MASTER

The effects of lighting characteristics on atmosphere perception

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Master Thesis
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Preface

This Master Thesis is the product of my graduation project, which is part of the Master's program in Human Technology Interaction. This project was conducted at Philips Research in the group 'Visual Experiences'. During this project I investigated the effects of lighting characteristics on atmosphere perception. I learned how to conduct and report a good research project and gained new insights in research on perception, emotion, atmosphere and lighting engineering.

During this project I got excellent supervision and valuable contributions from my supervisors at Eindhoven University of Technology and Philips Research. I would like to thank Wijnand IJsselsteijn and Yvonne de Kort, and my supervisors at Philips Research, Ingrid Vogels and Ingrid Heynderickx. Furthermore I would like to thank my colleagues and the students from the perception group for having a great time, and for their help and advice. Finally I would like to thank my family and my friends for their support and personal advice during this project.

Thomas van Erp
Eindhoven, April 28th 2008

Summary

Light is an important phenomenon in human life. People benefit for example from the visual and psychological effects of light. The psychological effects, like atmosphere perception, are of interest for companies like Philips since consumers pay more and more attention to the experience of products. However, hardly any study has been conducted on the effects of lighting on atmosphere perception.

This study was conducted to investigate how general lighting influences the perceived atmosphere in a space. Atmosphere can be described as the *appraisal of an environment with respect to the expected affective effect*. The lighting characteristics intensity (low vs. vs. high), correlated color temperature (cool vs. warm) and spatial distribution of light (directional light vs. diffuse light), were varied in different light settings.

Participants were asked to fill in (1) a questionnaire about the appearance of the light (2) a preferences questionnaire and (3) an atmosphere questionnaire. Additionally, participants were asked to give their associations with the lighting and to come up with suitable applications for each light setting.

The results of the lighting appearance questionnaire showed that participants were able to discriminate between the different levels of intensity, CCT and spatial distribution that were presented in the experiment. However, these lighting characteristics interact with each other, which mean that the perceptual attribute of a lighting characteristic is influenced by the value of several light characteristics. In addition, an effect of gender between light distribution on uniformity perception was found.

Participants had clear preferences for certain levels of intensity, CCT and spatial distribution. In general, high intensities were preferred over low intensities and light with a low CCT was preferred over light with a high CCT. Furthermore, directional light was slightly more preferred over diffuse light.

A factor analysis on the data of the atmosphere questionnaire revealed that perceived atmosphere can be described with four factors: *coziness, liveliness, tenseness* and *detachment*. It was found that exposure to different levels of lighting characteristics has an effect on each of these four dimensions.

A high intensity was perceived as more *lively*, less *tense* and less *cozy* (at a low CCT level). A high intensity was perceived as more *detached* for the diffuse light at high CCT and for the directional lights. For the diffuse settings a low CCT was perceived as more *cozy,* less *tense*, and less *detached* than a high CCT. In addition, for a medium and high intensity a low CCT was perceived as more *lively*. At low intensities both CCT levels are perceived as equally *lively*. Directional light was perceived as more *cozy,* more *lively,* and less *tense* compared to diffuse light at the same brightness.

The results from the application questionnaire show that intensity and CCT are an important factor in judging suitability for a functional application. The higher the intensity and CCT, the more suitable a setting is for a functional application. A low CCT is suitable for a relaxing application.

This study gives valuable insight in the effect of different lighting characteristics on atmosphere perception. In order to gain insight in the effects of lighting in everyday environments, this experiment should be repeated for a broader range of lighting characteristics (e.g. different types of decorative lighting) and environments (e.g. different types of furniture).

Contents

1. Introduction

Light is an important phenomenon in human life. People benefit indirectly from sunlight by consuming products of plants that use sunlight to grow, and directly by using sunlight to regulate hormones and to produce essential vitamins. Hence, light is a necessary condition for human life. However, people benefit also from the visual and psychological effects of light. Light can be used to make things visible and to support daily activities. It can also be used as a medium to express information. Painters, designers and architects, for example, use light to express and evoke emotions or to create a certain atmosphere in their work. However, they are often not aware of the psychological mechanisms behind these effects.

The psychological effects of lighting are of interest for companies like Philips. Consumers pay more and more attention to the experience of products instead of the plain commodities only. Knowledge about psychological effects can be used in the design of new lighting applications, or as a tool for lighting designers to enhance experience.

In the past, research on the effect of lighting has mainly focused on functional aspects, like visibility and visual comfort (e.g. glare and flicker). During the 1960's and 1970's lighting designers and researchers started to study the effect that lighting has on people's feelings when they are in an environment (for a review: Murdoch & Caughey, 2004). However, the psychological effects of lighting on experience and feelings were not extensively studied until the 1990's. Recent studies have measured the effect of lighting on people's appraisal, preference and affective states.

However, hardly any study has been conducted on the effects of lighting on atmosphere perception. Atmosphere can be described as the *appraisal of an environment with respect to the expected affective effect*. Hence, atmosphere is not an affective state but it has the potency to evoke an affective state in accordance with the atmosphere. Because the affective state of a person can be influenced by many other factors than the lighting of the environment, it might be better to investigate the perception of the atmosphere of an environment. For example, a relaxed environment can make you feel relaxed. However, if I think of all the work that I have to do in a short time I would still feel pretty stressed. In a stressful environment, on the other hand, I will never feel relaxed. The exact mechanisms behind the relation between atmosphere perception and affective states are unknown. Atmosphere perception has been studied by Vogels (2008) and De Vries and Vogels (2007). Vogels (2008) developed an instrument to asses and quantify the perceived atmosphere of an environment. De Vries et al. (2007) used the method of Vogels (2008) and found that light has an effect on perceived atmosphere. However, this study did not investigate the relation between light and atmosphere.

To investigate the effect of light on perceived atmosphere in a space, a distinction can be made between general lighting, accent lighting and decorative lighting. General lighting provides a general level of visibility, accent lighting emphasized a particular place, and decorative lighting is used for decoration. A logical order would be to first investigate the effect of general lighting on atmosphere perception. Subsequently, the effect of accent lighting and decorative lighting should be investigated. In this study the effect of lighting characteristics of general lighting on the perception of atmosphere is investigated. The research question of this study is:

How does general lighting influence the perceived atmosphere in a space?

There are several ways to characterize general lighting. Some lighting characteristics are: intensity, color temperature (CT), spatial light distribution of a light source and dynamics. Intensity refers to the amount of energy the light contains. Brightness is the perceptual attribute of intensity. CT is a way to express the color qualities of a white light source. The CT of a light sources ranges from a low CT, which is perceived as warm yellowish/reddish white, to a high CT, which is perceived as cool bluish white. Spatial light distribution of a light source refers to the distribution of the light from a single source, which can be directional or diffuse. Directional light sources are sources with a small beam angle and have a distinct light beam. Diffuse light sources, on the other hand, are sources with a large beam angle and no distinct beam. The spatial light distribution of a light source contributes to the distribution of light in a space, which can be perceived as uniform or non uniform. Notice that spatial light distribution in a space depends, next to the type of light source, also on, among other things, the number of light sources and the distance between the sources. Dynamics refers to changes of lighting characteristics over time. It results in temporal changes of the perception of the lighting characteristics.

In this study we consider intensity, CT and spatial light distribution of a light source as the most important lighting characteristics. Dynamics are of less importance for now, since most general lighting systems are static. Therefore the research question can be divided in the following sub questions:

- *What is the effect of intensity on the perceived atmosphere in a space?*
- *What is the effect of CT on the perceived atmosphere in a space?*
- *What is the effect of spatial light distribution of a light source on the perceived atmosphere in a space?*

These questions are investigated in this study. Chapter two presents a literature review on topics that are related to atmosphere perception. Additionally, the results from previously conducted experiments on atmosphere perception are discussed (De Vries and Vogels, 2007; Vogels, 2008). Chapter three continues with the experimental design of this study. In Chapter four the experiment is described and results are presented. Finally, in Chapter five, the results are discussed and suggestions for further research are made.

2. Literature review

To date not much is known about the effects of lighting on atmosphere perception. However, a number of studies have investigated topics that are strongly related to atmosphere perception. These topics are discussed in this chapter. This chapter starts with an overview of the perception of lighting characteristics and continues with a discussion of studies on preference of lighting characteristics. Subsequently, we give an overview of studies on affective states and studies on the effects of lighting on affective states. Finally, studies on environmental appraisal are discussed.

2.1. Perception of lighting characteristics

This paragraph gives an overview of the perception of lighting characteristics: intensity, correlated color temperature, color rendering index and spatial light distribution. Most general lighting systems can be described in terms of these characteristics. Therefore, we will not consider other characteristics such as dynamics, as they are not relevant for our study.

2.1.1. Intensity

Brightness of light corresponds to the perceived amount of light. The amount of light can be expressed in terms of illuminance and luminance. Illuminance refers to the amount of light that falls on a surface, expressed in lumens per square meter or lux. Luminance refers to the amount of light that comes off a surface, expressed in candelas per square meter. Stevens (1961, as cited in Boyce, 2003) was the first to show that there is a consistent relationship between luminance and brightness, using a self luminous target. Later, various experiments were conducted to investigate the effect of illumination level in a room on brightness perception. For example, Davis and Ginthner (1990), Baron, Rea and Daniels (1992) and McCloughan, Aspinall, and Webb (1999) found that participants rated a room with higher illuminance as brighter compared to a room with lower illuminance. Ishida and Ogiuchi (2002) found that the brightness of a space is highly correlated with the perceived amount of light in that space and not with the perceived strength of a light source. They asked participants to evaluate the intensity of their sense of 'the strength of the light source', 'the amount of light filling a space' and 'the brightness of the space' for several light settings in a light box with objects, without being able to see the light source.

Many studies have investigated the relation between the brightness of a room and the physical characteristics of the illumination. Researchers have found that brightness relates very well to the average luminance within a person's field of view (Loe, Mansfield & Rowlands, 1994; Iwai, Saito & Sumi, 2001 and Kato & Sekiguchi, 2005). Loe et al. (1994) defined this field of view as the 40 degrees vertical visual angle, and the whole horizontal visual field, at normal eye height. They state that it means that in relatively small rooms brightness perception relates to the average luminance of the wall surfaces. However in larger rooms, brightness impression is related to the average luminance of the wall, ceiling and floor surfaces. Loe et al. (1994) showed participants eighteen light settings with different luminance distribution in the room and asked them to fill in a questionnaire about the perception of the room illumination. Participants observed the light settings from a fixed location. Visual lightness, which is closely related to brightness, was one of the factors that was identified from the questionnaire. The experiment showed a high correlation between visual lightness and the logarithm of luminance averaged over a 40 degrees vertical visual angle centered at normal eye height. Iwai et al. (2001) asked participants to compare the brightness of several test light settings with a reference light setting. They used different types of downlights, which resulted in different average luminance distributions on the walls, the corners and the whole field of view. Participants observed the light settings from a fixed location. It was found that an increase in average luminance on the wall, corners and whole field of view resulted in an increase in estimated room brightness. Kato and Sekiguchi (2005) asked participants to judge the brightness of a room with light coming from a horizontal (ceiling) plane or a vertical (wall) plane. Participants observed the light settings from a fixed location, towards a desk and towards the observer's front. They concluded that the direction of light relative to the visual direction of the observer had an impact on brightness impression. Light from a horizontal direction was evaluated as brighter than from a vertical direction. Furthermore, the average illuminance from the surface perpendicular to the viewing direction correlated very well with brightness impression.

Brightness impression in a room has also been found to depend on spatial distribution of luminance across the walls. Tiller and Veitch (1995) found that a room with a non uniform distribution appears to be brighter than a room with a uniform distribution even when the average luminance across the participant's field of view is the same. Kato and Sekiguchi (2005) found the opposite results. Tiller et al. (1995) asked in their experiment to match the brightness between an office with a uniform and an office with a non uniform luminance distribution across the walls, by adjusting the illuminance of the working plane. Participants observed the light settings from a fixed location. They found that the offices with non uniform luminance distribution across the walls required five to ten percent less working plane illuminance to match the brightness of the offices with uniform luminance distribution. Kato et al. (2005) presented one, two, three, or four vertical, diffuse (wall) plane light sources, while keeping the total luminance across the room constant. They used three levels of total luminance, and asked participants to rate the brightness impression of the room. Participants were free to move in the room. They found that it is more effective to increase the number of plane light sources than the mean luminance per plane to obtain a higher brightness impression. This implies, in contrast to the study of Tiller et al. (1995), that a more homogenous luminance distribution appears brighter.

Other experiments have shows that brightness perception is not solely dependent on illumination, but also on gender and age (Knez & Enmarker, 1998; Knez & Kers, 2000). Knez et al. (1998) found that female participants estimated the room as less dim compared to male participants. However, they found no gender effect on the bright scale. In a later experiment, Knez et al. (2000) found that younger adults assessed the room as brighter than the older participants. They explained the effect of age by the fact that older people are less sensitive for light intensities due to age related impairments. No explanation was given by Knez et al. (1998) for the gender effect on brightness.

2.1.2. Correlated color temperature

Color temperature (CT) is used to characterize the color of light emitted by a light source. The basis of this measure is Planck's radiation law: the spectral emission and, consequently, the chromaticity coordinates of a black body radiator are a function of its temperature. Figure 1 shows the Planckian locus (or: black body curve) in the CIE 1931 color space.

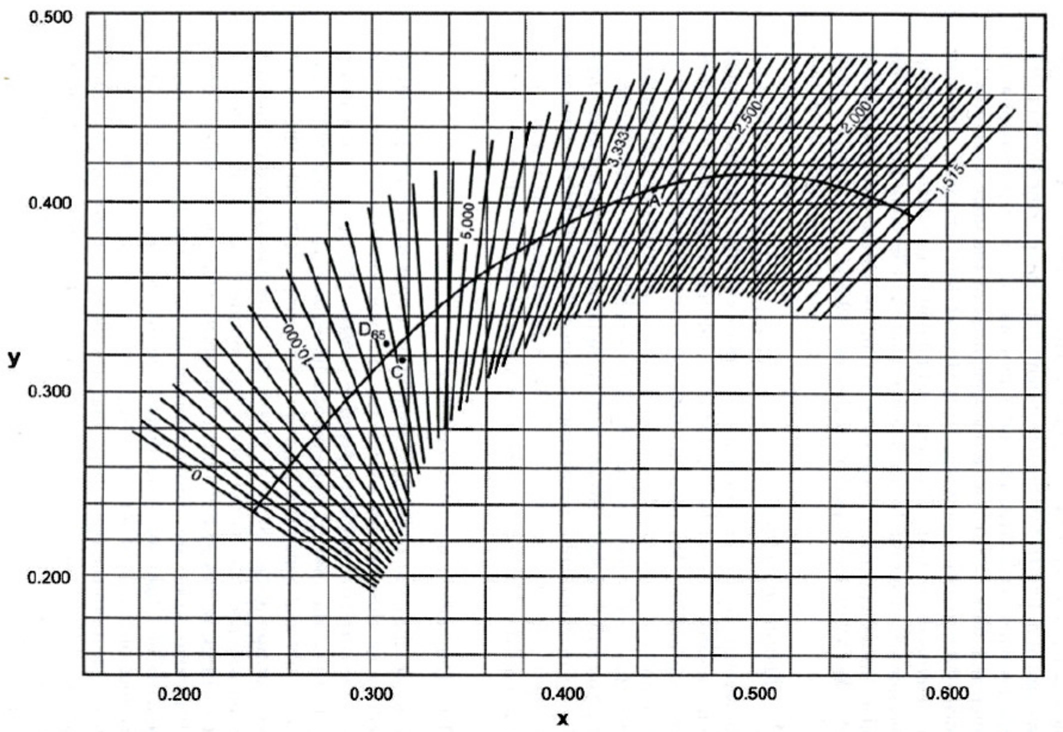


Figure 1: The Planckian locus plotted in the CIE 1931 chromaticity diagram. The lines crossing the locus are the lines of constant correlated color temperature. Incandescent lamps usually have a CCT of 2700K, tungsten halogen lamps have a CCT of 2900K and the CCT of fluorescent tube lights varies over a wide range up to 17000K (Boyce, 2003).

The lines crossing the locus are called the iso-temperature lines. This means that the perceived color of a point in the chromaticity space is most similar to the perceived color of the point on the locus that is connected through the iso temperature line. When the chromaticity coordinates of a light source lie on the Planckian locus, the color can be expressed by the CT (in [K]). All colors on an iso-temperature curve have the same correlated color temperature (CCT) which corresponds to the CT of the point on the locus. An alternative metric is the reciprocal CT, which is defined as 10^6/CT, and expressed in reciprocal megaKelvin (MK^{-1}). The advantage of this metric is that it is a good measure for perceived differences in CT (Boyce, 2003). Judd (1933a, as cited in Wyszecki & Styles, 1982) found that the threshold for CT discrimination is 5.5 MK^{-1} between 1800K and 11000K.

The perceived CT can be evaluated using a bipolar scale with warm and cool at the edges of the scale. Davis and Ginthner (1990) found that the perception of color tone (cool, warm) changes with CCT. A high CCT, of 5000K, was perceived as cool and a low CCT, of 2750K, was perceived as warm. In contrast, McCloughan et al. (1999) and Knez and Enmarker (1998) found no effect of CCT on a warmth scale. In both studies CCT was varied at two levels, 3000K and 4000K. The difference might lay in the fact that Davis et al. (1990) used CT levels that were more extreme compared to the levels of McCloughan et al. (1999) and Knez and Enmarker (1998).

However, Knez and Enmarker (1998) did find effects of gender and Knez and Kers (2000) find effects of age. Knez et al. (1998) varied the CCT (3000K vs. 4000K) and asked participants to judge the perceived CT. He found remarkable significant gender effects on a warmth scale and a trend for gender on a cool scale. In sum female participants found the 4000K condition significantly more warm than the 3000K condition, whereas male participants found the 4000K condition more cool compared to the 3000K condition. No explanations were given for this effect. In a later study, Knez et al. (2000) found that younger participants assessed the room light as cooler as than older participants. They explained the effect of age by the fact that older people are less sensitive for light intensities due to age related impairments.

