uni	78	27	132	0,34	1,70	0,69	65	5	153	0,07	2,36	1,51	94	34	132	0,36	1,40	0,59
7	50	50	Non-Uni	92	35	150	0,38	1,63	0,63	72	5	165	0,07	2,28	1,52	109	50	137	0,46	1,26	0,44
8	30	70	Non-Uni	110	36	233	0,33	2,12	0,81	82	5	171	0,06	2,08	1,54	126	61	164	0,48	1,30	0,43
9	0	100	Non-Uni	157	53	356	0,33	2,26	0,83	107	6	215	0,05	2,01	1,59	167	82	226	0,49	1,35	0,44
10	70	30	Mix	81	32	133	0,40	1,63	0,61	65	4	151	0,06	2,33	1,62	96	47	133	0,49	1,39	0,45
11	50	50	Mix	100	40	156	0,40	1,56	0,60	73	5	161	0,06	2,20	1,53	108	54	133	0,50	1,24	0,40
12	30	70	Mix	121	59	225	0,48	1,85	0,58	85	6	177	0,07	2,07	1,45	130	78	169	0,60	1,30	0,33
13	0	100	Mix	167	71	334	0,42	2,00	0,67	109	6	197	0,05	1,82	1,53	167	82	289	0,49	1,73	0,55

Table A3-4: Overview of Random effects significance (Likelihood Ratio Test):

parameter	LRT statistic	p-value	
1	Brightness	81.20178	2.038081e-19
2	Attractiveness	158.31598	2.639960e-36
3	Distinct - Radiant	159.37149	1.552283e-36
4	Comfort	111.40542	4.822721e-26
5	Coziness	88.71381	4.562680e-21
6	Liveliness	108.54055	2.046207e-25
7	Detachment	74.90347	4.943015e-18

Table A3-5: Numerical overview of Pearson correlations distribution per DV-pair

	Group 1 - percentiles			Group 2 - percentiles		
Correlation pair	25 %	50 %	75 %	25 %	50 %	75 %
brightness - distinct/radiant	0.30	0.56	0.78	-0.27	-0.13	0.26
brightness - detachment	-0.47	-0.21	0.01	0.35	0.50	0.60
brightness - liveliness	0.22	0.45	0.68	-0.50	-0.36	-0.24
brightness - coziness	0.43	0.52	0.70	-0.58	-0.46	-0.29
brightness - comfort	0.43	0.57	0.77	-0.60	-0.35	-0.22
brightness - attractiveness	0.55	0.72	0.79	-0.50	-0.34	0.01
attractiveness - distinct/radiant	0.70	0.84	0.94	0.51	0.70	0.79
attractiveness - detachment	-0.71	-0.54	-0.34	-0.70	-0.63	-0.58
attractiveness - liveliness	0.72	0.80	0.87	0.59	0.83	0.87
attractiveness - coziness	0.63	0.84	0.90	0.69	0.75	0.87
attractiveness - comfort	0.76	0.83	0.90	0.51	0.73	0.85
comfort - distinct/radiant	0.54	0.64	0.82	0.15	0.42	0.62
comfort - detachment	-0.57	-0.41	-0.25	-0.70	-0.56	-0.47
comfort - liveliness	0.49	0.65	0.77	0.21	0.52	0.71
comfort - coziness	0.65	0.71	0.74	0.38	0.66	0.72
coziness - distinct/radiant	0.58	0.73	0.82	-0.03	0.33	0.64
coziness - detachment	-0.72	-0.60	-0.43	-0.83	-0.75	-0.56
coziness - liveliness	0.53	0.76	0.83	0.57	0.75	0.82
liveliness - distinct/radiant	0.63	0.73	0.91	0.15	0.62	0.69
liveliness - detachment	-0.70	-0.50	-0.24	-0.74	-0.64	-0.58
detachment - distinct/radiant	-0.74	-0.38	-0.27	-0.50	-0.35	0.10

Table A3-6: Numerical overview of Pearson correlations distribution per brightness related DV-pair employing three grouping methods based on A: all DV's, B: Brightness data only, C: Brightness data minus excluded participants from grouping method A.

A: All DV grouping

	Group A1 - percentiles			Group A2 - percentiles		
Correlation pair	25 %	50 %	75 %	25 %	50 %	75 %
brightness - attractiveness	0.55	0.72	0.79	-0.50	-0.34	0.01
brightness - comfort	0.43	0.57	0.77	-0.60	-0.35	-0.22
brightness - coziness	0.43	0.52	0.70	-0.58	-0.46	-0.29
brightness - detachment	-0.47	-0.21	0.01	0.35	0.50	0.60
brightness - distinct/radiant	0.30	0.56	0.78	-0.27	-0.13	0.26
brightness - liveliness	0.22	0.45	0.68	-0.50	-0.36	-0.24

B: Brightness grouping

	Group B1 - percentiles			Group B2 - percentiles		
Correlation pair	25 %	50 %	75 %	25 %	50 %	75 %
brightness - attractiveness	0.44	0.73	0.80	-0.48	0.03	0.51
brightness - comfort	0.13	0.57	0.77	-0.29	0.02	0.46
brightness - coziness	-0.16	0.43	0.70	-0.46	-0.24	0.04
brightness - detachment	-0.44	0.18	0.52	0.04	0.39	0.58
brightness - distinct/radiant	0.29	0.48	0.78	-0.27	0.07	0.38
brightness - liveliness	-0.08	0.37	0.68	-0.37	-0.02	0.20

C: Brightness grouping minus excluded groups of all DV grouping

	Group C1 - percentiles			Group C2 - percentiles		
Correlation pair	25 %	50 %	75 %	25 %	50 %	75 %
brightness - attractiveness	0.44	0.73	0.80	-0.48	0.03	0.51
brightness - comfort	0.13	0.57	0.77	-0.29	0.02	0.46
brightness - coziness	-0.16	0.43	0.70	-0.46	-0.24	0.04
brightness - detachment	-0.44	0.18	0.52	0.04	0.39	0.58
brightness - distinct/radiant	0.29	0.48	0.78	-0.27	0.07	0.38
brightness - liveliness	-0.08	0.37	0.68	-0.37	-0.02	0.20

Table A3-7: Linear mixed models of DVs based on Ratio, Distribution, Group and their interactions

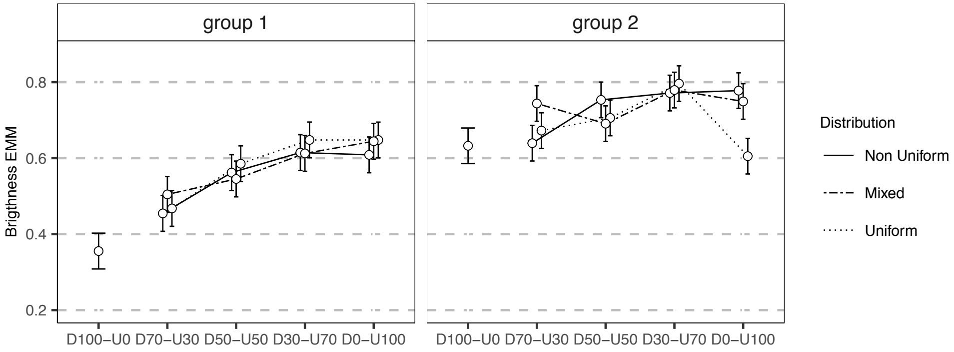
		df	*F*	*p*	R^2 *cond./marg.*[1.]
Brightness	Ratio	(3,275)	9.77	**< 0.001**	0.41 / 0.25
	Distribution	(2,275)	0.37	0.69	
	Group	(1,25)	18.53	**< 0.001**	
	Ratio*Distribution	(6,275)	1.37	0.23	
	Ratio*Group	(3,275)	2.63	**0.05**	
	Distribution*Group	(2,275)	1.55	0.22	
	Ratio*Distribution*Group	(6,275)	0.85	0.53	
Attractiveness	Ratio	(3,275)	4.16	**< 0.01**	0.49 / 0.14
	Distribution	(2,275)	1.60	0.20	
	Group	(1,25)	3.32	0.08	
	Ratio*Distribution	(6,275)	0.96	0.45	
	Ratio*Group	(3,275)	7.72	**< 0.001**	
	Distribution*Group	(2,275)	2.45	0.09	
	Ratio*Distribution*Group	(6,275)	0.80	0.57	
Distinct/Radiant	Ratio	(3,275)	6.82	**< 0.001**	0.47 / 0.12
	Distribution	(2,275)	4.56	**0.01**	
	Group	(1,25)	0.56	0.46	
	Ratio*Distribution	(6,275)	1.59	0.15	
	Ratio*Group	(3,275)	3.93	**0.01**	
	Distribution*Group	(2,275)	5.57	**< 0.01**	
	Ratio*Distribution*Group	(6,275)	0.38	0.89	
Comfort	Ratio	(3,275)	4.18	**0.01**	0.35 / 0.12
	Distribution	(2,275)	1.08	0.34	
	Group	(1,25)	3.01	0.10	
	Ratio*Distribution	(6,275)	1.16	0.33	
	Ratio*Group	(3,275)	5.00	**< 0.01**	
	Distribution*Group	(2,275)	1.52	0.22	
	Ratio*Distribution*Group	(6,275)	0.96	0.46	
Coziness	Ratio	(3,275)	3.09	**0.03**	0.38 / 0.16
	Distribution	(2,275)	0.50	0.61	
	Group	(1,25)	7.23	**0.01**	
	Ratio*Distribution	(6,275)	1.63	0.14	
	Ratio*Group	(3,275)	4.36	**< 0.01**	
	Distribution*Group	(2,275)	2.44	0.09	
	Ratio*Distribution*Group	(6,275)	1.65	0.13	
Liveliness	Ratio	(3,275)	8.37	**< 0.001**	0.40 / 0.15
	Distribution	(2,275)	1.13	0.32	
	Group	(1,25)	3.79	0.06	

	Ratio*Distribution	(6,275)	1.07	0.38	
	Ratio*Group	(3,275)	2.94	**0.03**	
	Distribution*Group	(2,275)	4.51	**0.01**	
	Ratio*Distribution*Group	(6,275)	0.49	0.81	
Detachment	Ratio	(3,275)	4.27	**< 0.01**	0.32 / 0.11
	Distribution	(2,275)	0.51	0.60	
	Group	(1,25)	2.36	0.14	
	Ratio*Distribution	(6,275)	1.34	0.24	
	Ratio*Group	(3,275)	1.80	0.15	
	Distribution*Group	(2,275)	1.40	0.25	
	Ratio*Distribution*Group	(6,275)	1.75	0.11	