2.1.3. Color rendering index

The color rendering index (CRI) is a measure that indicates how well a light source renders a set of standard colors, compared to a reference light on the black body curve with the same CCT. Perfect agreement between the two sources is rated with 100. Incandescent and tungsten halogen lamps have a CRI of 100, because their chromaticity coordinate lies on the black body curve, whereas the CRI of fluorescent lamps usually vary between 50 and 95. A light source with a CRI above 80 produces creates a perception of greater brightness and visual clarity. A light source with a CRI below 60 is unsatisfactory because the fact that skin tones and other natural objects are unattractively rendered (Boyce, 2003).

2.1.4. Spatial light distribution

Spatial light distribution refers to the way light is distributed from a light source. It can affect the distribution of light in a space, which can be uniform or non uniform. The perceptual attribute is perceived uniformity. Loe, Mansfield and Rowlands (1994) showed participants eighteen light settings with different luminance distribution in the room and asked them to fill in a questionnaire about the perception of the room illumination. Participants observed the light settings from a fixed location. Perceived light pattern uniformity was measured with a uniform-non-uniform scale. They found that perceived light pattern uniformity was highly correlated with the logarithm of the ratio of maximum to minimum luminance, within a 40 degrees vertical visual angle centered at normal eye height.

2.1.5. Conclusion

In sum, research conducted on brightness show that the average luminance in a person's field of view is a predictor for brightness. However, average luminance in a person's field of view seems not appropriate to predict brightness impression between light settings with different luminance distributions. Furthermore, age and gender might play a role. However, the role of gender is questionable, since it cannot be explained and was not found in other literature. Perceived CCT can be measured with a warm cool scale. The effects of changes in CCT are not always found on this scale, possibly due to the fact that the differences between CCT levels were not extreme enough. Older people seem to be less sensitive for changes in CCT. Furthermore perceived CCT seem to interact with gender, however, this role cannot be explained. Spatial light distribution has an effect on the uniformity of luminance distribution across the room surfaces. The perceptual attribute, perceived uniformity, can be measured on a uniform-non-uniform scale.

In the experiment we will measure brightness, perceived color temperature and perceived uniformity. To control for possible gender effects we will include gender in the analysis of the results.

2.2. Preference of lighting

Many researchers have investigated which illuminance and CCT levels are preferred by people. However, contradictory results have been found, probably because of differences in culture and application (Boyce, 2003).

National lighting standards give recommendations about the choice of CCT for different illuminance levels, in order to create pleasant light settings. These recommendations are based on the work of Kruithof (1941). The Kruithof curve is displayed in Figure 2. For example, it is recommended not to use lamps with high CCT below an illuminance level of 300-500 lx. Combinations of CCT and illuminance levels that lie in the lower shaded area of the Kruithof curve are usually perceived as cold and dim. Combinations that lie in the upper shaded area are most perceived as overly colorful and unnatural. Only the combinations between the shaded areas are considered to be pleasant.

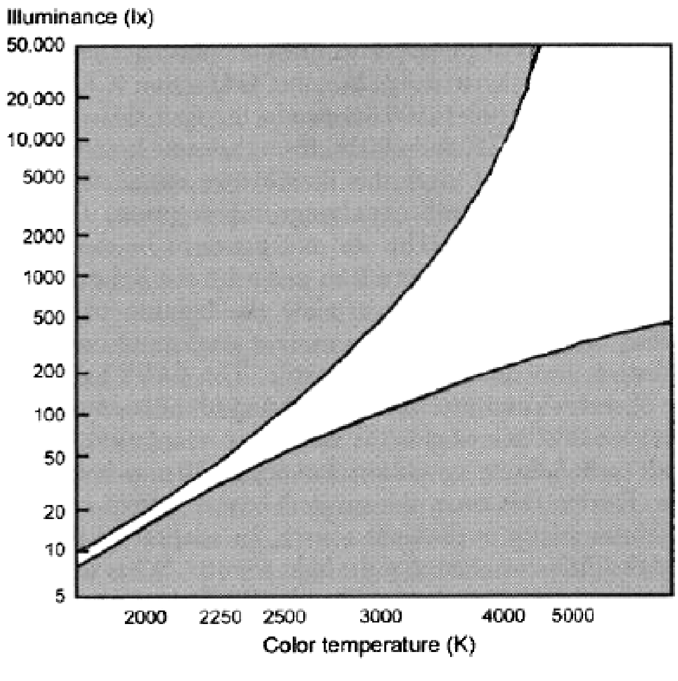


Figure 2: The Kruithof curve. The white area indicates the preferred combination of the CCT of a light source and the illuminance level. Combinations in the lower shaded area are claimed to produce cold and drab environments, whereas the combinations in the upper shaded area are said to produce overly colorful and unnatural environments (Boyce, 2003).

Boyce and Cuttle (1990) tested the Kruithof boundary conditions by presenting participants light settings at two different levels of CCT (2700K and 6500K) and four different illuminance levels (30, 90, 225 and 600 lx). Their main conclusion was that the preference of light was mainly determined by the illuminance level and not much by the CCT. High illuminance levels made the room appear more pleasant, comfortable, warm, uniform, and less hazy, oppressive, dim and hostile. They explained the absence of effects of CCT with chromatic adaptation. Because participants experienced the light for twenty minutes before they evaluated the room, their visual system was adapted to the chromaticity of the light source. Davis and Ginthner (1990) found similar results: preference ratings were influenced only by illumination level and not by CCT. Davis et al. (1990) asked participants to evaluate the room after sixty seconds. This means that adaptation might not play a role.

Researchers (e.g. Butler & Biner, 1987; Nakamura & Karasawa, 1999), have found that the preference of illuminance levels and CCT depends on many additional factors. Butler et al. (1987) found that preference for a light setting is dependent on the type of indoor environment, the behavior in that environment and gender. Nakamura et al. (1999) showed light settings that differed in illuminance level and asked Japanese participants to evaluate the atmosphere on a like-dislike scale for two imaginary settings: cheerfully conversing with family (communal state), and alone and relaxed while drinking a cup of coffee (solitary state). For both states the preference increased with illuminance levels, and decreases after a certain optimum. For the solitary state this was an optimum of 200 lux, and for the communal state 400 lx. Preference of space atmosphere was in general lower for the solitary state. Furthermore, for both states, low CCT levels were more preferred than high levels. Moreover, the results resemble the Kruithof curve for the communal state, but differ for the solitary state. As an explanation, Nakamura et al. (1999) state that the difference between the preference levels for the solitary state and the Kruithof curve might occur because Japanese people are more used to cool white fluorescent light compared to European people. They furthermore think that preference for lighting is dependent on activity. Also Oi and Takahashi (2007) found that the Kruithof curve is dependent on the situation in which certain lighting is applied. The only applications that fit in the curve were a Japanese dining space and gathering space. Applications that did not fit the Kruithof curve were: a cooking, studying, relaxing and a retiring space.

In sum people prefer certain intensity and CCT levels. However, preference seem to be influenced by the application of a light setting and possibly also by culture. It is nevertheless unclear how these mechanisms exactly work.

2.3. Emotions

Light has also an effect on people's mood and emotion. In this section we will first give a general overview of mood and emotions and ways to characterize these affective states. Finally we will present results from studies on the effects of lighting on affective states.

2.3.1. Theories

An affective state is a very broad term referring to the experience of feelings. It entails among other things emotions and moods. Emotions are affective states that last for a relatively short period of time and have very often clear causes. Whereas an emotion lasts for seconds or minutes, a mood can last for hours and even days. In contrast to emotion, mood most of the time has no obvious cause (Smith, Fredrickson, Loftus, & Nolen-Hoeksema, 2003). According to Lazarus (1991) an emotion is the result of a cognitive appraisal, which is a person's assessment of the meaning of the current circumstances. These circumstances can be for example a certain environment, an event, but also a relation with others or a thought. If these circumstances are assessed as important for our well being at that moment then an emotion is experienced. The intensity and type of emotion that we experience depends on the importance of the circumstance at that moment (Lazarus 1991; Smith, Fredrickson, Loftus, & Nolen-Hoeksema, 2003).

Emotions can be measured in numerous different ways based on, for example: behavioral variables, facial expression variables, physiological and cognitive variables.

There are many theories of emotions. Two theories are generally accepted to describe emotions. The first one is a categorical approach. This approach recognizes a number of universal basic emotions (e.g. Ekman, 1992). This is a discrete set, like fear, anger and enjoyment. Each basic emotion consists of a family of related states that share some characteristics. For example, there are numerous anger expressions. These expressions share some basic commonalities, but differ on some aspects, like controlled, provoked and simulated anger.

The second approach is a dimensional approach. According to this approach, an emotion can be described in a multidimensional space. Mehrabian and Russell (1974) proposed the PAD model. In this model emotions are described in terms of three dimensions: Pleasure, Arousal and Dominance. Pleasure is a state referring to the valence of an emotion, ranging from a positive to a negative evaluation. The arousal dimension refers to activity and alertness and ranges from arousal to non-arousal. The dominance dimension ranges from feelings of total lack of control or influence on events and surroundings to the opposite extreme of feeling influential and in control.

Different methods for measuring emotion are based on the PAD model. For example the semantic differential method of Mehrabian and Russell (1974), consist of eighteen bipolar mood adjectives. Russell, Weiss & Mendelsohn (1989) proposed the affect grid, which is a two-dimensional grid where people can asses their mood in terms of the two dimensions: pleasure-displeasure and arousal-sleepiness. Closely related, but more complete, is the self assessment manikin, or SAM, by Bradley and Lang (1994). Next to the dimensions Pleasure and Arousal, the Dominance dimension is measured in the SAM method. The three dimensions of the PAD model have to be rated on a pictorial scale.

Another multidimensional model is the Positive Affect, Negative Affect (PANAS) scale proposed by Watson, Clark and Tellegen (1988). This model assumes a two dimensional affective space. Positive affect (PA) and Negative affect (NA) are represented as two orthogonal dimensions. PA reflects a person's enthusiasm, activeness and alertness. This dimension ranges from high energy, full concentration and pleasurable engagement at high PA to sadness and lethargy. NA reflects distress and unpleasurable engagement. It ranges from anger, contempt, disgust, guilt, fear and nervousness at high NA to a state of calmness and serenity. PA and NA can be measured using a scale that is composed of ten unipolar scales representing PA and ten unipolar scales representing NA.

Mehrabian (1997) compared the PAD model with the PANAS model. He found that positive affect and negative affect can be described in terms of the dimensions pleasure, arousal and dominance; and that positive affect and negative affect correspond to the diagonals of the pleasure and arousal axes. Furthermore he found that the PANAS model cannot distinguish between anxiety and depression, whereas the PAD model can.

2.3.2. The effect of lighting characteristics on affective states

This paragraph provides a review of different studies about the affective experience of lighting.

The effects of intensity and CCT

Several researchers have investigated the effects of intensity and CCT of illumination on people's mood. However research conducted on this topic is, due to different measurement scales, procedures and environmental settings, difficult to compare and interpret.

Baron, Rea & Daniels (1992) manipulated intensity (500 lx and 1500 lx) and CCT (3000K and 4200K) and asked participants to fill in the PANAS questionnaire (Watson, Clark & Tellegen, 1988). No significant effects were found on the PA and NA scale. He only found a non-significant trend that people liked the warm-white light slightly more than the cool-white light. Therefore the experiment was repeated. However, instead of the PANAS scale the Current Feelings Survey was used. This survey consists of ten bipolar emotion scales. A significant interaction between illuminance level and CCT was found for the dimensions anxious-calm and sleepy-awake. In the condition with cool-white light no effect of light level on emotion was found. For the condition with warm-white light participants reported to be more calm and more awake in the 150 lx condition, compared to the 1500 lx condition. According to Baron et al. (1992) this provides some indication that these lighting conditions influenced positive affect.

Hygge and Knez (2001), Knez (1995a; 1995b), Knez and Enmarker (1998), Knez and Hygge (2002), and Knez and Kers (2000) did extensive research on the effect of lighting on emotion. In some studies they found no effect on lighting, in other studies they found some small effects of lighting on mood, and some complex interaction effects between CRI, CCT, illuminance and gender on PA and NA. For example Knez (1995a; 1995b) found no effect of illuminance on affect, consistent with a later study of Hygge and Knez (2001). However, Knez (1995a; 1995b) did also find an interaction effect between CCT and gender on Negative affect. Negative affect of females decreased in warm-white light and increased in the cool-white light. Negative affect of males increased in the warm, compared to the cool-white light. Knez and Hygge (2002) investigated the effects of CCT on affect, using another scale: the self reported affect scale. Using this scale, they did not find an effect of CCT on affect.

McCloughan, Aspinall, and Webb (1999) found initial and longer-term effects of lighting on mood. They varied average room illuminance on two levels (268 lx vs. 810 lx) and CCT on two levels (warm: 3000K vs. cool: 4000K) and assessed participant's mood on two moments in time: five and forty minutes after entering the experimental room. They assessed mood using a Multiple Affect Adjective Checklist. When mood was assessed after five minutes they found an effect of illuminance on sensation seeking, an effect of CCT on hostility and an effect of gender for Positive Affect and sensation seeking. After forty minutes they found several significant changes. They found an interaction effect of illuminance and CCT on anxiety and hostility. When illuminance increased, anxiety and hostility increased at low CCT levels and decreased at cool levels. Furthermore they found an interaction effect between CCT and gender on hostility and between illuminance and gender on dysphoria. For female participants hostility increased if CCT is more warm-white, whereas it stayed constant for male participants. These result for females are in line with Knez (1995a) but contradict Knez et al. (1998). Furthermore McCloughan et al. (1999) found an increase of dysphoria with illuminance for males whereas a reduction was found for females.

Fleischer et al. (2001) varied among others intensity, CCT and the ratio between direct and indirect light in an experimental setting. The room was side-lit with daylight; this was kept constant with shading facilities. They measured participant's emotion with the PAD questionnaire from Mehrabian and Russell (1974) and found effects of lighting characteristics on Pleasure, Arousal and Dominance. A high intensity increased the Pleasure component compared to a low intensity. Furthermore, CCT has an influence on the arousal component; cool white light (daylight color) was more stimulating compared to warm white. Dominance was affected by intensity. A high intensity (with an indirect component of 50%) leaded to a feeling of dominance. In contrast, low illuminance levels, especially with direct light, resulted in a feeling of inferiority.

Küller, Ballal, and Laike (2006) conducted a cross-cultural study and investigated among other things, the effects of intensity and the assessment of the intensity (a scale ranging from: 'clearly insufficient, much too dark' until 'very bright and glaring, too much light') on mood, in a real office environment. Mood was measured with 12 bipolar scales, which were combined into one index of emotional status. They found no relation between intensity and mood. However, Küller et al. (2006) did find a relation between intensity assessment and mood. When lighting was experienced as too dark or too bright, the mood was low. An optimum in mood was found when lighting levels were experienced as just right.

The effect of color

The effect of color on mood has been investigated in several studies. Blue and Violet blue are generally seen as pleasant. However, studies do not agree on the colors red, yellow and green. These differences might be due to differences in type of stimulus (e.g. colored light, painted walls or color chips) and differences in measuring the dependent variable.

Mahnke (1996) describes in his book a study conducted by Frieling in 1990. Participants were asked to look into different colors of light and comment on the light. However, it is not described how people had to look into the light. People found red light arousing without having a pleasure component. Furthermore, yellow, violet-blue and red were all found to be pleasant and calming.

Valdez and Mehrabian (1994) conducted a study on colored patches and emotion. They measured emotional reaction according to the PAD model in response to different colored patches according to the Munsell system. They found that brightness had a strong positive effect on pleasure and a negative effect on arousal and dominance. Saturation had a positive effect on pleasure, arousal and dominance. The effects emotion on hue tended to be weak. The most pleasant hues were: blue, blue-green, green, red-purple, purple, and purple-blue. The least pleasant hues were: yellow and green-yellow. The most arousing colors were green-yellow, blue-green and green. Purple-blue and yellow red were the least arousing. Greater dominance was induced with green yellow compared to red-purple.

Yildirim, Akalin-Baskaya & Hidayetoglu (2007) investigated the effect of indoor color on mood. A restaurant was presented in two ways: having yellow painted walls and having violet painted walls. Furniture and decorations remained the same. In line with Valdez et al. (1994), customers found the violet walls more pleasant compared to yellow walls. In general, younger people and male customers had a more positive attitude towards both environments.

2.3.3. Conclusion

Theories that are frequently used in studies on the effects of light on affective states are the PAD model and the PANAS. Studies on the effects of lighting on emotion report small or no effects that are inconsistent with other studies. Moreover, complex interaction effects are found which are often hard to explain and to understand intuitively. In sum these results make it hard to form a coherent view on the effects of lighting on emotion. It is expected that perceived atmosphere, as a dependent variable, will give larger and clearer effects.

2.4. Environmental perception, appraisal and atmosphere

According to Lazarus (1991), an emotion will only occur as a result of a situation if that situation is important for the person at that moment. Thus, in order to measure the effect of an environment or a certain light setting on emotion, this environment or light setting should be important for a person at the moment emotion is measured. If other factors are more meaningful at the moment, then this measured emotion is not, or only partly, caused by the environment. An Atmosphere is perceived by external elements and internal cognitive processes. External elements can be furniture, lighting color, fragrance and temperature for example.

Because an affective state can be affected by many non environmental factors measuring emotion might not be a proper tool to investigate the effect of the environment on people's experience. Therefore, it might be better not to ask about a person's affective state, but to ask about the evaluation of the environment. The environment can be evaluated by people on different levels. It can be described in objective terms, i.e. perceived environmental cues. It can be described in terms of appraisal, i.e. preference. But the environment can also be evaluated in terms of perceived atmosphere, i.e. the evaluation of a space in possible affective effects. Several theories on environmental evaluation exist.

The Kaplan and Kaplan environmental appraisal model (1975, as cited by Bell, Greene & Fisher, 2001; Veitch, 2001) states that people are attracted to scenes in which the processing of information is stimulated and in which this processing is successful. So, people prefer scenes that are understandable and make sense. But scenes must not be too simple or dull. They must be engaging and involving. According to the model of Kaplan and Kaplan appraisal is related to four information dimensions: coherence, legibility, complexity and mystery. A coherent setting is a setting that is organized and hangs together. Legibility refers to the degree of distinctiveness, so the viewer is able to understand or categorize the content of that scene. Complexity refers to the variety of elements of a scene. Mystery refers to the extent that people are drawn into a scene: a scene should contain a certain amount of hidden information to be drawn into. In general, preference for a scene increased as these dimensions increases. However, it should be noticed that an increase of one dimension might cause a reduction of another dimension.