1. R^2 of full model – conditional/marginal

A3-8 – Overview of results and post-hoc tests on the individual DVs per group

Brightness



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.120	0.050	176	-2.38	0.13
D100_U0 - D50_U50	-0.209	0.050	176	-4.13	**< 0.001**
D100_U0 - D30_U70	-0.270	0.050	176	-5.34	**< 0.001**
D100_U0 - D0_U100	-0.278	0.050	176	-5.51	**< 0.001**
D70_U30 - D50_U50	-0.089	0.036	176	-2.48	0.10
D70_U30 - D30_U70	-0.149	0.036	176	-4.19	**< 0.001**
D70_U30 - D0_U100	-0.158	0.036	176	-4.43	**< 0.001**
D50_U50 - D30_U70	-0.061	0.036	176	-1.70	0.43
D50_U50 - D0_U100	-0.069	0.036	176	-1.94	0.30
D30_U70 - D0_U100	-0.009	0.036	176	-0.24	1.00

Group 2: Significant interaction – analysis per distribution (p-value adjustment using Tukey method)
Non-Uniform:

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.007	0.054	44	-0.13	1.00
D100_U0 - D50_U50	-0.121	0.054	44	-2.25	0.18
D100_U0 - D30_U70	-0.139	0.054	44	-2.58	0.09
D100_U0 - D0_U100	-0.145	0.054	44	-2.70	0.07
D70_U30 - D50_U50	-0.114	0.054	44	-2.12	0.23
D70_U30 - D30_U70	-0.132	0.054	44	-2.46	0.12
D70_U30 - D0_U100	-0.138	0.054	44	-2.57	0.09
D50_U50 - D30_U70	-0.018	0.054	44	-0.34	1.00
D50_U50 - D0_U100	-0.024	0.054	44	-0.45	0.99
D30_U70 - D0_U100	-0.006	0.054	44	-0.12	1.00

Mixed:

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.111	0.061	44	-1.84	0.36
D100_U0 - D50_U50	-0.058	0.061	44	-0.96	0.87
D100_U0 - D30_U70	-0.147	0.061	44	-2.42	0.13
D100_U0 - D0_U100	-0.117	0.061	44	-1.93	0.32
D70_U30 - D50_U50	0.053	0.061	44	0.88	0.90
D70_U30 - D30_U70	-0.035	0.061	44	-0.58	0.98
D70_U30 - D0_U100	-0.005	0.061	44	-0.09	1.00
D50_U50 - D30_U70	-0.088	0.061	44	-1.46	0.59
D50_U50 - D0_U100	-0.059	0.061	44	-0.97	0.87
D30_U70 - D0_U100	0.030	0.061	44	0.50	0.99

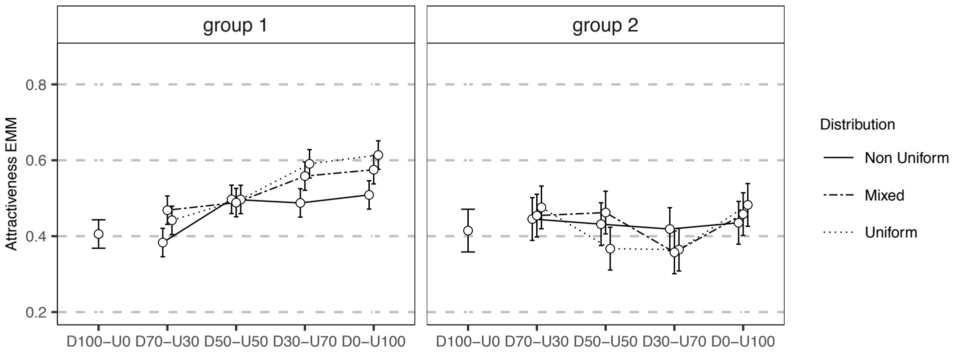
Uniform:

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.040	0.062	44	-0.64	0.97
D100_U0 - D50_U50	-0.073	0.062	44	-1.18	0.77
D100_U0 - D30_U70	-0.164	0.062	44	-2.62	0.08
D100_U0 - D0_U100	0.027	0.062	44	0.44	0.99
D70_U30 - D50_U50	-0.033	0.062	44	-0.53	0.98
D70_U30 - D30_U70	-0.124	0.062	44	-1.98	0.29
D70_U30 - D0_U100	0.067	0.062	44	1.08	0.82
D50_U50 - D30_U70	-0.090	0.062	44	-1.45	0.60
D50_U50 - D0_U100	0.101	0.062	44	1.61	0.50
D30_U70 - D0_U100	0.191	0.062	44	3.06	**0.03**

Group 2: Significant interaction – analysis per ratio (p-value adjustment using Tukey method)

contrast	ratio	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	D70_U30	0.033	0.054	121	0.61	0.81
uni - mix	D70_U30	-0.071	0.054	121	-1.32	0.39
(non-uni) - mix	D70_U30	-0.104	0.054	121	-1.93	0.13
uni - (non-uni)	D50_U50	-0.047	0.054	121	-0.88	0.66
uni - mix	D50_U50	0.015	0.054	121	0.28	0.96
(non-uni) - mix	D50_U50	0.063	0.054	121	1.16	0.48
uni - (non-uni)	D30_U70	0.025	0.054	121	0.46	0.89
uni - mix	D30_U70	0.017	0.054	121	0.31	0.95
(non-uni) - mix	D30_U70	-0.008	0.054	121	-0.14	0.99
uni - (non-uni)	D0_U100	-0.173	0.054	121	-3.19	**< 0.01**
uni - mix	D0_U100	-0.144	0.054	121	-2.66	**0.02**
(non-uni) - mix	D0_U100	0.028	0.054	121	0.53	0.86

Attractiveness



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.025	0.038	176	-0.66	0.96
D100_U0 - D50_U50	-0.088	0.038	176	-2.30	0.15
D100_U0 - D30_U70	-0.140	0.038	176	-3.64	**< 0.01**
D100_U0 - D0_U100	-0.160	0.038	176	-4.17	**< 0.001**
D70_U30 - D50_U50	-0.063	0.027	176	-2.32	0.14
D70_U30 - D30_U70	-0.114	0.027	176	-4.21	**< 0.001**
D70_U30 - D0_U100	-0.135	0.027	176	-4.96	**<0.001**
D50_U50 - D30_U70	-0.051	0.027	176	-1.90	0.32
D50_U50 - D0_U100	-0.072	0.027	176	-2.65	0.07
D30_U70 - D0_U100	-0.020	0.027	176	-0.75	0.94

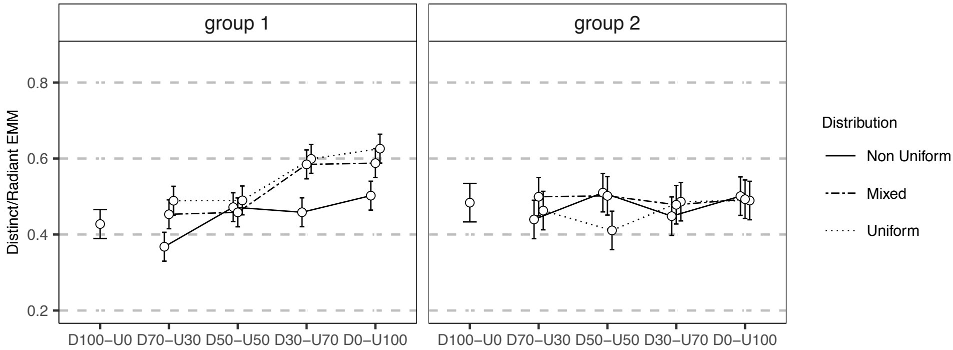
Group 1: Distribution post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	0.067	0.025	163	2.72	**0.02**
uni - mix	0.013	0.025	163	0.54	0.85
(non-uni) - mix	-0.053	0.025	163	-2.18	0.08

Group 2: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.044	0.045	140	-0.96	0.87
D100_U0 - D50_U50	-0.006	0.045	140	-0.12	1.00
D100_U0 - D30_U70	0.034	0.045	140	0.76	0.94
D100_U0 - D0_U100	-0.044	0.045	140	-0.97	0.87
D70_U30 - D50_U50	0.038	0.032	140	1.18	0.76
D70_U30 - D30_U70	0.078	0.032	140	2.43	0.11
D70_U30 - D0_U100	0.000	0.032	140	-0.01	1.00
D50_U50 - D30_U70	0.040	0.032	140	1.25	0.72
D50_U50 - D0_U100	-0.038	0.032	140	-1.19	0.76
D30_U70 - D0_U100	-0.078	0.032	140	-2.44	0.11

Distinct - Radiant



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

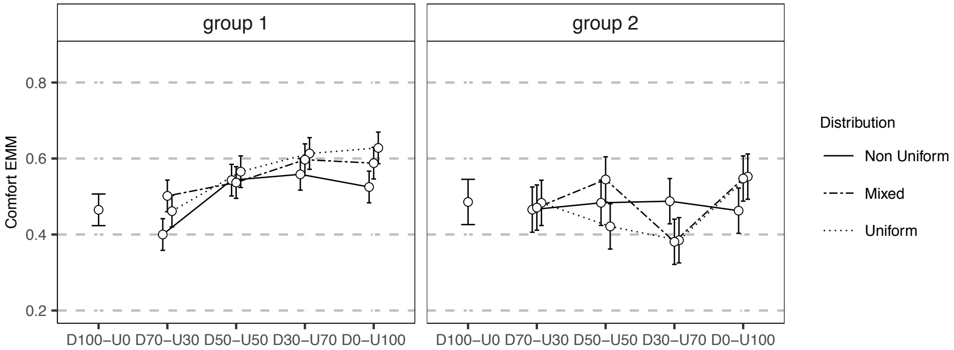
contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.009	0.041	176	-0.22	1.00
D100_U0 - D50_U50	-0.046	0.041	176	-1.12	0.80
D100_U0 - D30_U70	-0.120	0.041	176	-2.93	**0.03**
D100_U0 - D0_U100	-0.144	0.041	176	-3.53	**< 0.01**
D70_U30 - D50_U50	-0.037	0.029	176	-1.27	0.71
D70_U30 - D30_U70	-0.111	0.029	176	-3.83	**< 0.01**
D70_U30 - D0_U100	-0.135	0.029	176	-4.68	**< 0.001**
D50_U50 - D30_U70	-0.074	0.029	176	-2.56	0.08
D50_U50 - D0_U100	-0.099	0.029	176	-3.42	**< 0.01**
D30_U70 - D0_U100	-0.025	0.029	176	-0.85	0.91

Group 1: Distribution post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	0.101	0.026	163	3.91	< 0.001
uni - mix	0.030	0.026	163	1.16	0.48
(non-uni) - mix	-0.071	0.026	163	-2.75	0.02

Group 2: no significant effects

Comfort



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

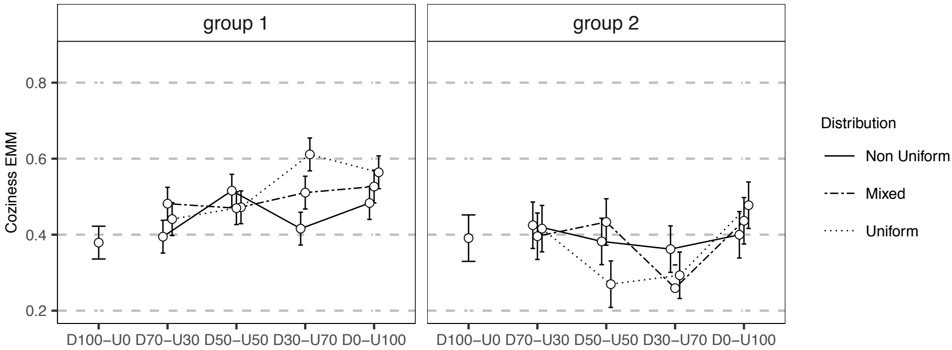
contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	0.011	0.043	176	0.25	1.00
D100_U0 - D50_U50	-0.083	0.043	176	-1.94	0.30
D100_U0 - D30_U70	-0.125	0.043	176	-2.89	**0.03**
D100_U0 - D0_U100	-0.115	0.043	176	-2.68	0.06
D70_U30 - D50_U50	-0.094	0.030	176	-3.09	**0.02**
D70_U30 - D30_U70	-0.135	0.030	176	-4.44	**< 0.001**
D70_U30 - D0_U100	-0.126	0.030	176	-4.13	**< 0.001**
D50_U50 - D30_U70	-0.041	0.030	176	-1.35	0.66
D50_U50 - D0_U100	-0.032	0.030	176	-1.04	0.83
D30_U70 - D0_U100	0.009	0.030	176	0.31	1.00

Group 1: Distribution post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	0.060	0.027	163	2.26	0.06
uni - mix	0.011	0.027	163	0.42	0.91
(non-uni) - mix	-0.049	0.027	163	-1.84	0.16

Group 2: no significant effects

Coziness



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.060	0.047	176	-1.28	0.70
D100_U0 - D50_U50	-0.107	0.047	176	-2.28	0.16
D100_U0 - D30_U70	-0.134	0.047	176	-2.85	**0.04**
D100_U0 - D0_U100	-0.146	0.047	176	-3.11	**0.02**
D70_U30 - D50_U50	-0.047	0.033	176	-1.41	0.62
D70_U30 - D30_U70	-0.074	0.033	176	-2.22	0.18
D70_U30 - D0_U100	-0.086	0.033	176	-2.59	0.08
D50_U50 - D30_U70	-0.027	0.033	176	-0.81	0.93
D50_U50 - D0_U100	-0.039	0.033	176	-1.18	0.77
D30_U70 - D0_U100	-0.012	0.033	176	-0.37	1.00

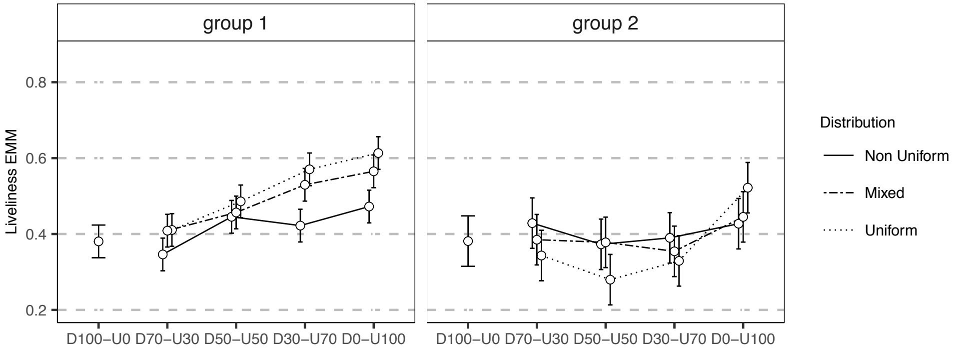
Group 1: Distribution post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	0.070	0.029	163	2.42	**0.04**
uni - mix	0.025	0.029	163	0.87	0.66
(non-uni) - mix	-0.045	0.029	163	-1.56	0.27

Group 2: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.021	0.057	140	-0.38	1.00
D100_U0 - D50_U50	0.029	0.057	140	0.51	0.99
D100_U0 - D30_U70	0.086	0.057	140	1.51	0.56
D100_U0 - D0_U100	-0.047	0.057	140	-0.83	0.92
D70_U30 - D50_U50	0.050	0.040	140	1.25	0.72
D70_U30 - D30_U70	0.107	0.040	140	2.67	0.06
D70_U30 - D0_U100	-0.026	0.040	140	-0.64	0.97
D50_U50 - D30_U70	0.057	0.040	140	1.41	0.62
D50_U50 - D0_U100	-0.076	0.040	140	-1.89	0.33
D30_U70 - D0_U100	-0.133	0.040	140	-3.31	**0.01**

Liveliness



Group 1: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.008	0.046	176	-0.17	1.00
D100_U0 - D50_U50	-0.082	0.046	176	-1.78	0.39
D100_U0 - D30_U70	-0.127	0.046	176	-2.76	**0.05**
D100_U0 - D0_U100	-0.170	0.046	176	-3.69	**< 0.01**
D70_U30 - D50_U50	-0.074	0.033	176	-2.28	0.16
D70_U30 - D30_U70	-0.119	0.033	176	-3.65	**< 0.01**
D70_U30 - D0_U100	-0.162	0.033	176	-4.97	**< 0.001**
D50_U50 - D30_U70	-0.045	0.033	176	-1.37	0.65
D50_U50 - D0_U100	-0.088	0.033	176	-2.69	0.06
D30_U70 - D0_U100	-0.043	0.033	176	-1.32	0.68

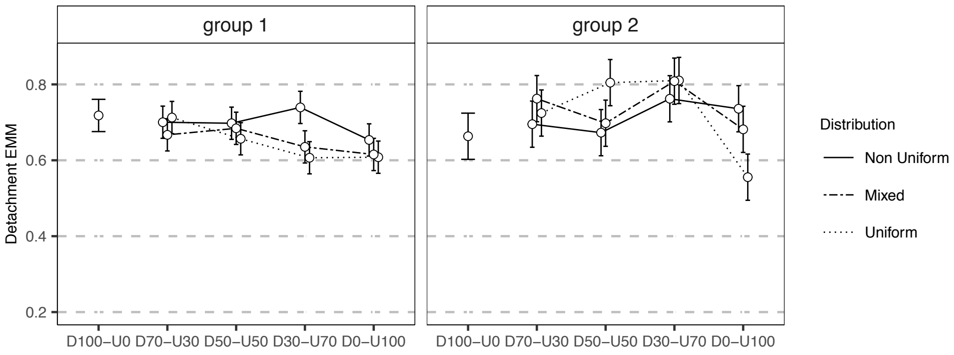
Group 1: Distribution post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
uni - (non-uni)	0.099	0.029	163	3.36	**< 0.01**
uni - mix	0.030	0.029	163	1.02	0.56
(non-uni) - mix	-0.069	0.029	163	-2.34	**0.05**

Group 2: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.004	0.060	140	-0.07	1.00
D100_U0 - D50_U50	0.038	0.060	140	0.64	0.97
D100_U0 - D30_U70	0.024	0.060	140	0.40	0.99
D100_U0 - D0_U100	-0.083	0.060	140	-1.40	0.63
D70_U30 - D50_U50	0.042	0.042	140	1.00	0.85
D70_U30 - D30_U70	0.028	0.042	140	0.66	0.96
D70_U30 - D0_U100	-0.079	0.042	140	-1.88	0.33
D50_U50 - D30_U70	-0.014	0.042	140	-0.34	1.00
D50_U50 - D0_U100	-0.121	0.042	140	-2.88	**0.04**
D30_U70 - D0_U100	-0.107	0.042	140	-2.54	0.09

Detachment



Group 1: no significant effects

Group 2: Ratio post-hoc comparison – averaged over distribution (p-value adjustment using Tukey method)

contrast	estimate	SE	df	t-ratio	p-value
D100_U0 - D70_U30	-0.064	0.059	140	-1.08	0.82
D100_U0 - D50_U50	-0.062	0.059	140	-1.04	0.84
D100_U0 - D30_U70	-0.130	0.059	140	-2.20	0.19
D100_U0 - D0_U100	0.006	0.059	140	0.10	1.00
D70_U30 - D50_U50	0.002	0.042	140	0.06	1.00
D70_U30 - D30_U70	-0.066	0.042	140	-1.58	0.51
D70_U30 - D0_U100	0.070	0.042	140	1.66	0.46
D50_U50 - D30_U70	-0.069	0.042	140	-1.64	0.48
D50_U50 - D0_U100	0.067	0.042	140	1.61	0.49
D30_U70 - D0_U100	0.136	0.042	140	3.24	**0.01**

Appendix 4: Supplemental materials - From luminance to brightness (Chapter 5)