Lighting design can influence the information dimensions and give meaning to a certain environment. However, a limited range of spaces have been studied yet (Veitch, 2001).

Flynn (1977a; 1977b) was one of the first to investigate the appearance of visual luminous conditions in spaces and the relation with appraisal. In his study he used semantic differential scaling to measure responses on different lighting conditions. The semantic differential scales were reduced to three factors. These factors are: perceptual clarity, evaluative impressions, and spaciousness. Perceptual clarity and spaciousness describes how an environment is visually perceived. The factor evaluative impression says something about preference.

Kaplan and Kaplan (1975, as cited by Bell, Greene & Fisher, 2001) and Flynn (1977a; 1977b) mainly studied how people assessed the environment terms of environmental cues. Researchers like Baron, Rea & Daniels (1992) and Knez (1995a) studied how lighting makes people feel. However, none of the studies took into account how an environment is appraised with respect to a potential affective state. None of the studies took into account atmosphere perception. Only Flynn (1977) and Manav (2007) asked to evaluate environments in terms of preference and some atmosphere words.

Atmosphere is not an affective state, but rather an appraisal of an environment with respect to a potential affective state. An experienced atmosphere has the potency to give rise to a certain emotion, in accordance with that atmosphere. This means that I can feel stressed in a relaxed environment if I am thinking of all the work that I have to do in such a short time. However in a stressful environment, I would never feel relaxed. Perceived atmosphere is among other things dependent on personal differences like age, culture and experiences, but is expected to be stable over a sort period of time (Vogels, 2008).

Vogels (2008) developed a tool to measure how an environment is experienced in terms of atmosphere. She developed a questionnaire that consists of thirty-eight atmosphere words in Dutch (see appendix 1). She demonstrated, by using factor analysis, that atmosphere can be interpreted as a multidimensional concept. Atmosphere could be described in terms of *coziness* and *liveliness*. Additionally, she found that this tool was able to discriminate between the atmospheres of different environments, like shops and restaurants (Vogels, 2008). In a follow-up study, De Vries and Vogels (2007) applied this tool on four extreme light settings in an experimental room. In this study she described atmosphere in two other, unrotated, dimensions: *pleasure* and *arousal*. She showed that this tool is able to discriminate atmospheres between different light settings. Furthermore, she showed that a Varimax rotated analysis reveals two other factors. The factors are according to her related to the diagonals of the dimensions *pleasure* and *arousal*, and could be interpreted as a *tenseness* (relaxed vs. tense) and *liveliness* (lively vs. bored). The dimension *liveliness* was also found in the study of Vogels (2008). Furthermore, a closer look to the Varimax rotated analysis reveals also a cluster of words that can be identified as the *coziness* factor, obtained by Vogels (2008).

A second experiment of De Vries et al. (2007) confirmed the assumption that the dimensions are related to the diagonals of the dimensions *pleasure* and *arousal.* In that experiment De Vries et al. (2007) asked participants to imagine a room with a given atmosphere and to evaluate this room on 12 pleasure and arousal word pairs, originated from Mehrabian and Russell (1974). In this way she could describe an atmosphere word in terms of *pleasure* and *arousal* and compare it with the unrotated factors that were found in the first experiment. This relation was high, indicating that the unrotated factors resemble the *pleasure* and *arousal* axes.

However, the results of de Vries et al. (2007) and Vogels (2008) are only partly in line with each other. It should be noted that in both studies a factor analysis is conducted on a small data set and that the experiments were conducted in a limited amount of spaces. The obtained factors might therefore not stable and complete.

In sum the atmosphere tool of Vogels (2008) is a different approach in environmental evaluation. The tool is able to discriminate atmosphere of different light settings. This tool will be used to investigate the effects of the lighting characteristics intensity, CCT and spatial light distribution on atmosphere perception. However, the underlying dimensions and the exact relation with affect are still unclear. In order to gain more insight in the underlying dimensions the data from the current experiment will be pooled with the data from Vogels (2008) and De Vries et al. (2007). In this way more stable dimensions are expected to be obtained with a factor analysis. Since the pooled data is measured on a variety of places, the obtained factors are expected to be more complete than in the two earlier studies.

3. Experimental conditions

In order to answer the research questions as stated in the introduction, we propose to create several light settings and change the intensity, CCT and spatial distribution independent from each other, at two different levels. Ideally this would result in an experiment with eight light settings using a 2 (Spatial distribution: diffuse vs. directional) x 2 (intensity: low vs. high) x 2 (CCT: warm vs. cool) within groups design.

In order to create these light settings, first all the luminaires need to be characterized. The intensity and CCT were measured as a function of the input values of the software interface. From these measurements it became clear that it is not possible to create the proposed design with the available luminaires. Therefore, pilot experiments were conducted to investigate to what extent it is possible to create a design that is as complete as possible. Findings from the measurements and pilot experiments were used in the realization of the final experimental design.

In this section the experimental room is introduced in the first paragraph. Paragraph two describes the physical behavior of the luminaires, paragraph three explains the steps towards the final experimental design and the reasons for the pilot experiments and, subsequently, the results of the pilot experiments are shown in paragraph four. Finally, in paragraph five the intensity of the light settings is expressed in physical quantities.

3.1. Experimental room

All experiments took place in an experimental room (L x W x H = 6.1m x 3.7m x 3.0m) at Philips Research. The room had white walls, a grey carpet and white shutters in front of the windows. The room contained different types of lighting systems. The luminaires of each system could be controlled separately or in groups using the software 'Flexible Multisystem V1.6' designed by 'CIT Engineering N.V.'.

In the experiment two lighting systems were used: halogen downlights and fluorescent downlights. For each lighting system six luminaires were mounted in the ceiling as displayed in Figure 3. The halogen downlights consisted of a luminaire (Philips LBS250 1xHAL-TC60W K ET 12 SI WH) and each luminaire contained a 60W halogen lamp (Philips MasterLine TC 60W G8.5 12V 1CT). The halogen downlights generated a focused light beam which is called directional light. The fluorescent downlights consisted of a luminaire (Philips TBS770 6x14W/827/865 HFD AC-MLO CVC) and each luminaire contained six lamps: four lamps with a high CCT (Philips Master TL5 HE 14W/865 SLV) and two lamps with a low CCT (Philips Master TL5 HE 14W/827 SLV). The fluorescent downlights generated diffuse light.

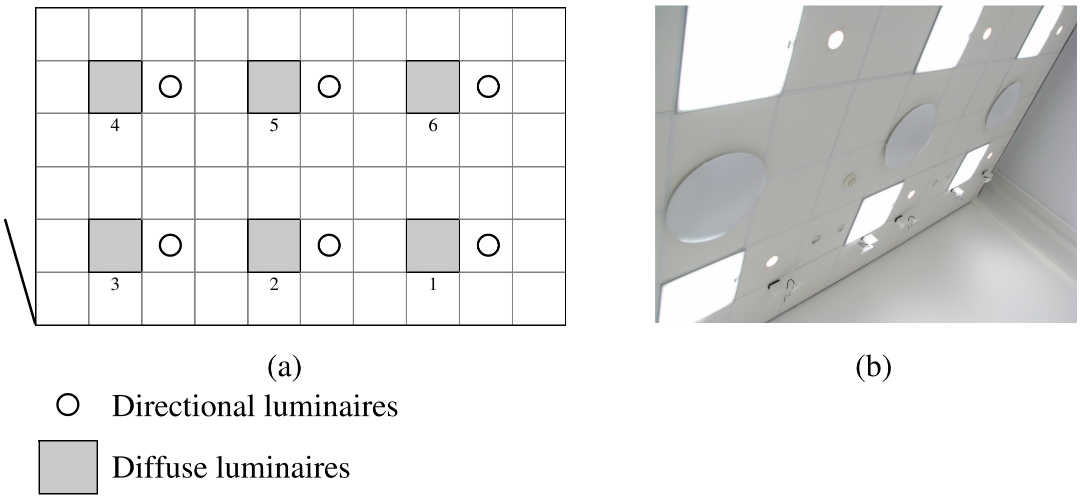


Figure 3: (a) A schematic overview of the ceiling of the experimental room. The grid represents the ceiling tiles. The number belongs to both the closest diffuse and directional luminaire. (b) A photo of the ceiling of the experimental room. The luminaires that are used in the experiment are turned on. The squared luminaires are the fluorescent downlights, and the circular luminaires are the halogen downlights.

3.2. Characterization of the luminaires

This section describes the behavior of the two lighting systems as a function of the software input values. The directional lighting system contained one lamp per luminaire and the intensity of the luminaire could be controlled by changing the value of a brightness slider. The diffuse lighting system contained two types of lamps: with a high and a low CCT. The intensity could be controlled by changing the value of a brightness slider, whereas the CCT could be controlled by changing the value of a whiteness slider. A change in whiteness level corresponded to a change in the ratio between the intensity of the cool and warm lamps.

3.2.1. The directional luminaires

In order to characterize the directional lighting system, the luminance in [cd/m^2] and the CCT in [K] of one of the luminaires were measured as a function of the brightness level as controlled by the software. The brightness level ranged from 0 to 100.

Measurements were conducted with a Topcon BM7 colorimeter. Since the directional luminaire is not homogenously colored, measuring the CCT directly at the surface of the luminaire might be inaccurate. Therefore, the colorimeter was focused on a reflectance plate (with a Spectraflect coating, from Lapsphere) which was positioned right under the luminaire on the floor of the experimental room. The luminance was normalized so that the luminance at maximum brightness level (=$Y_{dir,max}$) was equal to one. Normalized luminance is called intensity and is expressed as $Y/Y_{dir,max}$.

The results are displayed in Figure 4. The figure shows that intensity exhibits a non-linear relationship with brightness level. Furthermore the CCT of the directional lamp is not constant but changes with intensity, between 2200K and 3100K.

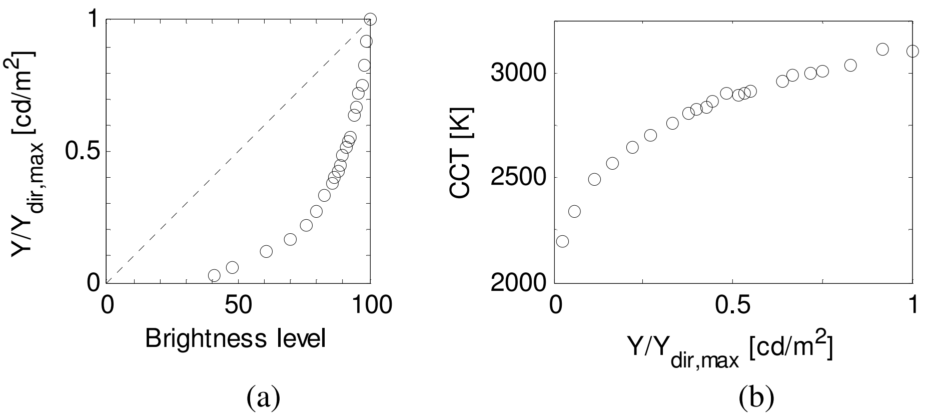


Figure 4: (a) Intensity of a directional lamp as a function of the software brightness level. (b) CCT as a function of the intensity of a directional lamp.

3.2.2. The diffuse luminaires

With the software interface the intensity and the CCT of the diffuse luminaires could be controlled. The intensity could be controlled by changing the software brightness level between 0 and 100. The CCT was controlled by changing the whiteness level between 15 (high CCT) and 45 (low CCT). The value of the whiteness level should correspond to $10^5 \cdot CCT^{-1}$ [K^{-1}].

To characterize the diffuse lighting system, the luminance in [cd/m^2] and the CCT in [K] of one luminaire was measured as a function of brightness level. The measurements were conducted at five whiteness levels (15, 20, 30, 35 and 45). The Topcon BM7 colorimeter was focused on the luminaire surface at the middle of the diffuser plate. Luminance and CCT distribution over the plate was measured and appeared to be constant. Luminance was normalized so that luminance at maximum brightness level ($Y_{dif,max}$) was equal to one. It is important to notice that the relative intensity of the directional luminaires cannot be compared to the relative intensity of the diffuse luminaires because the relative intensities of the luminaires are calculated with respect to a different maximum intensity.

The results are displayed in Figure 5. The left graphs show that intensity increases linearly with brightness level for all whiteness levels between 15 and 45. The right graphs show that when the whiteness level is 20, 30 and 35, the CCT varies with intensity. The variation of CCT with intensity occurs because at medium whiteness levels both the cool and warm lamps are on. When the whiteness level is 15 or 45, the CCT is independent of intensity. This relation is constant because at a maximum or minimum whiteness level only one lamp type is on. At a whiteness level of 15, CCT is approximately 6000K, and at a level of 45 CCT is approximately 2800K.

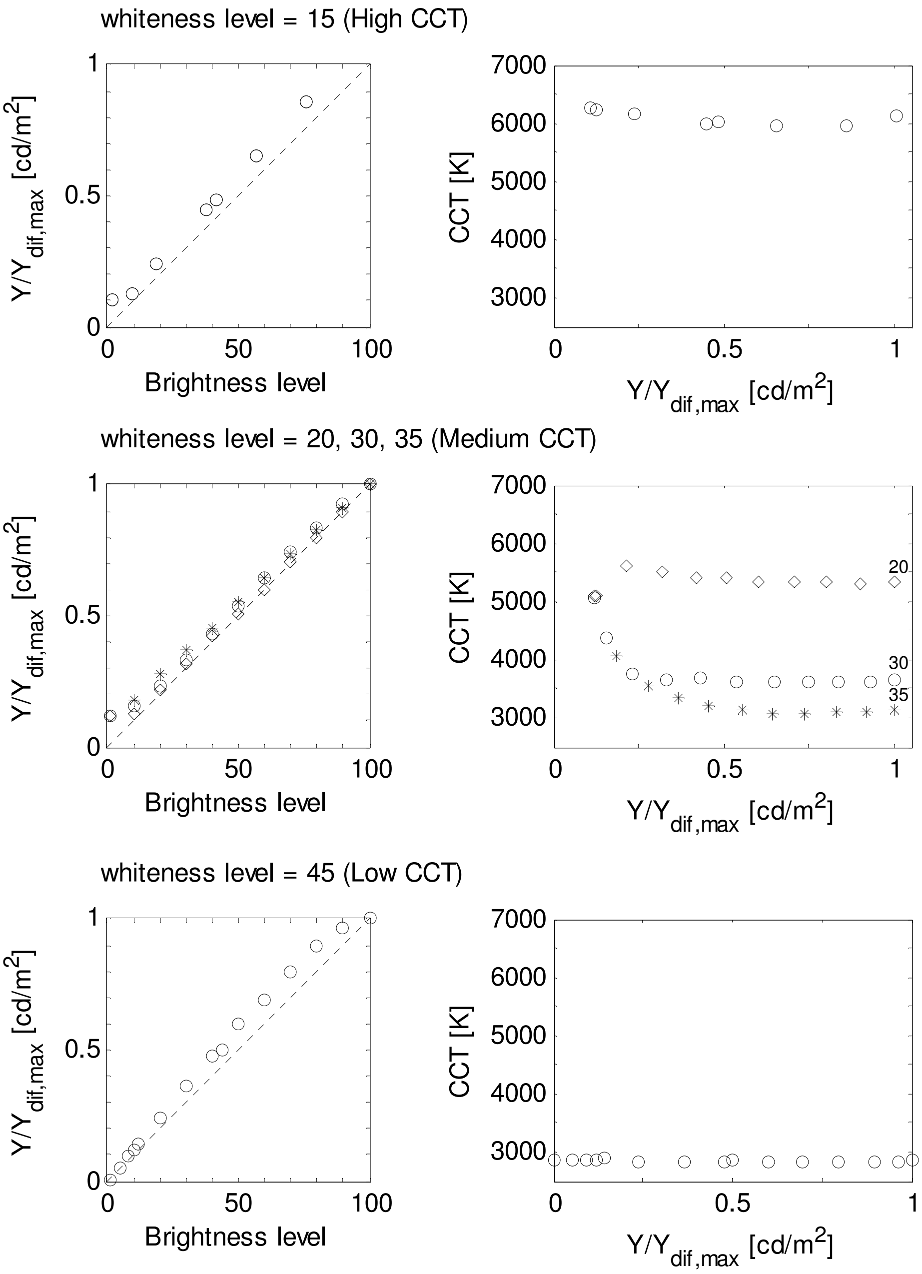


Figure 5: Relation between brightness level and intensity, in the left graphs, and intensity and CCT in the right graphs, for each five different whiteness levels. The dotted line in the left graphs represents the ideal response of intensity as a function of brightness level.

3.3. Steps towards the experimental design

Figure 4 and 5 show that the CCT of a luminaire is not always independent of the intensity. For the diffuse luminaire the CCT is only independent of intensity at a CCT of 2800K and 6000K. At these two CCT levels different intensity levels can be chosen without changing CCT. Figure 4 shows that because the directional luminaires have a limited CCT range it is not possible to create similar conditions for the directional luminaires as for the diffuse luminaires. With the directional luminaires the condition with a CCT of 2800K can be created but the condition of 6000K cannot be created. The condition with a CCT of 2800K can be created at an intensity of $0.4 \cdot Y_{dir,max}$. At different intensity levels the CCT deviates from 2800K. A pilot experiment was conducted to investigate if this CCT difference is noticeable and to see if it is possible to make a second condition with a clearly different intensity but the same perceived CCT. Although pilot 1 showed that a CCT of 3100K is perceived as cooler compared to the 2800K, it was decided to include a second directional setting of an intensity of $Y_{dir,max}$.

Once the intensity of the directional settings are determined, we need to create the same intensity with the diffuse luminaires. However, there are several ways to express intensity: in physical terms (e.g. average luminance or illuminance) or in perceptual terms. As there is no literature on what physical measure correlates to perceived room brightness, a second pilot experiment was performed to investigate when the directional setting at an intensity of $0.4 \cdot Y_{dir,max}$ and a CCT of 2800K is perceived as equally bright as a diffuse setting at 2800K. In this experiment participants had to remember the brightness impression of a setting, because the settings were presented after each other. Therefore pilot 3 was conducted to investigate whether brightness deteriorates with memory.