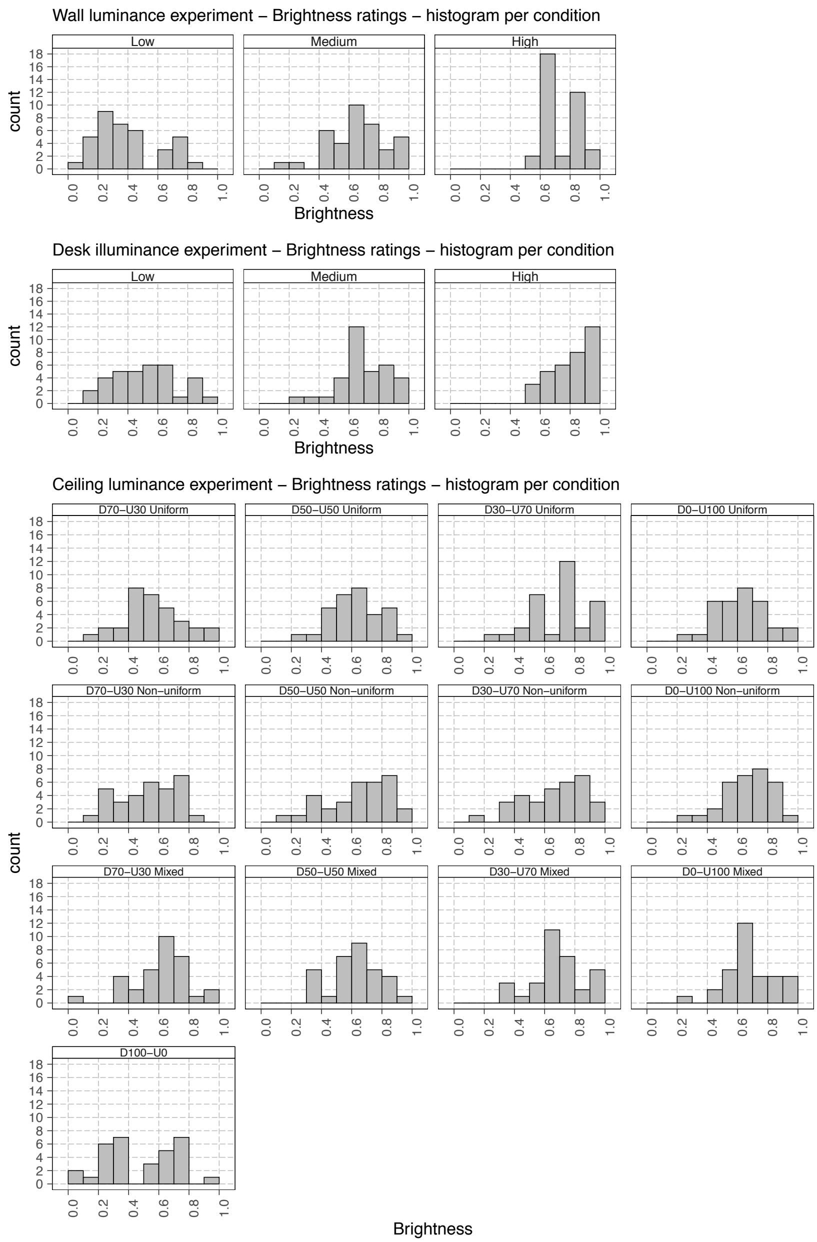


Figure A4-1: Histogram of brightness data for all three experiments, per condition, all participants

Table A4-2: Wall luminance experiment: Range indication (luminance or ratio) of different parameters per assessment area.

	mean		median		maximum		5th percentile		10th percentile		90th percentile		95th percentile		log_{10} (mean)		log_{10} (median)	
mask	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Level-based parameters – all in cd/m²																		
mask_b20	22.58	49.79	17.82	36.83	170	288	3.15	6.53	4.79	11.69	50	105	69	146	1.35	1.70	1.25	1.57
mask_b40	24.66	48.26	15.09	34.06	170	291	3.49	6.30	6.01	10.00	71	99	81	134	1.39	1.68	1.18	1.53
mask_b60	27.91	49.90	14.85	34.86	4430	6742	4.06	6.83	6.46	13.59	79	97	89	115	1.45	1.70	1.17	1.54
mask_c100	47.71	76.18	17.27	41.98	16850	25630	6.41	13.24	9.63	23.08	79	106	86	156	1.68	1.88	1.24	1.62
mask_c120	76.88	99.27	18.80	40.34	29810	36920	4.52	11.49	9.11	22.01	85	104	95	153	1.89	2.00	1.27	1.61
mask_c140	70.42	85.41	19.92	39.26	29810	36920	4.51	7.90	8.75	15.65	88	104	101	127	1.85	1.93	1.30	1.59
mask_c160	65.76	79.39	22.08	39.51	29810	36920	5.20	7.81	8.50	18.12	96	105	101	114	1.82	1.90	1.34	1.60
mask_c20	49.76	87.58	48.30	77.84	170	256	14.73	49.74	15.06	53.71	77	148	82	175	1.70	1.94	1.68	1.89
mask_c40	47.13	98.30	46.29	93.74	170	291	12.89	45.73	13.43	53.45	83	164	87	200	1.67	1.99	1.67	1.97
mask_c60	34.88	79.75	17.36	72.73	170	291	8.03	22.52	11.21	26.23	80	152	84	190	1.54	1.90	1.24	1.86
mask_c80	27.99	63.39	15.74	43.76	170	291	6.82	16.59	9.96	23.65	75	123	82	168	1.45	1.80	1.20	1.64

	L_{05}/mean		L_{05}/median		L_{95}/mean		L_{95}/median		L_{95}/L_{05}		$\log_{10}(L_{05}$/mean)		$\log_{10}(L_{05}$/median)		$\log_{10}(L_{95}$/mean)		$\log_{10}(L_{95}$/median)		$\log_{10}(L_{95}/L_{05})$	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Ratio-based parameters																				
mask_b20	0.10	0.16	0.13	0.21	2.34	3.27	2.87	4.45	17.59	31.32	-1.01	-0.80	-0.88	-0.67	0.37	0.51	0.46	0.65	1.25	1.50
mask_b40	0.10	0.15	0.15	0.26	2.48	3.54	3.49	5.96	18.24	26.40	-0.99	-0.81	-0.83	-0.59	0.39	0.55	0.54	0.78	1.26	1.42
mask_b60	0.12	0.15	0.17	0.30	2.24	3.18	3.22	6.06	16.85	21.84	-0.91	-0.82	-0.76	-0.52	0.35	0.50	0.51	0.78	1.23	1.34
mask_c100	0.13	0.18	0.25	0.44	1.51	2.18	3.21	5.27	8.97	15.01	-0.90	-0.75	-0.61	-0.36	0.18	0.34	0.51	0.72	0.95	1.18
mask_c120	0.06	0.12	0.16	0.38	1.11	1.61	3.45	5.08	10.42	23.45	-1.23	-0.94	-0.80	-0.42	0.04	0.21	0.54	0.71	1.02	1.37
mask_c140	0.06	0.09	0.15	0.29	1.32	1.49	3.15	5.13	15.12	22.59	-1.20	-1.03	-0.81	-0.53	0.12	0.17	0.50	0.71	1.18	1.35
mask_c160	0.08	0.10	0.18	0.26	1.42	1.59	2.86	4.76	14.13	20.21	-1.11	-1.00	-0.75	-0.59	0.15	0.20	0.46	0.68	1.15	1.31
mask_c20	0.26	0.61	0.25	0.70	1.42	2.20	1.51	2.70	2.31	6.59	-0.59	-0.21	-0.60	-0.15	0.15	0.34	0.18	0.43	0.36	0.82
mask_c40	0.24	0.47	0.23	0.53	1.41	2.19	1.43	2.49	3.13	7.75	-0.62	-0.33	-0.65	-0.27	0.15	0.34	0.15	0.40	0.50	0.89
mask_c60	0.19	0.33	0.22	0.60	1.76	2.50	1.77	5.14	5.49	12.96	-0.72	-0.49	-0.65	-0.22	0.24	0.40	0.25	0.71	0.74	1.11
mask_c80	0.19	0.31	0.27	0.53	2.11	3.02	3.15	5.83	6.79	14.53	-0.72	-0.51	-0.58	-0.27	0.32	0.48	0.50	0.77	0.83	1.16

Table A4-3 Desk illuminance experiment: Range indication (luminance or ratio) of different parameters per assessment area.

	mean		median		maximum		5th percentile		10th percentile		90th percentile		95th percentile		log_{10}(mean)		log_{10} (median)	
mask	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Level-based parameters – all in cd/m²																		
mask_b20	38.94	69.15	20.38	64.85	229	306	1.93	12.28	4.34	20.23	91	118	140	152	1.59	1.84	1.31	1.81
mask_b40	37.07	77.73	21.95	62.45	282	312	1.96	12.31	4.68	20.35	88	165	130	213	1.57	1.89	1.34	1.80
mask_b60	32.61	91.69	22.40	60.83	407	9035	2.64	13.61	4.68	26.60	80	234	108	272	1.51	1.96	1.35	1.78
mask_c100	43.32	118.29	26.09	65.58	1446	32670	2.69	16.41	6.32	34.06	92	233	144	265	1.64	2.07	1.42	1.82
mask_c120	41.33	212.02	25.32	71.62	2467	61020	2.66	20.03	7.14	36.26	85	286	126	312	1.62	2.33	1.40	1.86
mask_c140	40.91	285.70	25.10	81.28	2718	66540	2.91	19.89	7.49	40.14	80	321	114	370	1.61	2.46	1.40	1.91
mask_c160	40.30	348.80	24.92	87.56	3094	77460	3.74	21.08	6.77	41.67	71	339	104	405	1.61	2.54	1.40	1.94
mask_c20	81.64	90.02	66.43	76.76	190	281	36.22	55.19	44.07	58.97	135	155	151	184	1.91	1.95	1.82	1.89
mask_c40	91.34	96.30	80.29	91.68	216	307	34.17	55.13	41.31	58.68	148	172	170	208	1.96	1.98	1.90	1.96
mask_c60	69.64	85.84	60.18	79.93	239	307	8.79	44.37	11.04	51.46	136	156	162	198	1.84	1.93	1.78	1.90
mask_c80	52.04	79.70	32.89	64.17	239	307	4.27	30.60	9.35	42.71	115	143	157	174	1.72	1.90	1.52	1.81

	L_{05}/mean		L_{05}/median		L_{95}/mean		L_{95}/median		L_{95}/L_{05}		$\log_{10}(L_{05}$/mean)		$\text{Log}_{10}(L_{05}$/median)		$\text{Log}_{10}(L_{95}$/mean)		$\text{Log}_{10}(L_{95}$/median)		$\text{Log}_{10}(L_{95}/L_{05})$	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Ratio-based parameters																				
mask_b20	0.05	0.18	0.09	0.19	2.13	3.75	2.24	7.20	11.98	76.52	-1.31	-0.75	-1.03	-0.72	0.33	0.57	0.35	0.86	1.08	1.88
mask_b40	0.05	0.17	0.09	0.21	2.70	3.57	3.30	6.17	15.57	69.82	-1.29	-0.76	-1.06	-0.67	0.43	0.55	0.52	0.79	1.19	1.84
mask_b60	0.08	0.16	0.12	0.23	2.32	3.30	3.35	4.93	18.92	42.36	-1.11	-0.81	-0.93	-0.63	0.37	0.52	0.52	0.69	1.28	1.63
mask_c100	0.06	0.15	0.10	0.26	2.23	3.34	3.79	5.61	15.46	54.38	-1.21	-0.84	-1.00	-0.59	0.35	0.52	0.58	0.75	1.19	1.74
mask_c120	0.06	0.10	0.10	0.29	1.46	3.11	3.97	5.10	14.98	49.12	-1.20	-1.01	-0.99	-0.54	0.16	0.49	0.60	0.71	1.18	1.69
mask_c140	0.06	0.10	0.12	0.26	1.21	2.83	4.05	4.83	17.10	40.10	-1.24	-1.02	-0.94	-0.59	0.08	0.45	0.61	0.68	1.23	1.60
mask_c160	0.05	0.10	0.15	0.24	1.07	2.61	4.14	4.77	19.11	28.53	-1.28	-1.01	-0.82	-0.62	0.03	0.42	0.62	0.68	1.28	1.46
mask_c20	0.41	0.61	0.51	0.74	1.73	2.25	1.96	2.75	2.82	5.01	-0.38	-0.21	-0.29	-0.13	0.24	0.35	0.29	0.44	0.45	0.70
mask_c40	0.37	0.57	0.42	0.63	1.76	2.26	1.85	2.57	3.12	6.05	-0.43	-0.24	-0.37	-0.20	0.25	0.35	0.27	0.41	0.49	0.78
mask_c60	0.12	0.52	0.13	0.56	1.94	2.63	2.09	3.04	3.75	22.48	-0.93	-0.29	-0.88	-0.25	0.29	0.42	0.32	0.48	0.57	1.35
mask_c80	0.08	0.41	0.12	0.50	2.13	3.12	2.58	4.98	5.15	40.14	-1.11	-0.38	-0.91	-0.30	0.33	0.49	0.41	0.70	0.71	1.60

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Table A4-4 Direct/Indirect ratio experiment: Range indication (luminance or ratio) of different parameters per assessment area.

	mean		median		maximum		5th percentile		10th percentile		90th percentile		95th percentile		log_{10}(mean)		log_{10} (median)	
mask	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Level-based parameters – all in cd/m²																		
mask_b20	75.73	128.38	71.24	137.70	308	2553	7.51	12.83	12.62	21.91	112	200	223	253	1.88	2.11	1.85	2.14
mask_b40	84.91	144.35	66.37	137.40	1113	3730	9.02	16.80	17.39	42.04	133	243	221	282	1.93	2.16	1.82	2.14
mask_b60	98.91	157.30	63.62	144.00	1209	7151	9.76	16.93	19.65	50.88	145	274	216	365	2.00	2.20	1.80	2.16
mask_c100	124.54	189.96	58.12	156.50	1199	21440	7.24	12.07	14.47	22.47	158	366	235	582	2.10	2.28	1.76	2.19
mask_c120	156.56	197.00	62.76	156.90	1291	24390	9.19	14.66	21.43	41.73	151	372	231	600	2.19	2.29	1.80	2.20
mask_c140	177.04	205.07	66.36	154.20	1291	42610	10.94	18.42	21.61	72.48	153	394	226	652	2.25	2.31	1.82	2.19
mask_c160	171.35	208.36	68.18	152.40	1291	42610	11.20	21.20	23.83	76.18	153	406	216	692	2.23	2.32	1.83	2.18
mask_c20	128.97	166.13	82.04	192.50	291	2401	6.76	11.74	8.96	15.23	243	280	252	292	2.11	2.22	1.91	2.28
mask_c40	135.68	196.38	80.63	208.60	675	3191	7.66	13.37	20.30	23.38	241	354	247	426	2.13	2.29	1.91	2.32
mask_c60	118.16	185.86	57.68	171.40	969	4334	6.11	9.82	8.69	15.13	233	374	244	477	2.07	2.27	1.76	2.23
mask_c80	103.03	197.54	57.54	161.10	1199	5853	6.54	10.82	11.74	22.13	218	379	239	607	2.01	2.30	1.76	2.21

	L_{05}/mean		L_{05}/median		L_{95}/mean		L_{95}/median		L_{95}/L_{05}		$\log_{10}$ (L_{05}/mean)		$\log_{10}$(L_{05}/ median)		$\log_{10}$ (L_{95}/mean)		$\log_{10}$(L_{95}/ median)		$\log_{10}$ (L_{95}/L_{05})	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Ratio-based parameters																				
mask_b20	0.09	0.11	0.09	0.12	1.90	3.24	1.77	3.50	18.72	32.78	-1.04	-0.95	-1.05	-0.92	0.28	0.51	0.25	0.54	1.27	1.52
mask_b40	0.10	0.14	0.10	0.18	1.73	2.88	1.84	3.74	14.09	26.38	-1.02	-0.84	-0.99	-0.75	0.24	0.46	0.26	0.57	1.15	1.42
mask_b60	0.09	0.12	0.10	0.17	1.70	2.49	1.87	3.78	15.44	28.10	-1.05	-0.92	-1.02	-0.76	0.23	0.40	0.27	0.58	1.19	1.45
mask_c100	0.05	0.07	0.06	0.14	1.69	3.25	2.05	4.55	25.77	62.00	-1.29	-1.16	-1.22	-0.85	0.23	0.51	0.31	0.66	1.41	1.79
mask_c120	0.06	0.08	0.07	0.16	1.44	3.23	1.92	4.48	20.88	52.49	-1.23	-1.12	-1.14	-0.81	0.16	0.51	0.28	0.65	1.32	1.72
mask_c140	0.06	0.09	0.09	0.18	1.26	3.41	1.96	4.89	17.15	47.14	-1.22	-1.04	-1.04	-0.76	0.10	0.53	0.29	0.69	1.23	1.67
mask_c160	0.07	0.11	0.10	0.21	1.23	3.46	1.90	5.00	12.88	46.43	-1.18	-0.97	-1.02	-0.67	0.09	0.54	0.28	0.70	1.11	1.67
mask_c20	0.05	0.07	0.06	0.09	1.67	2.13	1.44	3.53	23.64	40.84	-1.29	-1.14	-1.23	-1.06	0.22	0.33	0.16	0.55	1.37	1.61
mask_c40	0.06	0.07	0.06	0.13	1.56	2.20	1.60	3.36	21.38	37.95	-1.26	-1.14	-1.25	-0.90	0.19	0.34	0.20	0.53	1.33	1.58
mask_c60	0.04	0.06	0.05	0.12	1.79	2.75	2.23	4.81	32.61	57.90	-1.36	-1.22	-1.31	-0.92	0.25	0.44	0.35	0.68	1.51	1.76
mask_c80	0.05	0.07	0.06	0.13	1.86	3.32	2.12	4.65	29.00	69.10	-1.32	-1.13	-1.25	-0.87	0.27	0.52	0.33	0.67	1.46	1.84

A

A4-5: Model fit overview from Figure 5.3 – using Satterthwaite estimation of degrees of freedom.

Mean						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,161)	57.92	2.2E-12	< 0.001	0.56	0.24
40° band	(1,150)	54.44	1E-11	< 0.001	0.56	0.23
60° band	(1,136)	49.43	9.1E-11	< 0.001	0.54	0.21
20° circle	(1,43)	1.95	0.17022	0.17	0.15	0.01
40° circle	(1,45)	12.03	0.00116	< 0.01	0.27	0.06
60° circle	(1,48)	20.39	4.1E-05	< 0.001	0.36	0.11
80° circle	(1,89)	28.09	8.3E-07	< 0.001	0.40	0.13
100° circle	(1,153)	51.85	2.5E-11	< 0.001	0.55	0.22
120° circle	(1,332)	41.64	3.9E-10	< 0.001	0.35	0.12
140° circle	(1,346)	34.03	1.2E-08	< 0.001	0.27	0.09
160° circle	(1,355)	39.31	1.1E-09	< 0.001	0.26	0.10

Log_{10}(mean)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,246)	99.69	6.3E-20	< 0.001	0.69	0.33
40° band	(1,250)	103.32	1.5E-20	< 0.001	0.72	0.34
60° band	(1,224)	79.65	1.7E-16	< 0.001	0.64	0.29
20° circle	(1,44)	5.45	0.0242	<0.05	0.19	0.03
40° circle	(1,58)	20.97	2.5E-05	< 0.001	0.34	0.10
60° circle	(1,72)	39.96	1.9E-08	< 0.001	0.49	0.19
80° circle	(1,146)	76.86	4.3E-15	< 0.001	0.67	0.31
100° circle	(1,239)	71.97	2.3E-15	< 0.001	0.61	0.26
120° circle	(1,344)	47.14	3.1E-11	< 0.001	0.37	0.13
140° circle	(1,342)	42.27	2.8E-10	< 0.001	0.33	0.12
160° circle	(1,348)	46.85	3.5E-11	< 0.001	0.33	0.12

Median						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,128)	55.00	1.5E-11	< 0.001	0.58	0.24
40° band	(1,135)	54.38	1.5E-11	< 0.001	0.58	0.24
60° band	(1,163)	55.58	5E-12	< 0.001	0.56	0.23
20° circle	(1,149)	17.20	5.6E-05	< 0.001	0.29	0.07
40° circle	(1,330)	45.13	8.1E-11	< 0.001	0.37	0.13
60° circle	(1,337)	85.33	2.9E-18	< 0.001	0.53	0.23
80° circle	(1,226)	60.95	2.2E-13	< 0.001	0.55	0.23
100° circle	(1,221)	63.26	9.3E-14	< 0.001	0.57	0.24
120° circle	(1,184)	59.44	7.6E-13	< 0.001	0.58	0.24
140° circle	(1,176)	58.90	1.1E-12	< 0.001	0.58	0.24
160° circle	(1,182)	57.69	1.6E-12	< 0.001	0.56	0.23