Once the intensity of the diffuse setting at 2800K is determined, we need to create the same intensity for the diffuse luminaires at 6000K. The luminance measured at the diffuser plate of the luminaire was used to create this setting. The level of intensity was $0.1 \cdot Y_{dif,max}$. A second and a third level of intensity, at a level of $0.5 \cdot Y_{dif,max}$ and $1 \cdot Y_{dif,max}$, were created for the diffuse settings at 2800K and 6000K. This was done to gain more insight in the effects of intensity in the experiment. However, a fourth pilot experiment was conducted to investigate whether the settings with different CCT but equal intensity are perceived as equal bright.

To summarize, for the diffuse settings the intensity and CCT can be changed independently from each other. For the directional settings the intensity can be changed on two levels, however, the CCT also varies. Two directional and diffuse settings can be compared on one level of brightness and CCT. This means that the design as proposed at the start of this section cannot fully be accomplished with these luminaires. Therefore the proposed 2x2x2 design should be transformed into the next three experimental designs:

- **Design 1: Diffuse light**
  This is a design for the diffuse lighting system only: a 3 (intensity: low vs. medium vs. high) x 2 (CCT: warm vs. cool) within groups design.
- **Design 2: Directional light**
  This is a design for the directional lighting system only: a one way within groups design with intensity (low vs. high) as independent variable.
- **Design 3: Diffuse versus directional light**
  This is a design for the diffuse and directional lighting systems on one level of CCT and at equal room brightness: a one way within groups design with spatial distribution (diffuse vs. directional) as independent variable.

The three designs will be used in the experiment as described in the next section. This section proceeds with the mentioned pilot experiments.

3.4. Pilot experiments

3.4.1. Discrimination of CT

This experiment was conducted to determine the smallest difference in CCT that people can perceive. The goal of this experiment was to investigate if the two levels of intensity of the directional luminaires are perceptually equal in CCT. It should be noticed that we used the diffuse luminaires in this experiment because these lamps can be varied in CCT at a constant intensity.

Method

Five participants joined the experiment, three male participants and two female participants. Their age ranged between 24 and 35 years with an average age of 27 years. None of the participants had a color deficiency.

The diffuse lights, at position 1 and 4 of the experimental room (see Figure 3a), were used in this experiment. The experiment followed a forced choice design with a fixed reference. Reference and test stimuli were presented simultaneously. The light at position 4 was the reference stimulus and had a fixed CCT of 3469K and an intensity of $Y_{dif,max}$. The light at position 1 was the test stimulus and had a fixed intensity of $Y_{dif,max}$. The CCT of the test light was randomly selected from a set of eleven stimuli, varying between and 3013K and 3986K with steps ranging between 81K and 123K.

Preceding the experiment, the two luminaires were turned on for thirty minutes in order to guarantee stable luminance and chromaticity levels (Van Keersop & Vogels, 2007). Participants were welcomed by the experimenter, conducted an Ishihara test for color blindness and the procedure was explained. During the experiment the reference light was shown together with one of the test stimuli. Participants were asked to judge whether the light at position 4 was more bluish than the light at position 1 (yes or no). Then the next test stimulus was shown. Between two settings participants were asked to close their eyes, and open them after the new setting was put on. The experimenter told when to open the eyes. This was done to avoid that observations were disturbed as a result of switching effects between lamps. All eleven test stimuli were presented twice.

Results

Figure 6 shows the percentage participants that rated the test light as more bluish as a function of the CCT. The figure shows that all participants indicated that a CCT of 3544K was more bluish than the reference CCT of 3469K. This means that a difference of 75K is noticed. None of the participants indicated that a CCT of 3364K was more bluish than the reference. This means that a difference of 105K is noticed. In sum, this means that the smallest difference in CCT that people can perceive is at least 75K. Therefore the CCT increase, as a function of intensity increase, of the directional luminaire (from 2800K to 3100K) is expected to be noticeable by participants.

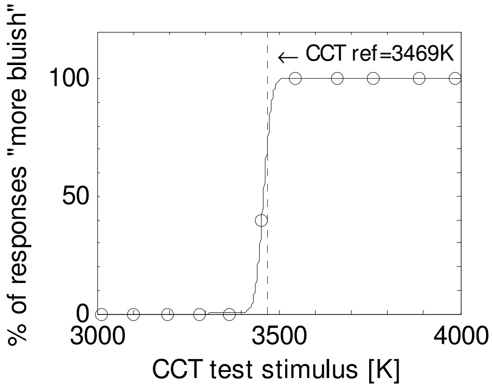


Figure 6: The percentage of participants that rated the test stimulus as more bluish than the reference stimulus. The data was expected to follow a cumulative normal distribution function, which is the curved line that is through the data points fitted.

3.4.2. Brightness matching of settings with different spatial distribution

This experiment was conducted to investigate when two light settings, one with diffuse and one with directional light, are perceived as equally bright.

Method

Sixteen participants joined the experiment: nine male participants and seven female participants. Their age ranged between 23 and 45 years with an average age of 28 years. None of the participants had a color deficiency.

Both the diffuse and directional luminaires, at position 1 to 6 (see Figure 3a), were used in this experiment. The experiment followed a forced choice design with a fixed reference. The reference and test settings were presented sequentially. First the reference setting was shown, followed by one of the randomly selected test settings. The reference setting was a setting with directional lights at an intensity of $0.4{\cdot}Y_{dir,max}$ and a CCT of 2827K. Eleven test settings were created. They consisted of diffuse luminaires at a CCT of approximately 2850K. The intensity was randomly selected from a set of eleven settings varying between $0.03{\cdot}Y_{dif,max}$ and $0.25{\cdot}Y_{dif,max}$.

Preceding the experiment, luminaires were turned on for thirty minutes. Participants were welcomed by the experimenter, conducted an Ishihara test for color blindness and the procedure was explained. During the experiment participants were shown the reference setting and asked to walk around in the experimental room. After a while, the experimenter asked participants to close their eyes. Then one of the test settings was switched on and participants were asked to open their eyes again. Participants were asked to compare the brightness impression of both settings and to say whether the test setting was brighter than the reference (yes or no). This was repeated for all of the eleven test settings.

Results

Figure 7 shows the percentage participants that rated the brightness impression of the diffuse light in the room as brighter than the brightness impression of the light from the directional luminaires. A cumulative normal distribution was fitted through the data points. The mean (i.e. 50% point) of the fitted function was $0.09{\cdot}Y_{dif,max}$ and the standard deviation is $0.035 \cdot Y_{dif,max}$. The threshold was calculated to be $0.12 \cdot Y_{dif,max}$. By convention this is the point where the comparison is judged brighter in 75% of the cases (Sekuler & Blake, 2002). The threshold is relatively low compared to $Y_{dif,max}$, which means that people are very precise in brightness tuning.

This means that the diffuse setting with a CCT of 2800K should have an intensity of $0.09 \cdot Y_{dif,max}$ in order to match the brightness of the directional setting with a CCT of 2800K and an intensity of $0.4 \cdot Y_{dir,max}$.

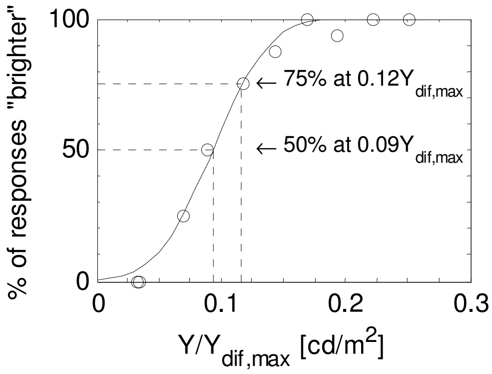


Figure 7: The percentage of participants that rated the brightness impression of the diffuse light in the room as brighter than the brightness impression of the light from the directional luminaires. The data was expected to follow a cumulative normal distribution function, which is the curved line that is fitted through the data points.

3.4.3. Effect of memory on memory on brightness matching

The previous experiment was about brightness matching. Participants had to close their eyes when the experimenter switched between two different light settings. Participants had to memorize the reference setting and compare it with the test setting. From literature it is known that the memorized brightness deteriorates over time (Uchikawa & Ikeda, 1986). Therefore the memorized brightness of the reference setting might be darker than the brightness when the setting is initially shown. This pilot experiment was conducted to check whether there is an effect of memory on the brightness.

Method

Fourteen participants joined this experiment: nine male and five female participants. The age of the participants ranged between twenty three and thirty three years old. None of the participants had a color deficiency.

In this experiment the six diffuse luminaires were used. The experiment followed a forced choice design with a fixed reference. The reference and test settings were presented sequentially. First the reference setting was shown, followed by one of the randomly selected test settings. Eleven test settings were created. The intensity ranged between $0.05 \cdot Y_{dif,max}$ and $0.18 \cdot Y_{dif,max}$. All settings had a constant CCT of 2850K. The reference setting was one of these eleven settings with an intensity of $0.12 \cdot Y_{dif,max}$.

Preceding the experiment, luminaires were turned on for thirty minutes. Participants were welcomed by the experimenter, they conducted an Ishihara test for color blindness and the procedure was explained. During the experiment participants were shown the reference setting and asked to walk around in the experimental room. After a while the experimenter asked participants to close their eyes. Then one of the test settings was switched on and participants were asked to open their eyes again. Participants had to compare the brightness impression of both settings and to indicate whether the test setting was brighter than the reference (yes or no). This was repeated for all of the eleven test settings. The switching time between two settings was kept constant at 7 seconds which is the maximum switching time between two settings in the former brightness experiments.

Results

Figure 8 shows the results of this experiment. A cumulative distribution function was fitted through the data points with a mean of $0.116 \cdot Y_{dif,max}$. First, the small standard deviation (of $0.01 \cdot Y_{dif,max}$) shows that people are very sensitive to brightness changes of two diffuse light settings. Second, the reference brightness is smaller than the threshold value of $0.122 \cdot Y_{dif,max}$. This means that people are able to memorize the brightness after seven seconds without deterioration. Therefore the conclusion can be drawn that the results of the previous experiment is not affected by memory effects.

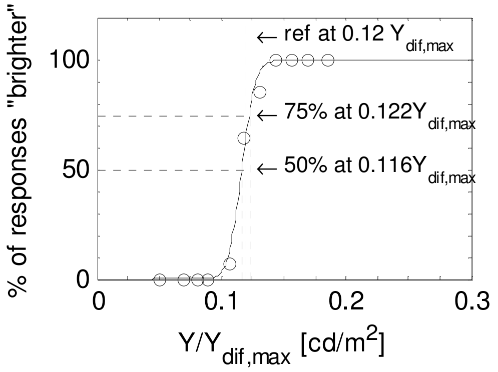


Figure 8: The percentage of participants that rated the brightness impression of the test stimulus as brighter than the brightness of the reference. The data was expected to follow a cumulative normal distribution function, which is the curved line that is fitted through the data points.

3.4.4. Brightness matching of settings with different CCT

The next experiment was conducted to investigate whether two different settings with different CCT but equal luminance settings are perceived as equally bright.

Method

Sixteen participants joined in this experiment: 8 male and 8 female participants. The age of the participants ranged between 22 and 47 years old, with an average of 27 years. None of the participants had a color deficiency.

In this experiment the six diffuse luminaires were used. The experiment followed a forced choice design with a fixed reference. The reference and test setting were presented sequentially. First the reference setting was shown, followed by one of the randomly selected test settings.

The experiment consisted of two parts. In the first part the effect of CCT on brightness was measured for low intensity. The reference stimulus consisted of the diffuse luminaires at a CCT of 6259K and an intensity of $0.092 \cdot Y_{dif,max}$. Eleven test stimuli were created. They had a fixed CCT of 2859K and the intensity varied between $0.036 \cdot Y_{dif,max}$ and $0.157 \cdot Y_{dif,max}$.

In the second part the effect of CCT on brightness was measured for high intensity. The reference stimulus consisted of the diffuse luminaires at a CCT of 2847K[1] and an intensity of $Y_{dif,max}$. Eleven stimuli were created at a CCT of 6115 with an intensity ranging between $0.60 \cdot Y_{dif,max}$ and $1.63 \cdot Y_{dif,max}$[2]. Each participant participated in both parts. Half of the participants started with the first part and half of them started with the second part.

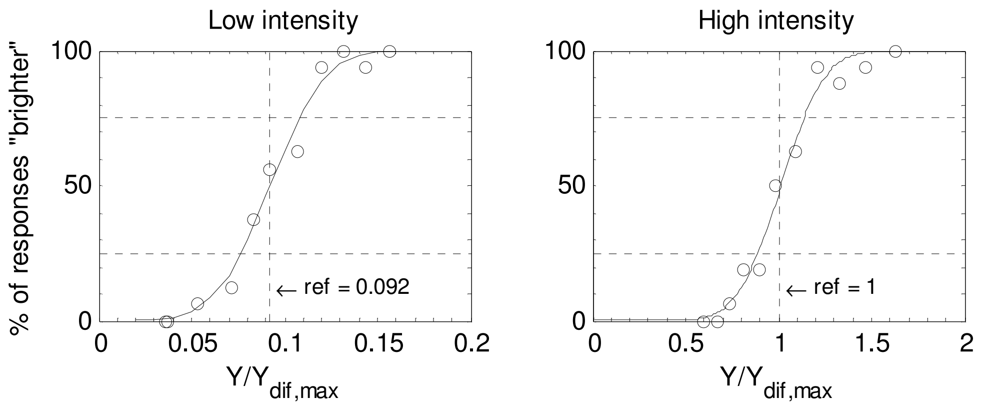
Preceding the experiment, the luminaires were turned on for thirty minutes. Participants were welcomed by the experimenter, conducted an Ishihara test for color blindness and the procedure was explained. Participants were first shown the reference stimulus. Participants were asked to walk around in the experimental room. Then participants were asked to close their eyes. The experimenter switched to one of the test settings and asked the participants to open their eyes again. Participants were asked to judge if the reference setting was brighter than the test setting (yes or no). This procedure was repeated for all of the eleven test settings and both parts of the experiment.

Results

The results of both experiments are shown in Figure 9. The data was fitted with a cumulative normal distribution. The means of the fitted functions are $0.092 \cdot Y_{dif,max}$ and $1.013 \cdot Y_{dif,max}$, for the low and high intensity respectively. The standard deviations are respectively $0.023 \cdot Y_{dif,max}$ and $0.184 \cdot Y_{dif,max}$. As can be seen, for both intensities the reference lies within threshold. This means that the settings at low intensity level and high CCT in the experimental design of paragraph 3.3, is perceived as equal bright than the setting at equal intensity but low CCT. Furthermore the settings with high and low CCT at high intensity level are perceived as equal bright.

[1] The reference stimulus in the case of a low intensity had a high CCT, and in the case of a high intensity a low CCT. This had a practical reason. It was not possible to adjust the intensity of the lamps with a high CCT below the intensity of the lamps with a low CCT. Also, it was not possible to adjust the intensity of the lamps with a low CCT above the intensity of the lamps with a high CCT.

[2] $Y_{dif,max}$ is the maximum intensity of the diffuse luminaires at a CCT of 2800K. The diffuse luminaires contain two lamps with a CCT of 2800K and four lamps with a CCT of 6000K. This means that the 6000K lamps can reach a maximum intensity of more than $Y_{dif,max}$.



(a) (b)

Figure 9: The percentage of participants that rated the brightness impression of the test stimulus as brighter than the brightness of the reference. The reference setting had a CCT of 6259K and an intensity of $0.092 \cdot Y_{dif,max}$ (a) or a CCT of 2859K and an intensity of $1 \cdot Y_{dif,max}$ (b). The horizontal dotted lines correspond to the visibility thresholds of 25% and 75%. The data was expected to follow a cumulative normal distribution function, which is the curved line that is fitted through the data points. The reference settings are displayed with a vertical dotted line.

3.5. The intensity levels of light settings in physical quantities

As a result from the measurements and the pilot experiments, the three designs will have the next intensity and CCT settings. In design 1 the diffuse lights will be varied on three intensity levels ($0.1 \cdot Y_{dif,max}$ vs. $0.5 \cdot Y_{dif,max}$ vs. $1 \cdot Y_{dif,max}$) and two CCT levels (2800K vs. 6000K). In design 2 the directional lights will be varied on two intensity levels ($0.4 \cdot Y_{dir,max}$ vs. $1 \cdot Y_{dir,max}$). Finally in design 3 the directional lights (with an intensity of $0.4 \cdot Y_{dir,max}$, and a CCT of 2800K) will be compared with the diffuse lights (with an intensity of $0.1 \cdot Y_{dif,max}$ and a CCT of 2800K).In this paragraph the levels of intensity of the settings are described in physical terms. The intensity is measured in terms of illuminance (E) and luminance (L).

For each light setting the minimum and maximum illuminance levels was measured in the experimental room. A lux meter (Lutron, LX-107) recorded illuminance levels at working surface height (0.8 m horizontally above the floor). Levels were recorded continuously at different locations in the experimental room. From the recorded data, minimum and maximum levels were automatically calculated.

Also the minimum, maximum and mean luminance levels for all the room surfaces (ceiling, floor and four walls) were measured for each light setting. For each surface the luminance distribution was recorded with a digital camera (Rollei d30 flex). The ceiling surface was not captured: the pictures were found to be unreliable because of too extreme luminance differences between the lights and the ceiling. The camera was controlled with software (Rollei d-image, version 1.12) and positioned perpendicular to each of the surfaces. It was not possible to take a picture of the whole surface at once. Therefore a surface was divided in parts and each part was captured. Six photos were needed to capture the floor surface, three photos for the right and left wall were needed and two photos each for the front and back wall. Each photo was analyzed using specialized software (Technoteam, LMK 2000, version 3.6.5.14). With this software the minimum, maximum and average luminance was calculated for each surface part at each light setting. Next, the photos were combined and values were calculated for each surface. Finally, for each light setting the mean luminance values were calculated by calculating the weighted (weighted by actual surface area) sum of the luminance values per surface. Furthermore, the minimum and maximum values were determined for each light setting. The results are summarized in this paragraph for each of the three experimental designs.

3.5.1. Design 1: Diffuse light

The results of the illuminance measurements for the diffuse lights are displayed in Table 1. The results of the luminance measurements are displayed in Table 2.

Illuminance
Illuminance increases with intensity and is similar for the two CCT's. The ratio between minimum and maximum measured illuminance for each setting is 0.5, and approximately constant.

The ratio between the illuminance levels between each setting was calculated for both the maximum and minimum measured values. When the illuminance at high intensity and low CCT is set to one, the ratio between the low, medium and high levels are about 0.1 : 0.5 : 1 at both CCT levels. This corresponds to the ratio of the settings expressed as relative luminance.

Table 1: The measured maximum and minimum illuminance, and the calculated ratio between minimum and maximum measured illuminance for the settings of design 1.

		Illuminance levels, E [lx]		
Intensity	CCT	Max	Min	Min/Max
low		41	20	0.49
medium	*high*	207	105	0.51
high		434	221	0.51
low		39	19	0.49
Medium	*low*	220	104	0.47
High		439	223	0.51

Luminance
Luminance increases with intensity and is similar for the two CCT's. The ratio between maximum and minimum measured luminance for each setting is approximately 0.007, and constant. Since the minimum luminance is very low it is recommended to investigate why.

The ratio between the measured mean luminance of the settings was calculated. The ratio between the low, medium and high luminance levels are about 0.1 : 0.5 : 1 at both CCT levels.

Table 2: The measured mean, maximum and minimum luminance, and the calculated ratio between minimum and maximum measured luminance for the settings of design 1.

		Luminance levels, L [cd/m^2]			
intensity	CCT	Mean	Max	Min	Min/Max
low		4.8	13.7	0.10	0.007
medium	*high*	24.0	72.3	0.45	0.006
high		47.9	131.9	0.91	0.007
low		4.4	10.8	0.08	0.008
medium	*low*	23.5	60.5	0.39	0.006
high		44.8	118.6	0.67	0.006

3.5.2. Design 2: Directional light

The results for the illuminance and luminance measurements for the directional lights are displayed below.

Illuminance

Table 3 shows that illuminance increases with intensity. The ratio between minimum and maximum measured illuminance for each setting is 0.03, and constant.

The ratio between the minimum illuminance between the two settings and between the maximum illuminance between the two settings is 0.4. This is in accordance with the relative luminance levels of the two settings.

Table 3: the measured maximum and minimum illuminance, and the calculated ratio between minimum and maximum measured illuminance for the settings of design 2.

		Illuminance levels, E [lx]		
intensity	CCT	Min	Max	Min/Max
low	low	12	416	0.03
high	low	33	1072	0.03

Luminance

Table 4 shows that luminance increases with intensity. The ratio between minimum and maximum measured illuminance for each setting is 0.004 and 0.007.

The ratio between the maximum illuminance between the two settings and between the minimum illuminance between the two settings is respectively 0.4 and 0.5. This is approximately in accordance with the relative luminance levels of the two settings.

Table 4: The measured mean, maximum and minimum luminance, and the calculated ratio between minimum and maximum measured luminance for the settings of design 2.

		Luminance levels, L [cd/m^2]			
intensity	CCT	Mean	Max	Min	Min/Max
low	low	4.5	41.1	0.18	0.004
high	low	11.6	81.8	0.56	0.007

3.5.3. Design 3: Diffuse versus directional light

The results for the illuminance and luminance measurements for the directional and diffuse lights at equal brightness and a low CCT are displayed below.

Illuminance
As can be seen in Table 5, the minimum and maximum measured illuminance levels differ substantially between the diffuse and directional lights. The ratio between minimum and maximum illuminance levels is much larger for the diffuse setting than for the directional setting. This means that the diffuse setting is more uniform.

Table 5: The measured maximum and minimum illuminance, and the calculated ratio between minimum and maximum measured illuminance for the settings of design 3.

		Illuminance levels, E [lx]		
intensity	CCT	Min	Max	Min/Max
Diffuse	low	19	39	0.49
Directional	low	12	416	0.03

Luminance
The ratio between minimum and maximum measured illuminance is 0.004 and 0.008, and approximately constant for the light settings.

Table 5 and Table 6 show that the ratio between minimum and maximum illuminance and luminance is different for each light setting. The mean luminance of both settings are equal. This is a very interesting result: it might entail that brightness perception of a room is a process in which the luminance values of all room surfaces are integrated.

Table 6: The measured mean, maximum and minimum luminance, and the calculated ratio between minimum and maximum measured luminance for the settings of design 3.

		Luminance levels, L [cd/m^2]			
intensity	CCT	Mean	Max	Min	Min/Max
Diffuse	low	4.4	10.8	0.08	0.008
Directional	low	4.5	41.1	0.18	0.004

4. Experiment: the effect of lighting characteristics on perceived atmosphere

In this experiment the effect of different lighting characteristics on the perceived atmosphere in a space was studied. As explained before, the experiment consisted of three experimental designs. In the first design, the effect of intensity and CCT was investigated for diffuse light, in the second design, the effect of intensity was investigated for directional light; and in the third design, the difference between diffuse and directional light was investigated for equal brightness and CCT.

The questionnaire of Vogels (2008) was used to measure the perceived atmosphere. A free association protocol and additional questionnaires were used to measure the preference of the settings, the suitability of the setting for different applications and the associations that people had with respect to the settings.

4.1. Method

4.1.1. Participants

Thirty-two native Dutch speaking people participated in this experiment. They were all employees at Philips Research. Half of them were male, half of them were female. Their age ranged between 22 and 34 years, with an average of 26 years. None of the participants had color vision deficiencies according to the Ishihara test.

4.1.2. Equipment

The experiment was performed in an experimental room (L x W x H = 6.1m x 3.7m x 3.0m) containing several different lighting systems. Two lighting systems were used in this experiment: a directional light system containing six halogen lamps and a diffuse light system containing six fluorescent lamps. Intensity could be controlled for each system. CCT could only be controlled for the diffuse lighting system. The CCT of the directional lighting system varied with intensity. A more comprehensive description of the equipment can be found in chapter 3.

4.1.3. Design and stimuli

The experiment consisted of three experimental designs. In total eight light settings were created. The settings for each experimental design are presented below. Notice that some settings were used in two designs.

Design 1: Diffuse light

In this part of the experiment the effect of intensity and CCT was investigated for diffuse light. The experiment followed a 3 (Intensity: low vs. medium vs. high) x 2 (CCT: warm vs. cool) within-group design. The tested light settings were created with the diffuse luminaires. The lights were varied in intensity: low = $0.1 \cdot Y_{dif,max}$, medium = $0.5 \cdot Y_{dif,max}$ and high = $1 \cdot Y_{dif,max}$. $Y_{dif,max}$ is the measured luminance on the surface of one fluorescent luminaire at maximum intensity and low CCT. For each level of intensity, two levels of CCT were presented: warm (corresponding to a low CCT of about 2800K), and cool (corresponding to a high CCT of about 6000K). The settings are displayed in Figure 10.

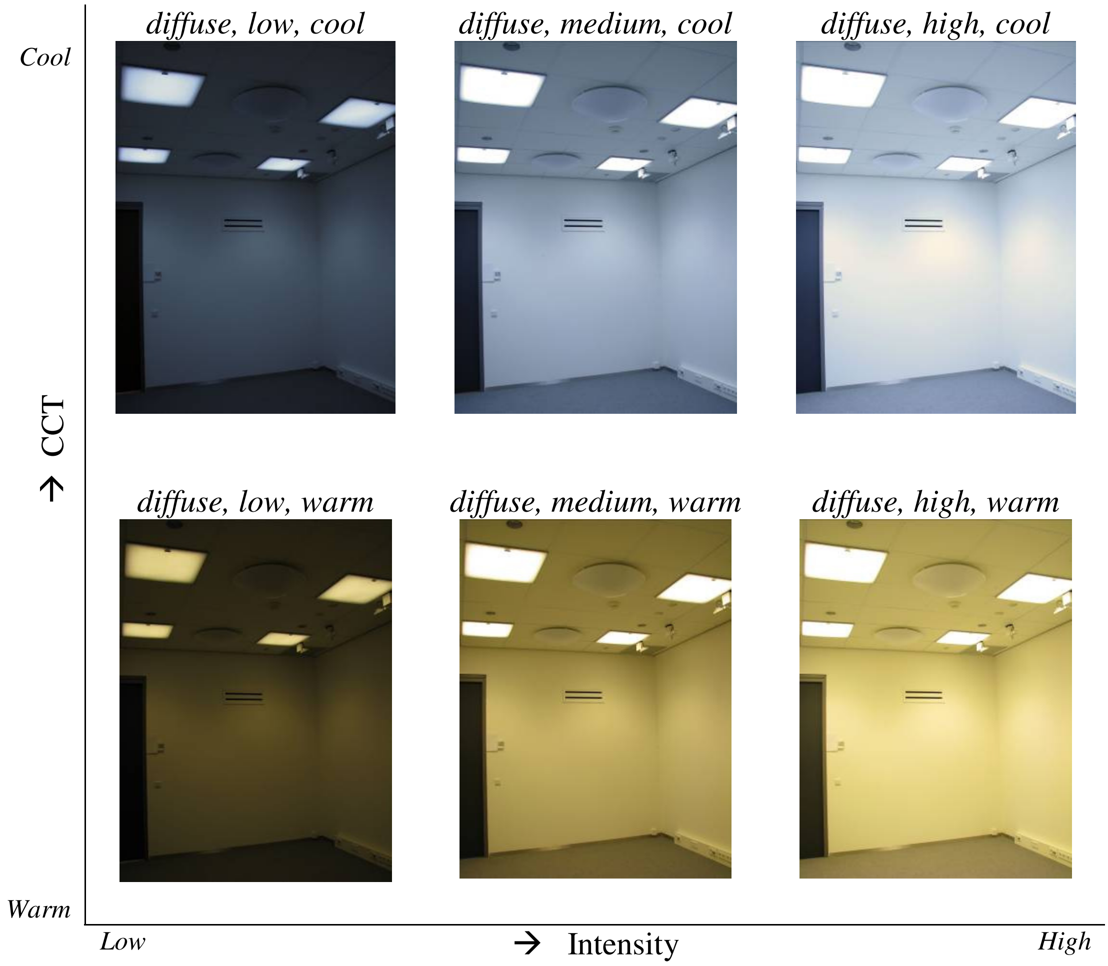


Figure 10: The six diffuse light settings as used in design 1. The light settings were varied in three levels of intensity. For each intensity level, two levels of CCT were presented.

Design 2: Directional light

In the second part of the experiment, the effect of intensity for the directional light was investigated. The experiment followed a one way within groups design with intensity (low vs. high) as independent variable. The light settings were created with the directional luminaires. The two light settings were varied in intensity: low = $0.4 \cdot Y_{dir,max}$ and high = $1 \cdot Y_{dir,max}$. $Y_{dir,max}$ is the measured luminance on a patch at the floor under one halogen lamp at maximum intensity. Since CCT varied with intensity, the low and high intensity settings do not match in CCT. Their CCT was 2800K and 3100K for the low and high intensity, respectively. Therefore we cannot prove that the perceived difference between the two settings is only caused by an effect of intensity. Figure 11 shows the two light settings.

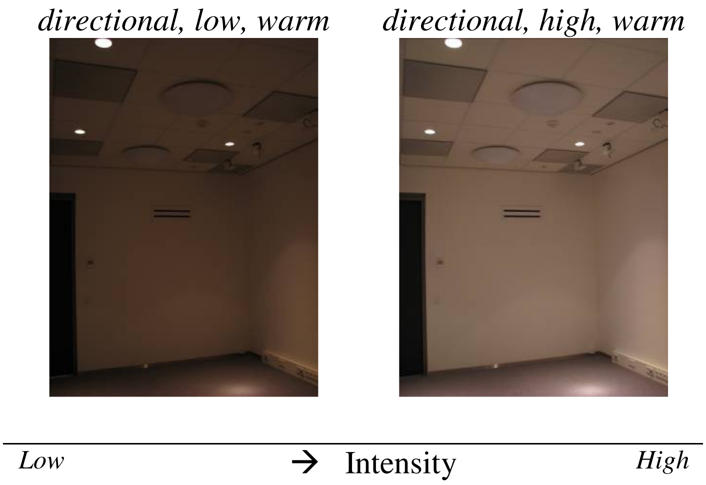


Figure 11: The two directional light settings as used in design 2. The light settings were varied in two levels of intensity.

Design 3: Diffuse versus directional light

The third design in this experiment was a one way within groups design with Spatial Distribution (diffuse vs. directional) as independent variable. One setting was created with the directional luminaires, the other setting with the diffuse ones. Both light settings were equal in room brightness and CCT. The intensity of the directional setting was $0.4 \cdot Y_{dir,max}$. The intensity of the diffuse setting was $0.1 \cdot Y_{dif,max}$. Figure 12 shows the two light settings. Notice that the directional setting is the same as one of the settings of design 2, and that the diffuse setting is the same setting as one of the settings of design 1.

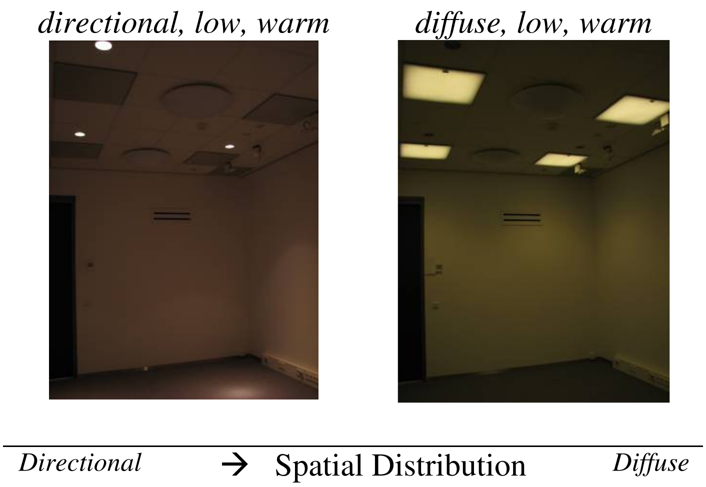


Figure 12: The directional and diffuse light settings as used in design 3. The light settings are equal in room brightness and CCT, and differ in spatial distribution: directional and diffuse.

4.1.4. Dependent measures

For each of the eight light settings participants were asked to give their first impression. Subsequently, they had to fill in five questionnaires: an atmosphere questionnaire, a preference questionnaire, a lighting appearance questionnaire, an application questionnaire, and a time of day questionnaire. The questionnaires can be found in appendix 5.

First impression
First of all, participants were asked to give their first impression of the room and: (1) to tell which associations came to mind, (2) to describe the atmosphere of the room with their own words, and (3) to come up with applications for which the light setting would be suitable.

Atmosphere questionnaire
The atmosphere questionnaire, developed by Vogels (2008), measures how participants perceive the atmosphere in an environment. This questionnaire was changed on three points. First of all, as suggested by De Vries and Vogels (2007), the words "actief" (active) and "kalm" (calm) were added to have a more complete questionnaire containing forty items. In this way the questionnaire covers a larger part of the atmosphere space. Secondly, a seven point bipolar Likert scale instead of a five point scale was used in order to gain more variance during the atmosphere measurements. Finally, the scale point labels were adjusted in order to improve reliability, and the understandability of the scale points. Instead of labeling only the ending points of the scale, scale points were now labeled as "Absoluut niet van toepassing" (absolutely not applicable), "Nauwelijks van toepassing" (hardly applicable), "Niet zo van toepassing" (slightly not applicable), "Neutraal" (neutral), "Enigszins van toepassing" (slightly applicable), "Goed van toepassing" (well applicable), "Zeer goed van toepassing" (very well applicable).

Preference questionnaire
The preference questionnaire measured how participants appreciated the presented light setting. Participants had to rate the light setting on three word pairs, using a seven point bipolar semantic differential scale with the end points labeled: "aantrekkelijk-onaantrekkelijk" (attractive-unattractive), "mooi-lelijk" (beautiful-ugly) and "prettig-onprettig" (pleasant-unpleasant).

Lighting appearance questionnaire
The lighting appearance questionnaire measured how participants perceived the lighting characteristics that were manipulated in this experiment. The presented light setting had to be rated on three word pairs, using a seven point bipolar semantic differential scale with the end points labeled: "helder-donker" (bright-dim), "uniform-niet uniform" (uniform-not uniform) and "warm-koud" (warm-cold).

Application questionnaire
In the application questionnaire, participants were asked how suitable they thought the light setting would be for six everyday environments: study room, bed room, living room, office, hotel room and shop. The suitability had to be rated on seven point bipolar Likert scales. The scale points were labeled as "Absoluut niet geschikt" (absolutely not suitable), "Nauwelijks geschikt" (hardly suitable), "Niet zo geschikt" (slightly not suitable), "Neutraal" (neutral), "Enigszins geschikt"(slightly applicable), "Goed geschikt" (well suitable), "Zeer goed geschikt" (very well suitable). Additionally,

participants had the possibility to write down other environments that would be suitable for the presented light setting.

Time of day questionnaire
In the time of day questionnaire, participants were asked to indicate which part or parts of the day they associated with the presented light setting. Participants had the choice between: morning, afternoon, evening and night. Furthermore, they had the option to write down additional associations that came to mind.

4.1.5. Procedure

According to Van Keersop & Vogels (2007) the chromaticity and light intensity of the lamps stabilizes within respectively twelve minutes for the fluorescent lamps and thirty minutes for the halogen lamps. Therefore all lamps were turned on thirty minutes before the start of the experiment.

Participants entered the experimental room while a neutral light setting was turned on. The neutral setting consisted of diffuse luminaires with a light intensity of $0.4 \cdot Y_{dif,max}$. The neutral setting had a CCT of 3900K, which is the perceptual middle between 2800K and 6000K, according to the reciprocal MegaKelvin law of Judd (1933a, as cited in Wyszecki & Styles, 1982)

Participants were welcomed by the experimenter and the procedure was explained. Participants were asked to read and sign the informed consent form which contained a short summary of the procedure. After signing the form, some demographic questions were asked. Finally, an Ishihara test for color deficiencies was conducted.