Log_{10}(median)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,279)	105.95	2.8E-21	< 0.001	0.71	0.34
40° band	(1,293)	122.49	5E-24	< 0.001	0.76	0.37
60° band	(1,311)	135.18	3.4E-26	< 0.001	0.78	0.38
20° circle	(1,92)	22.45	7.9E-06	< 0.001	0.35	0.11
40° circle	(1,316)	66.93	6.9E-15	< 0.001	0.48	0.20
60° circle	(1,346)	119.75	3.9E-24	< 0.001	0.59	0.28
80° circle	(1,321)	137.70	1.1E-26	< 0.001	0.75	0.37
100° circle	(1,333)	145.57	4.6E-28	< 0.001	0.77	0.38
120° circle	(1,312)	127.84	4.5E-25	< 0.001	0.75	0.37
140° circle	(1,288)	109.32	6.6E-22	< 0.001	0.71	0.34
160° circle	(1,270)	92.48	5.1E-19	< 0.001	0.66	0.30

L_{05}/mean						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,349)	13.46	0.00028	< 0.001	0.14	0.04
40° band	(1,346)	6.81	0.00946	< 0.01	0.13	0.02
60° band	(1,237)	16.59	6.3E-05	< 0.001	0.15	0.05
20° circle	(1,42)	48.01	1.8E-08	< 0.001	0.37	0.21
40° circle	(1,42)	45.65	3.2E-08	< 0.001	0.35	0.20
60° circle	(1,123)	32.53	8.2E-08	< 0.001	0.22	0.11
80° circle	(1,114)	22.59	5.9E-06	< 0.001	0.18	0.08
100° circle	(1,86)	28.88	6.5E-07	< 0.001	0.23	0.11
120° circle	(1,103)	34.01	6.4E-08	< 0.001	0.21	0.11
140° circle	(1,253)	0.80	0.37115	0.37	0.10	0.00
160° circle	(1,272)	9.36	0.00244	< 0.01	0.12	0.03

$Log_{10}(L_{05}$/mean)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,354)	16.04	7.6E-05	< 0.001	0.15	0.04
40° band	(1,350)	9.37	0.00238	< 0.01	0.15	0.03
60° band	(1,245)	16.73	5.9E-05	< 0.001	0.15	0.05
20° circle	(1,43)	23.94	1.4E-05	< 0.001	0.21	0.11
40° circle	(1,46)	21.25	3.2E-05	< 0.001	0.19	0.09
60° circle	(1,61)	20.83	2.5E-05	< 0.001	0.18	0.08
80° circle	(1,74)	15.55	0.00018	< 0.001	0.15	0.06
100° circle	(1,85)	25.58	2.4E-06	< 0.001	0.21	0.10
120° circle	(1,95)	36.21	3.3E-08	< 0.001	0.22	0.12
140° circle	(1,252)	0.82	0.36516	0.37	0.10	0.00
160° circle	(1,288)	13.11	0.00035	< 0.001	0.13	0.04

L_{05}/median						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,99)	3.44	0.06673	0.07	0.10	0.01
40° band	(1,176)	0.01	0.9117	0.91	0.10	0.00
60° band	(1,155)	0.55	0.45983	0.46	0.12	0.00
20° circle	(1,53)	43.62	2E-08	< 0.001	0.32	0.18
40° circle	(1,56)	38.38	7.5E-08	< 0.001	0.28	0.16
60° circle	(1,141)	1.60	0.20865	0.21	0.10	0.01
80° circle	(1,96)	3.98	0.04895	<0.05	0.10	0.02
100° circle	(1,103)	0.26	0.61318	0.61	0.10	0.00
120° circle	(1,115)	1.34	0.24975	0.25	0.10	0.00
140° circle	(1,135)	0.82	0.36667	0.37	0.10	0.00
160° circle	(1,110)	0.14	0.71287	0.71	0.10	0.00

$Log_{10}(L_{05}$/median)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,90)	3.96	0.04949	<0.05	0.10	0.02
40° band	(1,170)	0.14	0.70806	0.71	0.10	0.00
60° band	(1,136)	0.10	0.74665	0.75	0.11	0.00
20° circle	(1,51)	19.23	5.7E-05	< 0.001	0.17	0.08
40° circle	(1,61)	12.94	0.00065	< 0.001	0.13	0.05
60° circle	(1,81)	2.77	0.10001	0.1	0.10	0.01
80° circle	(1,71)	3.90	0.05229	0.05	0.10	0.02
100° circle	(1,92)	1.42	0.2371	0.24	0.10	0.01
120° circle	(1,101)	1.53	0.2194	0.22	0.09	0.01
140° circle	(1,118)	0.61	0.43628	0.44	0.10	0.00
160° circle	(1,98)	0.09	0.76648	0.77	0.10	0.00

L_{95}/mean						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,329)	104.76	1.6E-21	< 0.001	0.43	0.20
40° band	(1,351)	156.01	7.2E-30	< 0.001	0.67	0.30
60° band	(1,250)	21.77	5E-06	< 0.001	0.30	0.08
20° circle	(1,348)	4.88	0.02779	<0.05	0.14	0.01
40° circle	(1,354)	2.59	0.10871	0.11	0.13	0.01
60° circle	(1,326)	5.60	0.01851	<0.05	0.13	0.01
80° circle	(1,333)	13.06	0.00035	< 0.001	0.16	0.03
100° circle	(1,353)	0.05	0.83119	0.83	0.10	0.00
120° circle	(1,355)	0.13	0.71501	0.72	0.10	0.00
140° circle	(1,350)	0.15	0.70306	0.7	0.10	0.00
160° circle	(1,351)	0.37	0.54514	0.55	0.10	0.00

$Log_{10}(L_{95}$/mean)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,328)	100.02	1E-20	< 0.001	0.41	0.19
40° band	(1,354)	132.37	3.1E-26	< 0.001	0.63	0.28
60° band	(1,232)	19.26	1.7E-05	< 0.001	0.29	0.07
20° circle	(1,349)	4.77	0.02969	<0.05	0.13	0.01
40° circle	(1,355)	3.24	0.07279	0.07	0.13	0.01
60° circle	(1,326)	5.64	0.01809	<0.05	0.13	0.01
80° circle	(1,334)	11.67	0.00071	< 0.001	0.16	0.03
100° circle	(1,350)	0.51	0.47628	0.48	0.10	0.00
120° circle	(1,344)	0.02	0.90057	0.9	0.10	0.00
140° circle	(1,352)	0.15	0.69624	0.7	0.10	0.00
160° circle	(1,351)	1.14	0.28544	0.29	0.10	0.00

L_{95}/median						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,355)	62.51	3.4E-14	< 0.001	0.41	0.15
40° band	(1,355)	151.05	3.7E-29	< 0.001	0.69	0.32
60° band	(1,329)	68.80	2.8E-15	< 0.001	0.51	0.21
20° circle	(1,351)	9.61	0.00209	< 0.01	0.17	0.03
40° circle	(1,346)	33.46	1.6E-08	< 0.001	0.22	0.08
60° circle	(1,326)	113.58	6E-23	< 0.001	0.36	0.22
80° circle	(1,342)	73.76	3.2E-16	< 0.001	0.36	0.16
100° circle	(1,355)	46.55	3.9E-11	< 0.001	0.35	0.12
120° circle	(1,267)	8.06	0.00488	< 0.01	0.19	0.03
140° circle	(1,327)	0.44	0.50721	0.51	0.11	0.00
160° circle	(1,347)	0.88	0.34949	0.35	0.10	0.00

$Log_{10}(L_{95}$/median)						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,355)	71.19	8.3E-16	< 0.001	0.45	0.18
40° band	(1,355)	157.51	3.8E-30	< 0.001	0.74	0.35
60° band	(1,293)	61.78	7.4E-14	< 0.001	0.53	0.21
20° circle	(1,351)	7.56	0.00627	< 0.01	0.16	0.02
40° circle	(1,348)	30.69	6E-08	< 0.001	0.21	0.08
60° circle	(1,324)	109.56	2.8E-22	< 0.001	0.35	0.21
80° circle	(1,344)	56.98	4E-13	< 0.001	0.32	0.13
100° circle	(1,348)	27.30	3E-07	< 0.001	0.28	0.08
120° circle	(1,256)	2.57	0.11018	0.11	0.14	0.01
140° circle	(1,327)	0.00	0.98363	0.98	0.10	0.00
160° circle	(1,347)	1.27	0.2607	0.26	0.09	0.00

L_{95}/L_{05}						
Mask	***df***	***F***	***p***	***p***	**$R^2_{cond.}$**	**$R^2_{marg.}$**
20° band	(1,348)	45.76	5.7E-11	< 0.001	0.28	0.10
40° band	(1,355)	42.62	2.3E-10	< 0.001	0.31	0.11
60° band	(1,355)	36.42	4E-09	< 0.001	0.28	0.09
20° circle	(1,50)	21.44	2.6E-05	< 0.001	0.20	0.09
40° circle	(1,52)	13.85	0.00048	< 0.001	0.14	0.06
60° circle	(1,72)	8.37	0.00506	< 0.01	0.11	0.03
80° circle	(1,119)	6.66	0.01109	<0.05	0.11	0.02
100° circle	(1,267)	8.27	0.00436	< 0.01	0.12	0.03
120° circle	(1,322)	3.12	0.07816	0.08	0.10	0.01
140° circle	(1,347)	0.22	0.63884	0.64	0.10	0.00
160° circle	(1,343)	0.78	0.37832	0.38	0.11	0.00

$Log_{10}(L_{95}/L_{05})$						
Mask	***df***	***F***	***p***	***p***	**$R^2_{cond.}$**	**$R^2_{marg.}$**
20° band	(1,336)	51.91	3.8E-12	< 0.001	0.27	0.12
40° band	(1,354)	53.79	1.5E-12	< 0.001	0.37	0.14
60° band	(1,354)	38.98	1.2E-09	< 0.001	0.30	0.10
20° circle	(1,40)	26.76	6.7E-06	< 0.001	0.24	0.12
40° circle	(1,45)	25.50	7.9E-06	< 0.001	0.22	0.11
60° circle	(1,79)	23.84	5.4E-06	< 0.001	0.19	0.09
80° circle	(1,114)	21.43	9.8E-06	< 0.001	0.17	0.08
100° circle	(1,175)	10.39	0.00152	< 0.01	0.14	0.03
120° circle	(1,258)	4.88	0.0281	<0.05	0.11	0.02
140° circle	(1,334)	0.56	0.45562	0.46	0.10	0.00
160° circle	(1,333)	0.54	0.46127	0.46	0.11	0.00