The experiment was divided in two parts. In both parts, the eight light settings were shown after each other. To control for sequence effects the eight settings were completely counterbalanced in a way that each participant is exposed to all the light settings, each setting is presented one time for each participant and each setting preceded and followed each other setting once for the whole experiment (Graziano, 2004). To eliminate adaptation effects the neutral setting was shown for 10 seconds before each setting. Participants were asked to walk around in the room before they started to evaluate the light setting. In the first part of the experiment participants had to give their first impression, describe the atmosphere of the room and mention applications that came to in mind by seeing the light setting. The first impressions were asked for two reasons. First, we wanted to test whether the terms used in the questionnaires were complete or whether people spontaneously came up with other terms. Second, by showing the settings, participants got familiar with them and, therefore, are more tended to use the whole scale range in the questionnaires of the second part of the experiment. The responses of the participants were noted by the experimenter and recorded with an mp3 player. During the second part of the experiment, participants were again shown the eight light settings. For each light setting participants were asked to fill in the five questionnaires. After four light settings were shown, participants had a short coffee break of five to ten minutes. After the break, participant entered the experimental room while the neutral setting was on. Then the last four settings of the sequence were shown and evaluated.

4.2. Results

The results of the five questionnaires as well as participant's first impressions will be presented in this section. The results of each questionnaire will be discussed for each experimental design separately. First the lighting appearance questionnaire is discussed, second, the preference questionnaire, and third, the atmosphere questionnaire. Subsequently the results of the time of day questionnaire are presented together with the spontaneously mentioned associations and atmospheres. Finally, the results of the application questionnaire are presented together with spontaneously mentioned applications.

4.2.1. Lighting appearance

Participants had to rate the brightness (bright - dim), color temperature (warm - cold) and uniformity (uniform - not uniform) for each light setting on a seven point scale. For each design a repeated measures ANOVA was conducted to test for the complete design and gender. In repeated measures analysis two methods can be used to calculate the effect sizes. We report the results of the multivariate analyses. If the results of this analysis deviate from the results of the univariate method, we will report the results from the univariate method in the footnote (see also: Minke, 1997). Additionally, a contrast analysis was conducted for design 1 to test for significant differences between the three levels of intensity and to explore the interaction between intensity and CCT. Only the significant effects are reported in appendix 2.

A regression analysis was conducted to investigate predictors for room brightness. This analysis is included at the end of the paragraph.

Design 1: Diffuse light

The results of the three items of the light appearance questionnaire (brightness, color temperature and uniformity) for the diffuse light are plotted in Figure 13. The figure shows that (a) brightness increases with intensity, (b) perceived color temperature is different for the low and high CCT, and (c) the perceived uniformity slightly increases with intensity. This means that participants were able to distinguish between the different levels of intensity and CCT.

The effects on brightness are discussed first. The ANOVA revealed significant effects for Intensity on brightness ($F(2,28) = 160.67$, $p<0.001$, partial $\eta^2 = 0.92$). This is a large effect according to Cohen (1977)[3]. A contrast analysis revealed a significant effect between the low and medium and the medium and high intensity. Additionally, a (large) interaction effect was found between Intensity and CCT ($F(2,28) = 5.69$, $p = 0.008$, partial $\eta^2 = 0.29$)[4]. A contrast analysis revealed that at high CCT the high intensity was perceived as brighter than at low CCT. All other effects were not significant ($p > 0.05$).

Secondly a repeated measures ANOVA revealed a significant (and large) effect for CCT ($F(1, 30) = 130.91$, $p < 0.001$, partial $\eta^2 = 0.81$). All other effects were not significant ($p > 0.05$).

[3] Cohen (1977) characterizes the effect sizes $\eta^2 = 0.01$ as small, $\eta^2 = 0.06$ as medium and $\eta^2 = 0.14$ as a large. Although there is a difference between partial η^2 and η^2, they differ very little if the sample size is larger than 50 (Stevens, 1996).

[4] The univariate test was only marginal significant using the Greenhouse-Geisser correction, ($F(1.4, 40.3) = 2.98$, $p<0.08$, partial $\eta^2 = 0.093$)

Finally, the effects on perceived uniformity were tested. A (large) effect of Intensity ($F(2, 29) = 5.22$, $p = 0.012$, partial $\eta^2 = 0.27$) was found. A contrast analysis revealed a significant effect between the low and medium intensity. Furthermore, a (large) effect was found for Gender ($F(1, 30) = 5.97$, $p = 0.021$, partial $\eta^2 = 0.17$). All other effects were not significant ($p > 0.05$). The gender effect showed that male participants rated the diffuse light settings as more uniform than female participants.

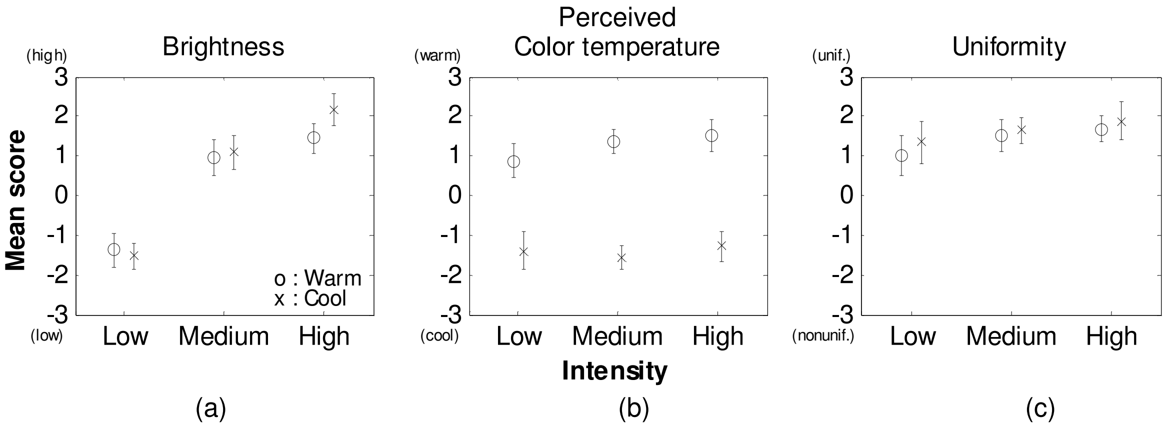


Figure 13: The effects of intensity and CCT on the items: (a) brightness, (b) perceived color temperature and (c) perceived uniformity for the diffuse lamps. The error bars indicate the 95% confidence intervals of the mean.

Design 2: Directional light

The results of the three items of the light appearance questionnaire for the directional lights are displayed in Figure 14. Figure 14a shows that participants can discriminate the two intensity levels. Figure 14b shows that the low intensity may be evaluated as slightly warmer than the high intensity. Finally, Figure 14c shows that perceived uniformity slightly increases with intensity.

An ANOVA revealed that Intensity had a large significant effect on brightness ($F(1, 30) = 54.70$, $p < 0.001$, partial $\eta^2 = 0.65$), no significant effect on perceived color temperature ($p>0.05$), and a significant effect on perceived uniformity ($F(1, 30) = 4.61$, $p = 0.04$, partial $\eta^2 = 0.13$). The effect of Intensity on perceived uniformity is in line with the effect found for the diffuse lights.

The effect of Gender was only significant for perceived uniformity ($F(1,30) = 6.48$, $p = 0.02$, partial $\eta^2 = 0.18$). However, the effect is reversed compared to the effect found for the diffuse lights: the direct settings are perceived as more uniform by female than by male participants.

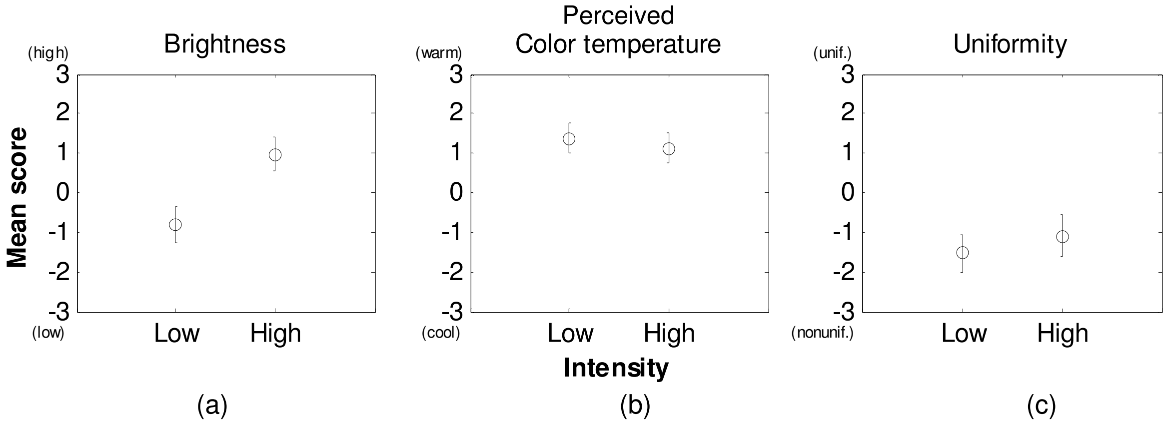


Figure 14: The effect of intensity on the items: (a) brightness, (b) perceived color temperature and (c) perceived uniformity for the directional lamps. The error bars indicate the 95% confidence intervals of the mean.

Design 3: Diffuse versus directional light

The results for the diffuse versus directional lights are shown in Figure 15. Figure 15c shows that the direct light settings were perceived as less uniform compared to the diffuse settings. Hence, participants were able to perceive the differences in spatial distribution for the two settings. From Figure 15a and 15b it seems that the brightness and perceived color temperature are nearly equal for the two settings.

The effect of Spatial Distribution on brightness and perceived CT was not significant ($p<0.05$). However, the effect on perceived uniformity ($F(1, 30) = 45.84$, $p < 0.001$, partial $\eta^2 = 0.60$) was significant and large. The diffuse setting was perceived as less uniform than the directional setting.

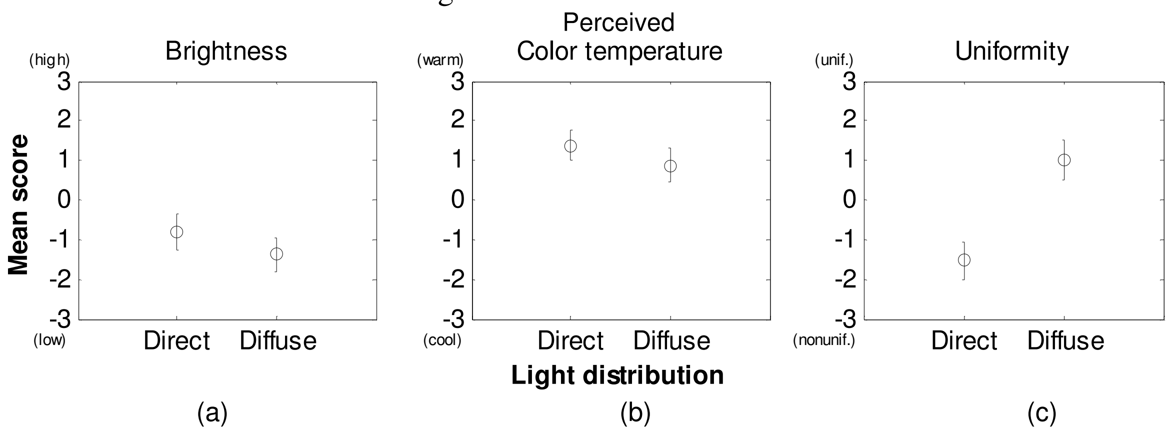


Figure 15: The effect of spatial light distribution on the items: (a) brightness, (b) perceived color temperature and (c) perceived uniformity for the diffuse and. directional lamps. The error bars indicate the 95% confidence intervals of the mean.

Additionally, in line with the significant results from design 1 and design 2, a trend was found for the interaction effect between Gender and Spatial Distribution on perceived uniformity ($F(1,30) = 3.08$, $p = 0.09$, partial $\eta^2 = 0.09$). The diffuse setting was judged as more uniform by male participants compared to female participants, whereas the directional setting was judged as more uniform by female participants compared to males (Figure 16).

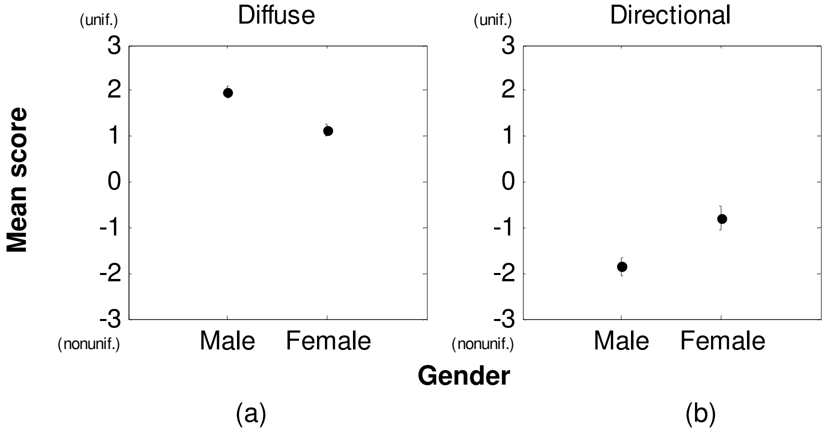


Figure 16: The average score on perceived uniformity for male and female participants. In (a) the score averaged over all the six diffuse light settings is displayed. In (b) the score averaged over the two directional light settings is displayed. The error bars indicate the 95% confidence intervals of the mean.

Predictors for brightness

As mentioned in the introduction, it is not known what the physical correlate is of perceived room brightness. In the experiment the brightness impression of the room was evaluated. In addition, the luminance of the walls and floor was measured for each setting.

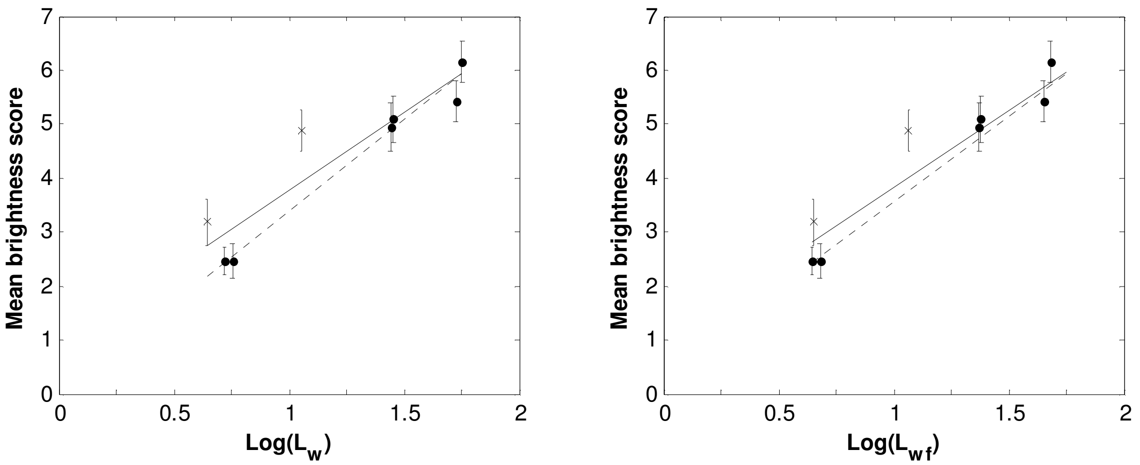
From literature it is known that the average luminance on the walls contributes to the brightness impression of a room. Kato and Sekiguchi (2005) found a correlation between the logarithm of the average wall luminance and brightness. Loe et al. (1994) found a correlation between the logarithm of average luminance of a person 40 degrees vertical field of view and brightness. This means that in relatively small rooms brightness perception relates to the average luminance of the wall surfaces, and in larger rooms it relates to the average luminance of the wall, ceiling and floor surfaces[5].To investigate if average luminance of the walls is a good predictor for room brightness, when intensity and spatial distribution are varied, a regression analysis was conducted. The analysis was conducted between the brightness averaged across participants and settings, and the logarithm of the luminance averaged across all walls for each setting (Figure 17a). The analysis resulted in the following equation:

$$B = 0.89 + 2.88 \cdot \log (L_w)$$

With brightness represented by B, and average luminance of the walls by L_w. The slope of the relation is significantly different from zero. The logarithm of average luminance is therefore significantly related to brightness, with a correlation of 0.93 ($R^2 = 0.86$). This

[5] The relationship between the physical luminance and subjectively perceived brightness is approximately logarithmic

means that average luminance of the walls is a good predictor of room brightness. The regression model is displayed in Figure 17a as the dashed line.



(a) (b)

Figure 17: Mean brightness score of the diffuse settings (·) and the directional settings (x) as a function of the logarithm of the average luminance. In (a) the luminance is averaged across the walls. In (b) the luminance is calculated across the walls and floor. A regression analyses was performed on all settings (—) and on the diffuse settings only (- -). The error bars indicate the 95% confidence intervals of the mean.

Figure 17a, shows that, at equal average luminance of the surfaces, the brightness impression of the diffuse settings (indicated with a dot) is lower compared to the brightness impression of the directional settings (indicated with a cross). This is in line with Tiller & Veitch (1995). They found that two settings with equal average luminance but different spatial luminance distribution can differ in brightness: settings with a non uniform luminance distribution appear brighter than settings with a uniform luminance distribution. Therefore the data could be modeled better if for each light distribution a different regression function would be fitted. A regression analysis for the directional lights makes no sense as we have only two data points. A second regression analysis was conducted on the diffuse settings only to test if the correlation between brightness, and the logarithm of the luminance averaged across the walls improves if the data of the directional lights are excluded. This analysis resulted in the next equation:

$$B = -0.005 + 3.39 \cdot \log (L_w)$$

The slope of the relation is significantly different from zero. The logarithm of average luminance is therefore significantly related to brightness, with a correlation of 0.99 (R^2 = 0.98). This correlation is higher than the correlation of the regression analysis including the data points of the directional lights (displayed in Figure 17a as the dotted line).

To investigate whether participants do also take into account the luminance of the floor in their judgment of room brightness a third regression analysis was conducted to evaluate the relation of brightness and the logarithm of the luminance averaged across the wall and floor surfaces (Figure 17b). The third analysis resulted in the next equation:

$$B = 0.83 + 3.06 \cdot log\ (L_{wf})$$

With brightness represented by B, and average luminance of the walls and floor by L_{wf}. The slope of the relation is significantly different from zero. The logarithm of average luminance is therefore significantly related to brightness, with a correlation of 0.95 (R^2 = 0.91). This means that average luminance of the walls and floor is a good predictor of room brightness. The regression model is displayed in Figure 17b as the dashed line.

A fourth regression analysis was conducted on the diffuse settings only to test if the correlation between brightness, and the logarithm of the luminance averaged across the wall and floor improves if the data of the directional lights are excluded (Figure 17b). The fourth analysis resulted in the next equation:

$$B = 0.24 + 3.39 \cdot log\ (L_{wf})$$

The slope of the relation is significantly different from zero. The logarithm of average luminance is therefore significantly related to brightness, with a correlation of 0.99 (R^2 = 0.98). This correlation is higher than the correlation for the regression analysis including the data points from the directional lights (displayed in Figure 17b as a dotted line).

The analyses show that there is a correlation between brightness impression of a room and the logarithm of the average of the luminance. The correlation slightly increases when the floor is included (for all data). The correlation increases when the directional lights are excluded. Therefore, the average luminance seems to be a good model to predict the change in brightness impression of a room with a particular spatial light distribution. However, the model seems not appropriate to predict the difference in brightness impression of two different spatial distributions.

Conclusions

This experiment shows that participants are able to discriminate between different levels of intensity, CCT and spatial distribution. An increasing intensity was found to increase brightness and to increase perceived uniformity. An increasing CCT was found to change the perceived color temperature towards cool, and to increase the brightness of diffuse light at a high intensity level. Diffuse light was found to increase perceived uniformity compared to directional light.

An interesting interaction effect occurred between Gender and Spatial Distribution on perceived uniformity. Female participants rated directional light settings as more uniform than males, whereas male participants rated diffuse settings as more uniform than female participants.

The average luminance seems to be a good model to predict the change in brightness impression of a room within a particular spatial light distribution.

4.2.2. Preference

Participants were asked to evaluate the light settings on three preference scales: the 'attractive-unattractive' scale, the 'beautiful-ugly' scale and the 'pleasant-unpleasant' scale.

The degree of internal consistency of the preference questionnaire was calculated with a Cronbach's alpha for each of the eight light settings. The Cronbach's alpha varied between 0.84 and 0.95, with an average of 0.88. This means a high internal consistency. Therefore the three items can be pooled together to obtain one item with a higher accuracy. The data was pooled by calculating the average of the three items for each participant and light setting.

The results of the preference questionnaire will be discussed for each of the three designs. For each design a repeated measures ANOVA was conducted to test for the complete design and gender. We report the results of the multivariate analyses. If the results of this analysis deviate from the results of the univariate method, we will report the results from the univariate method in the footnote. A contrast analysis was conducted for design 1 to test for significant effects between the three levels of intensity and interaction effects between intensity and CCT. Only the significant effects are reported. The statistics for these effects can be found in appendix 2.

Design 1: Diffuse light

The preference scores for the diffuse light are displayed in Figure 18. Preference increases from low to medium intensity but was more or less the same for medium and high intensity. Preference decreased with CCT. It is interesting to notice that the light settings with a high CCT were all scored between not preferred and neutral. The settings with a low CCT, on the other hand were not preferred for the low intensities, but they were preferred for the medium and high intensities.

The conducted ANOVA revealed a significant (and large) effect of Intensity ($F(2, 29) = 18.47$, $p < 0.001$, partial $\eta^2 = 0.56$). A contrast analysis revealed only a significant difference between the low and medium intensity level. Also a significant effect was found for CCT ($F(1, 30) = 30.57$, $p < 0.001$, partial $\eta^2 = 0.51$). No significant interaction effects were found ($p < 0.05$).

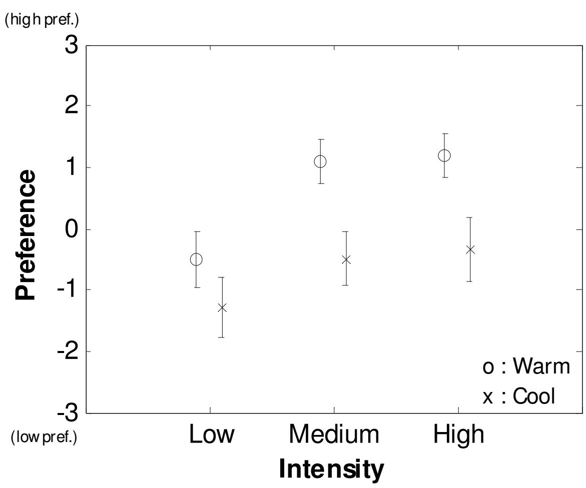


Figure 18: The effect of intensity and CCT on preference for the diffuse lamp. The error bars indicate the 95% confidence intervals of the mean.

Design 2: Directional light

The scores on preference for the directional settings are displayed in Figure 19. Both settings were evaluated positively. The graph shows that the two directional settings were equally preferred on preference for the diffuse lights. A repeated measures ANOVA revealed no significant effect of Intensity and Gender on preference (p>0.05).

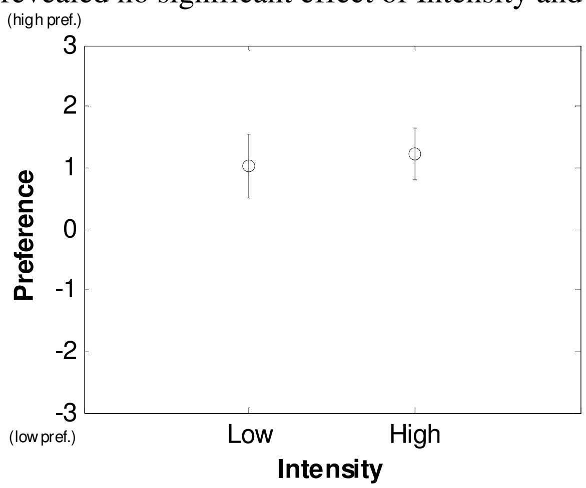


Figure 19: The effect of intensity on preference for the directional lamps. The error bars indicate the 95% confidence intervals of the mean.

Design 3: Diffuse versus directional light

The results of the scores on preference for the diffuse and directional lights are displayed in Figure 20. From the results it can be clearly seen that, at low intensity levels, direct lighting was preferred over diffuse lighting. The directional light was clearly positively scored, whereas the diffuse light was scored slightly negative.

An ANOVA was conducted and revealed a (large) significant effect of spatial distribution on preference ($F(1, 30) = 23.35$, $p < 0.001$, partial $\eta^2 = 0.44$). No effect of Gender was found ($p < 0.05$).

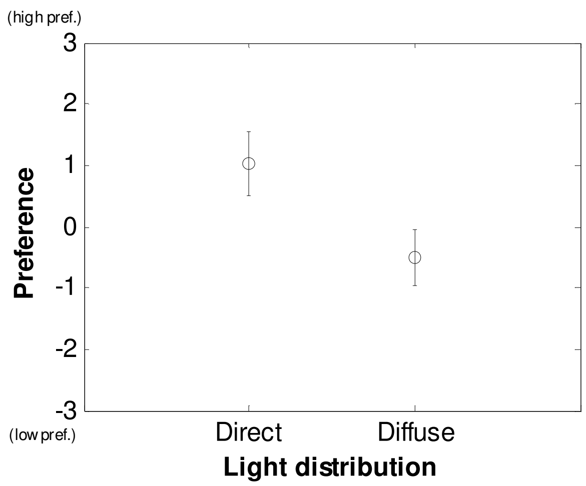


Figure 20: The effect of spatial distribution on preference for the diffuse and directional lamps. The error bars indicate the 95% confidence intervals of the mean.

Conclusions
This experiment shows that higher intensities were preferred over low intensities. However, the preference saturates at the medium and high intensity levels. Warm white light was preferred over cool white light. At a low intensity and warm white light, directional light was preferred over diffuse light. However, it should be noticed that these results might depend on the application for which the light setting is used (see: chapter 2).

4.2.3. Atmosphere

For each light setting participants rated forty atmosphere words. The score for each word on each design is displayed in appendix 3.

Underlying dimensions
Perceived atmosphere can be described in forty variables, i.e. in terms of the forty words as displayed in appendix 1. Using factor analysis these forty variables can be 'summarized' in a smaller set of variables, called factors. Each word can then be described in terms of these factors.

A factor analysis was conducted on this data of the atmosphere words in order to find a factor structure. A factor analysis reduces a large number of variables to a smaller number of latent variables. Each latent variable is a linear combination of the forty items. The latent variables represent the underlying factor structure.

A factor analysis requires a certain sample size in order to produce stable factors. However, other than the fact that the sample size should be sufficiently large, there is little agreement among researchers about the minimal amount of participants needed. Researchers have developed different guidelines (Pett, Lackey & Sullivan, 2003)[6]. In order to increase the reliability of the factor structure of our data, data of the current experiment was pooled with data of former experiments from Vogels (2008) and De Vries and Vogels (2007). Before pooling, the current data set was reshaped in order to fit the format of the other sets. Firstly, two words, actief (active) and kalm (calm), were removed because they were not used in the experiments of Vogels (2008) and De Vries et al. (2007). Secondly, our data set was rescaled from a seven point scale to a five point. As a result, the pooled data set consisted of 524 different cases with 85 different participants on 27 different locations.

The underlying dimensions of the items of the atmosphere questionnaire were analyzed using a principal axis factor analysis. A scree plot was used in order to determine the number of factors that represent the dimensions of atmosphere. The plot shows for each factor the eigenvalue, which is the variance that can be explained by the given factor divided by the total variance of all factors. The plot for this analysis is displayed in Figure 21. For the first four factors the variance is relatively high, however at the fifth factor the variance rapidly drops. This point is called the 'elbow'. An often used criterion is to choose the components before the 'elbow', since each component after the elbow explains only a minor amount of the total variance. In this case four factors accounted for the major amount of the total variance.

[6] Comrey and Lee (1992, as cited in Pett, Lackey & Sullivan, 2003) offer the following guidelines for the sample size: 50 is very poor, 100 is poor, 200 is fair, 300 is good, 500 is very good and 1000, or more, is excellent. Nunally (1978, as cited in Pett, Lackey & Sullivan, 2003) suggests that 10 participants per item is needed. (Tabachnick and Fidel, as cited in Pett et al., 2003) suggest that a sample size of 300 is comforting for factor analysis, and that a smaller sample size (but larger than 150) would be sufficient if there are several items with a loading higher than 0.8.

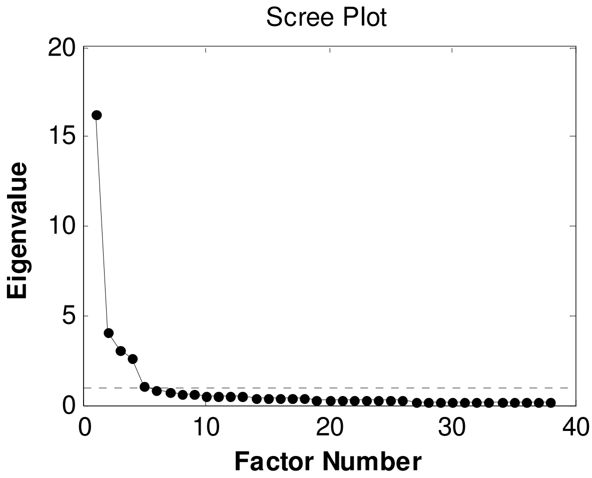


Figure 21: The scree plot of the factor analysis. For each factor the eigenvalue is displayed. The factors with an eigenvalue below 1 lie under the dotted line.

These four factors accounted for respectively 42.0%, 9.7%, 7.1% and 5.8% of the variance and had an eigenvalue larger than one. In order to enhance interpretation, these factors were rotated using a Varimax rotation procedure. This procedure rotates the factors in the atmosphere space, but keeps the angle between them 90° degrees (orthogonal). The solution of this rotation yielded four interpretable factors that accounted for respectively 22.3%, 18.0%, 15.2% and 9.2% of the variance. Additionally, an Oblimin rotation was conducted. An Oblimin rotation is a procedure that rotates the factors but allows the angle between them to change. Table 7 shows the angle between the factors after Oblimin rotation. In addition, the correlation between the factors is presented, which corresponds to the cosine of the angle.

Table 7: This table shows the mutual dependency between each of the factors, expressed as a correlation and an angle.

Factor		1	2	3	4
1	corr	1.00	-0.26	-0.33	-0.19
	angle	*0.0*	*105.3*	*109.4*	*101.2*
2	corr	-0.26	1.00	0.34	0.08
	angle	*105.3*	*0.0*	*70.2*	*85.3*
3	corr	-0.33	0.34	1.00	0.17
	angle	*109.4*	*70.2*	*0.0*	*80.1*
4	corr	-0.19	0.08	0.17	1.00
	angle	*101.2*	*85.3*	*80.1*	*0.0*

If two factors are orthogonal (with a correlation of zero), they are independent. If the angle between factors deviates from orthogonal, dependence increases. As can be seen in Table 7, factors are not orthogonal, suggesting a degree of dependency. Therefore Oblimin rotation was chosen for further analysis.

The contribution of an item on a factor is called the factor loading. An item with a high loading on a factor and a low loading on the other factors contributes high to that factor. The loading of each item on each of the factors are used to interpret each of the four factors. In Table 8 the factor loadings of each item on each factor are displayed. The items that have a 'very good' or 'excellent' loading (> 0.63) on a factor and less than a fair loading (< 0.4) on the other factors are displayed in bold[7]. Translations of the Dutch words in English can be found in appendix 1.

Table 8: The 'pattern matrix' shows the factor loadings of each item. The items are sorted for each factor, based on the factor loadings. The loadings higher than 0.3 are printed in bold[7].

	Factor					*Factor*			
Item	*1*	*2*	*3*	*4*	*Item*	*1*	*2*	*3*	*4*
geborgen	**0.78**	-0.05	-0.06	-0.14	sloom	**0.35**	**-0.64**	0.16	0.22
intiem	**0.76**	-0.12	-0.03	-0.30	vrolijk	**0.37**	**0.63**	-0.04	-0.11
knus	**0.74**	0.00	-0.14	-0.23	bedompt	0.18	**-0.56**	**0.39**	0.08
romantisch	**0.74**	0.02	0.00	-0.25	saai	0.10	**-0.53**	0.19	**0.44**
persoonlijk	**0.70**	0.19	-0.02	-0.11	toegankelijk	**0.37**	**0.43**	**-0.32**	0.28
gemoedelijk	**0.69**	0.12	-0.24	-0.08	bedreigend	-0.06	-0.02	**0.82**	0.00
ontspannen	**0.67**	0.04	**-0.36**	0.06	beangstigend	0.00	-0.08	**0.80**	0.04
behaaglijk	**0.63**	0.16	**-0.30**	-0.04	beklemmend	0.03	-0.21	**0.76**	-0.05
rustgevend	**0.63**	-0.13	**-0.38**	0.27	vijandig	-0.16	-0.04	**0.74**	0.02
warm	**0.63**	0.17	-0.07	**-0.35**	gespannen	-0.11	0.00	**0.73**	0.12
gezellig	**0.60**	0.28	-0.21	-0.14	ongemakkelijk	-0.16	-0.12	**0.70**	0.07
gastvrij	**0.51**	**0.30**	**-0.31**	-0.05	onrustig	-0.22	0.29	**0.65**	-0.09
ongedwongen	**0.48**	0.24	-0.23	0.05	deprimerend	0.01	**-0.39**	**0.56**	0.17
mysterieus	**0.47**	0.06	**0.37**	0.01	afstandelijk	-0.15	-0.10	**0.50**	**0.44**
luxueus	**0.36**	0.30	-0.17	0.14	zakelijk	-0.20	0.03	-0.10	**0.74**
stimulerend	0.13	**0.84**	0.08	0.15	formeel	-0.13	0.01	0.00	**0.64**
enerverend	0.07	**0.80**	0.17	0.08	ruimtelijk	0.01	**0.45**	-0.09	**0.60**
levendig	0.19	**0.77**	0.02	-0.02	koud	-0.22	-0.11	**0.31**	**0.57**
inspirerend	0.25	**0.72**	-0.03	0.12	kil	-0.23	-0.14	**0.34**	**0.54**

The items 'geborgen', 'intiem', 'knus', and 'romantisch' score 'excellent' on factor 1, and less than 'fair' on the other factors. The items 'behaaglijk', 'gemoedelijk', 'ontspannen' and 'persoonlijk' score 'very good' on factor 1, and less than 'fair' on the other factors. The factors 'gezellig', 'rustgevend', and 'warm' score 'good' on factor 1, and less than 'fair' on the other factors. This factor can be interpreted as *coziness*.

The items 'enerverend', 'inspirerend', 'levendig', and 'stimulerend' score 'excellent' on factor 2, and less than 'fair' on the other factors. Furthermore the item 'vrolijk' scores 'very good' on factor two, and less than 'fair' on the other factors. Additionally, the item 'sloom' scores 'very good' and negative; and 'bedompt' scores 'good' and negative. They both score less than 'fair' on the other factors. This factor can therefore be interpreted as *liveliness*.

The items 'beangstigend', 'bedreigend', 'beklemmend', 'gespannen' and 'vijandig' score 'excellent' on factor 3, and less than 'fair' on the other factors. Furthermore the items 'ongemakkelijk' and 'onrustig' score 'very good' on factor 3, and less than 'fair' on the other factors. The factor 'deprimerend' score 'good' on factor 1, and less than 'fair' on the other factors. This factor therefore might be interpreted as *tenseness*.

[7] According to Pett e.a. (2003) no item that has a loading less than 0.30 should be part of defining a factor. When an item score is 0.45 it scores fair. When an item score is 0.63, it scores very good and should be included when defining a factor. Items with a load of 0.71 or higher score excellent.

The items 'formeel' and 'zakelijk' scores 'very good' on factor 4, and less than 'fair' on the other factors. Furthermore, the factor 'koud' scores 'good' on factor four, and less than 'fair' on the other factors. This factor might be interpreted as *detachment*.