5th percentile (L_{05})						
Mask	***df***	***F***	***p***	***p***	**$R^2_{cond.}$**	**$R^2_{marg.}$**
20° band	(1,334)	70.97	1.1E-15	< 0.001	0.46	0.20
40° band	(1,226)	52.25	7.5E-12	< 0.001	0.49	0.20
60° band	(1,280)	58.64	3.1E-13	< 0.001	0.48	0.20
20° circle	(1,87)	79.58	6.2E-14	< 0.001	0.47	0.29
40° circle	(1,101)	80.06	1.9E-14	< 0.001	0.44	0.27
60° circle	(1,295)	82.88	1.4E-17	< 0.001	0.33	0.21
80° circle	(1,354)	93.02	1.1E-19	< 0.001	0.31	0.21
100° circle	(1,316)	94.60	1E-19	< 0.001	0.33	0.18
120° circle	(1,353)	63.72	2E-14	< 0.001	0.32	0.15
140° circle	(1,345)	49.78	9.5E-12	< 0.001	0.35	0.13
160° circle	(1,326)	51.51	4.8E-12	< 0.001	0.40	0.15

10th percentile (L_{10})						
Mask	***df***	***F***	***p***	***p***	**$R^2_{cond.}$**	**$R^2_{marg.}$**
20° band	(1,284)	62.02	7.3E-14	< 0.001	0.48	0.20
40° band	(1,155)	42.70	8.7E-10	< 0.001	0.49	0.19
60° band	(1,257)	57.60	5.9E-13	< 0.001	0.52	0.21
20° circle	(1,81)	66.77	3.5E-12	< 0.001	0.40	0.24
40° circle	(1,162)	75.84	3.4E-15	< 0.001	0.36	0.23
60° circle	(1,327)	101.55	5.6E-21	< 0.001	0.34	0.24
80° circle	(1,345)	107.31	4.5E-22	< 0.001	0.33	0.22
100° circle	(1,318)	105.22	1.6E-21	< 0.001	0.36	0.20
120° circle	(1,355)	86.17	1.7E-18	< 0.001	0.44	0.20
140° circle	(1,292)	64.62	2.3E-14	< 0.001	0.53	0.22
160° circle	(1,290)	68.34	5E-15	< 0.001	0.55	0.23

90th percentile (L_{90})						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,288)	39.37	1.3E-09	< 0.001	0.35	0.12
40° band	(1,272)	49.04	2E-11	< 0.001	0.43	0.16
60° band	(1,338)	54.53	1.2E-12	< 0.001	0.38	0.15
20° circle	(1,58)	0.41	0.52284	0.52	0.10	0.00
40° circle	(1,66)	0.22	0.64003	0.64	0.11	0.00
60° circle	(1,64)	0.76	0.38811	0.39	0.12	0.00
80° circle	(1,61)	3.17	0.07975	0.08	0.16	0.01
100° circle	(1,210)	33.77	2.3E-08	< 0.001	0.38	0.13
120° circle	(1,339)	53.05	2.3E-12	< 0.001	0.38	0.15
140° circle	(1,351)	59.38	1.3E-13	< 0.001	0.38	0.15
160° circle	(1,355)	62.69	3.1E-14	< 0.001	0.37	0.15

95th Percentile (L_{95})						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,59)	0.04	0.85222	0.85	0.11	0.00
40° band	(1,55)	7.57	0.00802	< 0.01	0.21	0.04
60° band	(1,194)	29.32	1.8E-07	< 0.001	0.34	0.11
20° circle	(1,64)	0.04	0.84861	0.85	0.10	0.00
40° circle	(1,117)	4.11	0.04491	<0.05	0.16	0.02
60° circle	(1,150)	7.41	0.00724	< 0.01	0.19	0.03
80° circle	(1,201)	8.07	0.00495	< 0.01	0.19	0.03
100° circle	(1,238)	18.51	2.5E-05	< 0.001	0.26	0.06
120° circle	(1,295)	29.68	1.1E-07	< 0.001	0.30	0.09
140° circle	(1,312)	30.35	7.5E-08	< 0.001	0.29	0.09
160° circle	(1,328)	32.52	2.6E-08	< 0.001	0.29	0.10

Maximum						
Mask	*df*	*F*	*p*	*p*	$R^2_{cond.}$	$R^2_{marg.}$
20° band	(1,175)	37.64	5.5E-09	< 0.001	0.22	0.12
40° band	(1,95)	29.36	4.5E-07	< 0.001	0.21	0.11
60° band	(1,351)	1.26	0.26296	0.26	0.10	0.00
20° circle	(1,201)	29.44	1.6E-07	< 0.001	0.22	0.10
40° circle	(1,119)	33.86	5.1E-08	< 0.001	0.22	0.12
60° circle	(1,116)	32.72	8.4E-08	< 0.001	0.22	0.12
80° circle	(1,144)	27.81	4.8E-07	< 0.001	0.22	0.10
100° circle	(1,302)	6.38	0.01202	<0.05	0.12	0.02
120° circle	(1,320)	15.47	0.0001	< 0.001	0.13	0.04
140° circle	(1,353)	8.17	0.0045	< 0.01	0.12	0.02
160° circle	(1,354)	11.22	0.0009	< 0.001	0.12	0.03

A

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Summary

Lighting in office spaces should support knowledge workers in performing their tasks, for instance through creating visibility, and facilitating alertness and cognition. But the workplace should also be appealing to the user, and a place they feel comfortable in. This implies that various light parameters in the full space may play a role and should be considered in a broad, integrative context. To this end, light effects should not only be studied in confined laboratory settings, but also in more realistic settings, which include the overall décor as well as the presence of other occupants.

In a series of experiments, we investigated users' responses and functioning in semi-realistic open plan office environments, with multiple participants 'working' in the space at the same time. In these spaces, we carefully isolated different lighting design parameters (i.e., illuminating the walls, desk, and ceiling) to understand the effects of these individual parameters on a wide array of dependent variables ranging from task performance to room appraisal.

Our first experiment (Chapter 2) focused on the effect of wall luminance with the intent to create different levels of spatial brightness, knowing that brightness is one of the key components in room appraisal, which in turn could lead to changes in positive or negative affect and subsequent performance. Key in this setup was that both the desk illuminance and the illuminance on the eyes of the participants were kept constant to eliminate effects of visual acuity improvements or increased stimulation of the ipRPG's through the non-image forming pathway. Our findings showed that even though both the brightness and the attractiveness were affected, mood, divergent and convergent thinking (tasks related to problem solving) and executive functioning were not. However, an increase in wall luminance appeared to support the participants in maintaining their level of subjective alertness instead of experiencing a decline over the 1,5-hour test session.

Next, we repeated the experiment, but this time we varied the desk and eye illuminance, keeping the appearance of the rest of the space similar by fixing the wall luminance (Chapter 3). Although we expected this to result in increased performance on tasks, we found close to no results, i.e., we did not find an effect on the performance tasks, nor did we see an effect on mood and attractiveness. What we did found, however, was an increase in the perceived brightness, indicating that not all brightness increases also result in an increase in attractiveness.

In our third experiment (Chapter 4), we focused on the ceiling as the primary stimulus to investigate in particular the effects on appearance of the space. Given the results of the first two experiments, we discarded performance and alertness effects for this study, to make room for a more diverse set of stimuli, testing 5 different direct/indirect light ratios, in combination with 3 different luminance distributions on the ceiling. This study led to several new insights, of which the first was that next to the ratio of direct/indirect light, also the luminance distribution on the ceiling impacted the appraisal of the space. It was shown that the most positive appraisals were achieved with 100 % indirect light, with the most uniform ceiling distribution. Our findings also pointed us to two distinct sub-groups of participants. The first group responded to the different stimuli more strongly and appeared to show a positive (high) correlation between brightness and attractiveness, whereas the second group appeared to be more indifferent to the stimuli and even showed a negative (substantially weaker) correlation between brightness and attractiveness.

As both the first and third experiment showed a clear link between brightness and attractiveness, we set out to better understand how various light parameters result in brightness ratings. To this end, we performed a meta-analysis of the data of the three experiments, using the high-resolution luminance data to extract different characteristics of the luminance distribution over different areas of the visual field from the perspective of each participant (Chapter 5). We found that the logarithm of the median luminance, calculated over the 60° horizontal band, and the logarithm of the 95^{th} percentile/median luminance ratio, calculated over the 40° horizontal band provided comparably high model fits for the brightness responsive participants (~ 75 % fit), and ~50 % fit across all participants.

In the overall discussion, we reflect on the insights gained in this series of experiments. We conclude that when meaningfully different light parameters were varied across a substantial range in our semi-realistic office setting, the (short term) effects that were most dominant and measurable were those pertaining to the appraisal of the space. A notable second finding is that in contrast to changing the illuminance on the eye, changing the appearance of the space was shown to support subjective alertness, but not task performance or emotional state. This is especially important in the context of studies into the non-visual effects of light as it highlights that the visual appearance of the space is an essential parameter to take into account. In addition, it was shown that there is a clear correlation between the perceived brightness and the attractiveness of the space with the walls playing a dominant role in the determination of the brightness. Next to these general lighting related effects, it is also worthwhile to note that we found clear interpersonal differences, not only in attractiveness ratings, but also in brightness ratings. In particular, we found that participants could be clustered into either a brightness-responsive or brightness-indifferent group, highlighting the need to take interpersonal differences into account for future studies in which room appraisal and/or brightness are expected to play a role. Next to this, it also has implications for lighting designers who need to design for a diverse workforce.

Collectively, our findings contribute to a better understanding of the short-term effects of the lit environment on office workers and highlight the need to study (and design for) the psychological and physiological effects in parallel when striving for integrative lighting.

Samenvatting

Verlichting in kantoren hoort kenniswerkers te ondersteunen in hun taken, onder andere door zichtbaarheid te verbeteren en alertheid en concentratie te faciliteren. Daarnaast zou de werkplek aantrekkelijk moeten zijn voor gebruikers en een plek waar zij zich comfortabel voelen. Vanuit een lichtontwerp betekent deze brede doelstelling dat niet alleen de verlichting op het bureau, maar juist ook de verlichting/aanlichting van de hele ruimte belangrijk is. Het is dan ook essentieel dat onderzoek in dit veld niet alleen in laboratoria plaatsvindt, maar juist ook in meer realistische omgevingen, waarbij niet alleen het decor, maar ook de aanwezigheid van collega's een rol kan spelen.

In een reeks experimenten hebben we de effecten van specifieke licht-interventies op de ervaringen en het functioneren van kantoorgebruikers bestudeerd in een semi-realistische kantoortuin waarin meerdere mensen tegelijk aan het werk waren. Om in deze realistische omgevingen toch verschillende potentiële effecten van de verlichting te kunnen onderscheiden, werden de interventies zo ontworpen dat ze hoofdzakelijk de verlichting van een specifiek deel van de ruimte beïnvloedden, zonder de andere/naburige vlakken te beïnvloeden. Zo hebben we het effect gemeten van het aanlichten van respectievelijk alleen de wand, alleen het bureau en alleen het plafond, waarbij de verlichting van de andere vlakken onveranderd bleef. Tegelijk hebben we een breed scala aan afhankelijke variabelen gemeten, variërend van taakprestatie tot beoordeling van de ruimte.

In het eerste experiment (Hoofdstuk 2) lag de focus op het variëren van de helderheid in de ruimte door variaties aan te brengen in de luminantie van de wand. Hierbij was het uitgangspunt dat waargenomen helderheid in een ruimte een belangrijke bijdrage levert aan de beleving van die ruimte en als zodanig een effect op emotie zou kunnen veroorzaken, dat vervolgens een effect kan hebben op het presteren van kenniswerkers. Essentieel in deze opzet was dat zowel de verlichtingssterkte op het oog als die op het bureau constant werden gehouden om effecten door verbeterd zicht of verhoogde stimulering van de ipRGC's (het non-visuele pad) te vermijden. Onze resultaten lieten zien dat helderheid en aantrekkelijkheid van de ruimte inderdaad werden beïnvloed door de luminantie van de wand, maar dat dit niet resulteerde in effecten op emotie, op divergent of convergent denken, of op executieve functies van het brein. Een verhoging van de luminantie op de wand ondersteunde kantoorgebruikers wel in het handhaven van hun alertheid tijdens de 1,5 uur durende testsessie, terwijl die alertheid afnam bij lagere helderheden op de wand.

Het tweede experiment (Hoofdstuk 3) volgde eenzelfde opzet als het eerste (m.b.t. ruimte, taken etc.), maar nu werd de verlichtingssterkte op het oog en het bureau gevarieerd, waarbij de luminantie van de wand constant werd gehouden. Hoewel de verwachting was dat dit zou leiden tot een verbetering van de taakprestatie, werden er weinig tot geen effecten gevonden op de diverse taken, noch op alertheid, emotie of aantrekkelijkheid. Wel had de verlichtingssterkte een effect op de waargenomen helderheid in de ruimte, waaruit kan worden geconcludeerd dat niet elke verhoging in waargenomen helderheid automatisch resulteert in een verhoging van aantrekkelijkheid van de ruimte.

In het derde experiment (Hoofdstuk 4) stond het plafond centraal. Op basis van de resultaten van de eerste twee experimenten werd besloten om hoofdzakelijk de effecten van verschillende lichtverdelingen op de ruimtebeleving te analyseren. Effecten op taakprestatie en alertheid werden niet gemeten in dit experiment. Hierdoor was het mogelijk de tijd per lichtinstelling te verkorten en daarmee een meer diverse set van lichtverdelingen aan te bieden. In dit experiment zijn vijf verschillende ratio's van directe (naar beneden gericht) en indirecte (op plafond gericht) verlichting aangeboden in combinatie met drie verschillende lichtverdelingen voor de indirecte verlichting op het plafond. Dit experiment leidde tot een aantal nieuwe inzichten, waaronder het inzicht dat niet alleen de verhouding van directe tot indirecte verlichting, maar ook een meer uniforme lichtverdeling op het plafond de beleving en waardering van de kantoorgebruikers positief beïnvloedde. Daarnaast werd duidelijk dat de groep proefpersonen opgedeeld konden worden in 2 subgroepen met betrekking tot hun beoordeling van de ruimte. De eerste groep reageerde sterker op de verschillende stimuli, en liet ook een sterk positieve correlatie zien tussen helderheid en aantrekkelijkheid van de ruimte. De tweede groep gaf aan weinig verschillen te zien in waargenomen helderheid voor de verschillende oplossingen en liet ook een (zwakke) negatieve correlatie zien tussen helderheid en aantrekkelijkheid.

Aangezien zowel het eerste als het derde experiment een duidelijk verband toonde tussen helderheid en aantrekkelijkheid van de ruimte, hebben we dit verband verder onderzocht in Hoofdstuk 5, door een meta-analyse uit te voeren op de data van de eerste drie experimenten. Hierbij hebben we de helderheidsscores van de proefpersonen gerelateerd aan diverse karakteristieken van de luminantie verdeling in het gezichtsveld. De resultaten van deze meta-analyse lieten zien dat waargenomen helderheid het best gemodelleerd kon worden op basis van de logaritme van de mediaan van de luminantie berekend over de 60° horizontale band van het gezichtsveld (gezien vanuit de positie van de gebruiker, recht vooruit kijkend), of op basis van de logaritme van de ratio van het 95e percentiel en de mediaan van de luminantie berekend over de 40° horizontale band.

In de discussie wordt gereflecteerd op de bevindingen en concluderen we dat bij het variëren van relevante lichtontwerpparameters in een semi-realistisch kantoor, gebruik makend van een groot luminantiebereik, de korte termijn effecten zich vooral beperken tot effecten op de beleving van de ruimte. Een opvallend resultaat is dat niet de verhoging van de verlichtingssterkte op het oog, maar wel een verhoging van de luminantie van de wand subjectieve alertheid lijkt te ondersteunen, zonder dat dit impact heeft op taakprestatie of emotie. Dit is vooral relevant in de context van studies die kijken naar de niet-visuele effecten van licht, aangezien onze resultaten aantonen dat het uiterlijk van de ruimte een belangrijke rol kan spelen bij subjectieve alertheid. Daarnaast geven onze studies aan dat er een duidelijke correlatie is tussen de helderheidsbeleving en de aantrekkelijkheid van de ruimte, waarbij de luminantie van de wanden een dominante rol speelt. In de diverse studies hebben we substantiële verschillen tussen proefpersonen gevonden, niet alleen op basis van hun beoordeling van aantrekkelijkheid, maar juist ook in hun beoordeling van de helderheid van de ruimte. Uit onze data blijkt dat de deelnemers in te delen zijn in twee groepen die juist sterk, of juist bijna niet reageren op helderheidsverschillen in de ruimte. Dit geeft aan dat het essentieel is dat interpersoonlijke verschillen meegenomen worden in toekomstige studies waarbij aantrekkelijkheid of helderheid een rol spelen. Dit is niet alleen relevant voor onderzoek, maar natuurlijk ook bij het inrichten van de kantooromgeving, waar de ontwerper rekening moet houden met een diverse populatie van kantoormedewerkers.

Alles bij elkaar genomen, dragen onze bevinden bij aan het begrijpen van de korte-termijn effecten van verlichting in kantoortuinen, met als duidelijke conclusie dat in onderzoek en lichtontwerp men zowel de psychologische als ook de fysiologische gevolgen van licht moeten meenemen om tot integratief lichtontwerp te komen.

List of publications

Journal papers

A. de Vries, J.L. Souman, B. de Ruyter, I. Heynderickx, Y.A.W. de Kort, Lighting up the office: The effect of wall luminance on room appraisal, office workers' performance, and subjective alertness, Build. Environ. 142 (2018) 534–543. doi:10.1016/j.buildenv.2018.06.046.

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A. de Vries, I. Heynderickx, J.L. Souman, Y.A.W. de Kort, Putting the ceiling center stage – The impact of direct/indirect lighting on room appraisal, Build. Environ. (2021). doi:10.1016/j.buildenv.2021.107989.

A. de Vries, I. Heynderickx, Y.A.W. de Kort, From luminance to brightness – a data driven approach to predicting brightness in open plan offices. – submitted/under review Light. Res. Technol. (2021)

Conference papers

A. de Vries, I. Heynderickx, Y.A.W. de Kort, B. de Ruyter, Wall illumination - beyond room appraisal, Proc. 28th CIE Sess. (2015) 284–290.

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When I started work on this thesis back in 2013 I thought of it as a great way to both broaden and deepen my knowledge of the lighting application field. I'm happy to say that was indeed the case. I also thought it would "only" take me 4, maybe 6 years (part-time). However, like many before me, I rather underestimated that and without the many people supporting/motivating me (knowingly or unknowingly) I would never have been where I am today.

Starting with the long list of supervisors I had during this period: Eddine Sarroukh, who saw the potential of starting a PhD project in his research project and Sjoerd Mentink for seeing the relevance and making it more concrete by linking it to the lighting flagship collaboration between Philips and the TU/e. With this transition, also the role of the university was formalized, and I was assigned an official 1^{st} promotor, Yvonne de Kort. Yvonne, first of all, thanks for sticking with me throughout the entire process. It was a long process and progress wasn't always as quick as I wanted it to be, but thank you for your patience and always positive mindset in both guiding and mentoring me during this process. We had spirited discussions on numerous occasions, and you had to prevent me from 'lucht-fietsen' on even more occasions. However, our discussions were always constructive, and even though it usually resulted in me rewriting large sections of the manuscripts, it only helped in improving the overall quality. Thank you for that!

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Curriculum Vitae

Adrie de Vries was born on 19-02-1984 in Den Ham, the Netherlands. After obtaining his VWO degree at CSG het Noordik in Almelo in 2002, he enrolled in the Architecture, Building and Planning bachelor program at the Eindhoven University of Technology, followed by a master in Building Physics at same university, specializing in lighting. After graduating on the topic of the effects of (day)light on the performance of office users in 2008, he worked as a lighting consultant and designer for several years at the regional office of Royal Philips in the Netherlands. This was followed by several years in a consultancy role, supporting Philips product development in identifying the lighting and product requirements for the office product portfolio. As of 2017, Adrie started working in the Research branch of Signify (formerly known as Philips Lighting) focusing his efforts on the effects of lighting on office workers and developing new propositions around these effects. In addition, he is active in several standardization bodies working on global and European standards involving lighting design and workplace requirements (CIE, ISO, CEN). In parallel with the above-described activities, as of 2013, Adrie started pursuing his PhD degree at the Human Technology and Interaction group at the Eindhoven university of which the results are presented in this dissertation. In addition, this work resulted in being awarded the 2020 Walsh Weston Award (together with Yvonne de Kort and Jan Souman).

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