For each dimension the reliability is determined for the items with a loading that is higher than 0.4 on that dimension. The reliability was determined by calculating the Cronbach's alpha for each of the eight light setting. The first dimension, *coziness*, has a Cronbach's alpha between 0.89 and 0.94, with an average of 0.92. The second dimension *liveliness* has a Cronbach's alpha between 0.83 and 0.90, with an average of 0.87. The third dimension *tenseness* has a Cronbach's alpha between 0.85 and 0.95 with an average of 0.91. The fourth dimension *detachment* has a Cronbach's alpha between 0.51 and 0.80, with an average of 0.66.

Hence, the 38 atmosphere words can be reduced to four underlying dimensions that describe the atmosphere space. These factors are interpreted as *coziness*, *liveliness*, *tenseness* and *detachment*. A next step is to see how these atmosphere dimensions are affected by lighting characteristics.

Perceived atmosphere of light settings

Instead of describing the data of each participant and each light setting with the score on the 38 atmosphere words, the data can be described with a factor score per participant on each of the four factors. The scores for a given factor were calculated using the Bartlett Method. These scores are a linear combination of all of the variables, weighted by the corresponding factor loading. The atmosphere of each light setting can now be described by the average across participants for each dimension. Notice that these factor scores should be interpreted as relative numbers because the factor analysis normalizes the data. Hence, the zero point on a factor corresponds to the average score across all conditions that were included in the factor analysis. The calculated factor scores are displayed and discussed for each light design in the next sections. For each design a repeated measures ANOVA was conducted to test for the complete design and gender. We report the results of the multivariate analyses. If the results of this analysis deviate from the results of the univariate method, we will report the results from the univariate method in the footnote. A contrast analysis was conducted for design 1 to test for significant effects between the three levels of intensity and interaction effects between intensity and CCT. Only the statistics for the significant effects are reported and can be found in appendix 2.

Design 1: Diffuse light

The factor scores on each dimension for the diffuse light settings are displayed in Figure 22. The figure shows that an increase in Intensity is perceived as less *cozy*, more *lively*, less *tense* and more *detached* compared to a low CCT. A high CCT is perceived as less *cozy*, less *lively*, more *tense* and more *detached*. It seems that there are also some interaction effects between intensity and CCT on *coziness*, *liveliness* and *detachment*.

A repeated measures ANOVA on *coziness* revealed no significant effect of Intensity[8], a large effect of CCT ($F(1, 30) = 83.15$, $p < 0.001$, partial $\eta^2 = 0.74$), and a significant and large interaction effect between intensity and CCT ($F(2, 29) = 3.93$, $p = 0.31$, partial $\eta^2 = 0.21$)[9]. A contrast analysis revealed a significant effect between the medium and

[8]The univariate test was significant using the Greenhouse-Geisser correction ($F(1.6, 47.8) = 4.0$, $p = 0.03$, partial $\eta^2 = 0.12$)

[9] The univariate test was not significant using the Greenhouse-Geisser correction ($F(1.4, 42.7) = 1.67$, $p = 0.21$, partial $\eta^2 = 0.053$)

high intensity. A low CCT is less *cozy* at a high intensity. All other effects were not significant ($p > 0.05$).

For *liveliness* the effect of Intensity was significant ($F(2, 29) = 67.04$, $p < 0.001$, partial $\eta^2 = 0.82$). A contrast analysis revealed a significant effect between the low and medium, and the medium and high intensity. The effect of CCT was significant and large ($F(1, 30) = 6.05$, $p = 0.02$, partial $\eta^2 = 0.17$) and the interaction effect between Intensity and CCT was significant ($F(2, 29) = 4.05$, $p = 0.03$, partial $\eta^2 = 0.22$). A contrast analysis revealed a significant effect between the low and high intensity. *Liveliness* was dependent on CCT for high intensity but not for low intensity. All other effects were not significant ($p > 0.05$).

The effect of Intensity on *tenseness* was significant and large ($F(2, 29) = 15.68$, $p < 0.001$, partial $\eta^2 = 0.52$) A contrast analysis revealed only a significant difference between the low and medium intensity. Also the effect of CCT on *tenseness* was significant and large ($F(1, 30) = 54.77$, $p < 0.001$, partial $\eta^2 = 0.65$). All other effects were not significant ($p > 0.05$).

For *detachment* the effect of Intensity was large and significant ($F(2, 29) = 10.92$, $p < 0.001$, partial $\eta^2 = 0.43$). A contrast analysis revealed only a significant difference between the low and medium intensity. The effect of CCT on *detachment* was also significant and large ($F(1, 30) = 158.89$, $p < 0.001$, partial $\eta^2 = 0.84$). Finally, the interaction effect between intensity and CCT on *detachment* was significant and large ($F(2, 29) = 7.25$, $p = 0.003$, partial $\eta^2 = 0.33$). A contrast analysis revealed only a significant difference between the low and medium intensity. The increase in *Detachment* as intensity increases was significantly more pronounced for the high CCT. All other effects were not significant ($p > 0.05$).

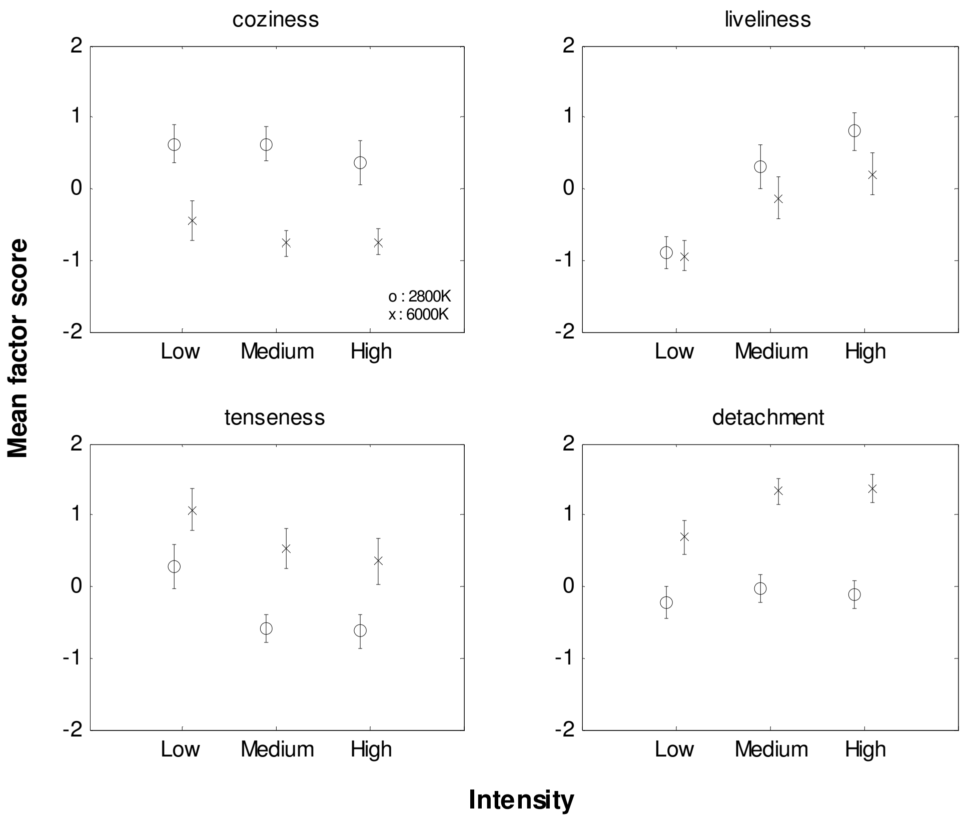


Figure 22: The effect of intensity and CCT on the factors coziness, liveliness, tenseness and detachment, for the diffuse lights. The error bars indicate the 95% confidence intervals of the mean.

Design 2: Directional light

Figure 23 shows the factor scores for the four atmosphere dimensions for the directional lights. The figure shows that an increase in intensity of the directional light is perceived as less *cozy*, more *lively*, less *tense* and more *detached*.

Four repeated measures ANOVA's were conducted. The analyses revealed a significant and large effect of Intensity on *coziness* ($F(1, 30) = 7.39$, $p = 0.011$, partial $\eta^2 = 0.20$), a significant and large effect on *liveliness* ($F(1, 30) = 21.36$, $p < 0.001$, partial $\eta^2 = 0.42$), a non significant effect on *tenseness* ($F(1, 30) = 3.83$, $p = 0.06$, partial $\eta^2 = 0.11$), and a significant and large effect on *detachment* ($F(1, 30) = 12.20$, $p = 0.002$, partial $\eta^2 = 0.29$). All other effects were not significant ($p > 0.05$).

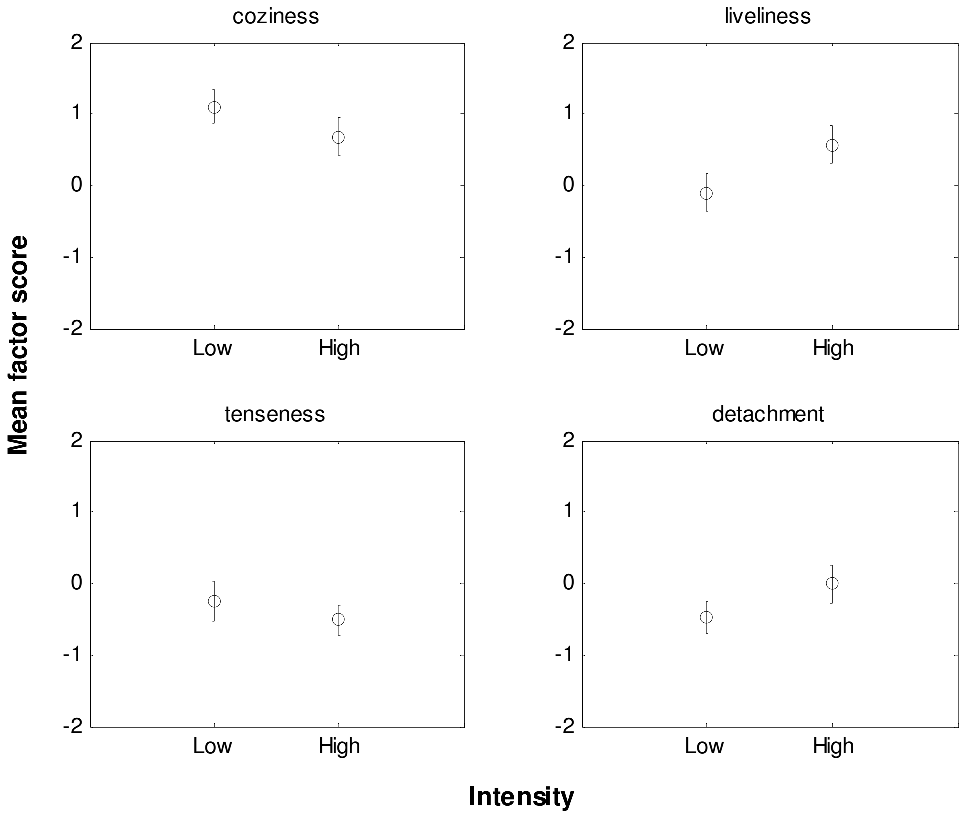


Figure 23: The effect of intensity on the factors coziness, liveliness, tenseness and detachment, for the directional lights. The error bars indicate the 95% confidence intervals of the mean.

Design 3: Diffuse versus directional light

The effect of Spatial Distribution on the four atmosphere dimensions are displayed in Figure 24. From Figure 24 it can be seen that directional light is perceived as more *cozy*, more *lively*, less *tense* and slightly less *detached* compared to diffuse light.

An ANOVA revealed that the effect of Distribution on *coziness* was significant and large ($F(1, 30) = 7.69$, $p = 0.009$, partial $\eta^2 = 0.20$). Distribution also had a large and significant effect on *liveliness* ($F(1, 30) = 33.04$, $p < 0.001$, partial $\eta^2 = 0.52$) and *tenseness* ($F(1, 30) = 8.96$, $p = 0.005$, partial $\eta^2 = 0.23$). The effect on *detachment* and all other effects were not significant.

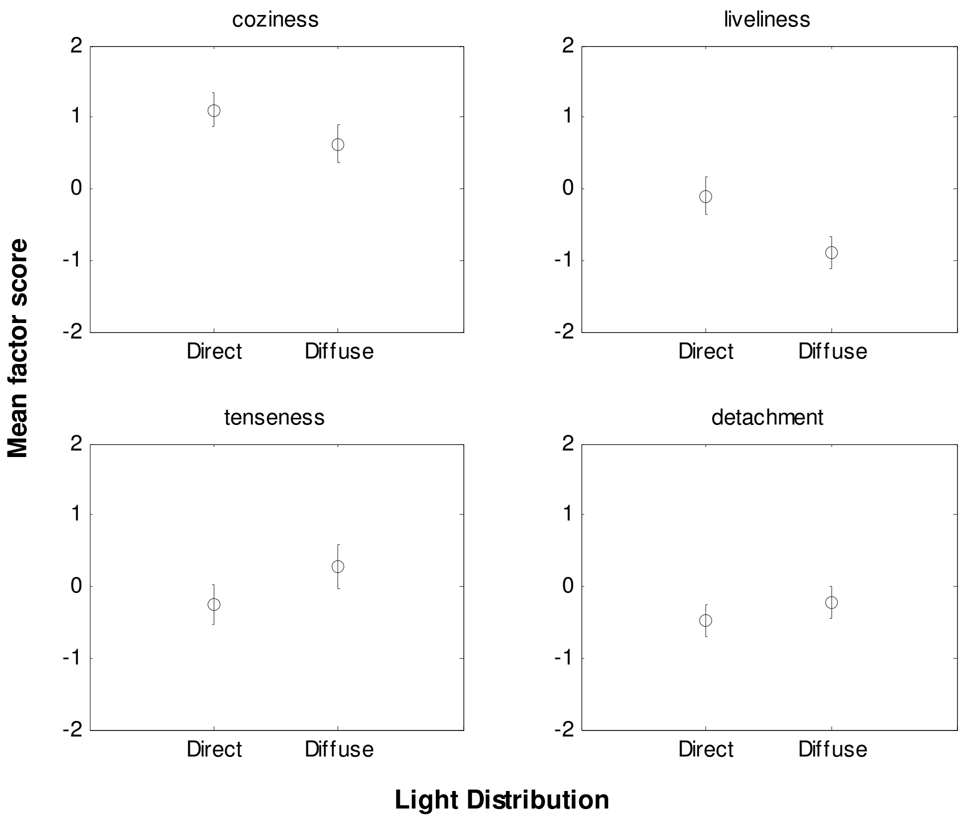


Figure 24: The effects of spatial distribution (direct or diffuse) on the factors coziness, liveliness, tenseness and detachment. The error bars indicate the 95% confidence intervals of the mean.

Conclusions

The results of this experiment show that for both the diffuse and directional light a high intensity is more *lively* than a low intensity. A high intensity is less tense for the diffuse light, and the same (non significant) trend was visible for the directional light. A high intensity is more *detached* for the diffuse light at high CCT and for the directional light. For both the diffuse and directional light a high intensity is less *cozy* at a low CCT level.

For the diffuse settings a low CCT is more *cozy,* less *tense*, and less *detached* than a high CCT. In addition, for a medium and high intensity a low CCT is more *lively*. At low intensities both CCT levels are perceived as equally *lively*.

Directional light is perceived as more *cozy,* more *lively,* and less *tense* compared to diffuse light at the same brightness.

4.2.4. Associations

In the first part of the experiment participants were shown the light settings and asked to give their impression about the atmosphere and to tell what associations came to mind. In the time of day questionnaire in the second part of the experiment, participants were asked to indicate which part(s) of the day they associated with the presented light setting. Additionally, they had the opportunity to write down other associations that came into mind. For each design, first the results of the spontaneous associations will be discussed. Additionally associations with the time of the day will be discussed.

Design 1: Diffuse light

The associations mentioned by the participants are summarized in Table 9. The number between brackets indicates the number of participants that gave that particular answer as a first impression. A number with a ‘Q’ in superscript indicates the number of participants that wrote down that particular association at the end of the time of day questionnaire. To avoid interpretation differences, the atmosphere words are also displayed in Dutch.

Table 9: First impressions and associations for each light setting of design 1. The associations mentioned in the questionnaire are displayed with a ‘Q’ as subscript. Only the most frequently mentioned words are displayed.

diffuse, low, cool	*diffuse, medium, cool*	*diffuse, high, cool*
Atmosphere koud/cold (10) kil/chilly (8) ongezellig/unpleasant (6) afstandelijk/detached (4) saai/boring (3) **Association** hospital (4) chilly (4^Q) boring (3^Q) *no answer (4^Q)*	**Atmosphere** koud/cold (11) kil/chilly (11) ongezellig/unpleasant (7) saai/boring (4) klinisch/clinical (4) zakelijk/businesslike (4) afstandelijk/detached (3) **Association** hospital (11, 5^Q) office (5) laboratory (5, 3^Q) aquarium (3) dentist (3) chilly (7^Q) businesslike (4^Q)	**Atmosphere** kil/chilly (11) koud/cold (9) klinisch/clinical (4) functioneel/functional (4) ongezellig/unpleasant (3) onpersoonlijk/impersonal (3) **Association** hospital (10, 7^Q) laboratory (5) working (5) dentist (4) office (3) fluorescent lamps (3) businesslike (5^Q) chilly (3^Q) clear (3^Q)
diffuse, low, warm	*diffuse, medium, warm*	*diffuse, high, warm*
Atmosphere gezellig/pleasant (6) warm/warm (5) ongezellig/unpleasant (5) saai/boring (4) bedompt/musty (3) *no answer (3)* **Association** *no answer (7, 2^Q)* twilight (4) calmness (3^Q) boring (2)	**Atmosphere** warm/warm (15) gezellig/pleasant (6) rustig/quiet (4) rustgevend/tranquil (3) *no answer (3)* **Association** living room (5) day light (4) bed room (3) sunny (3) beach (3) *no answer (4, 4^Q)*	**Atmosphere** warm/warm (12) vrolijk/cheerful (5) zakelijk/businesslike (3) **Association** sunny (4) working (4) beach (3) living room (3) hospital (3) *no answer (3, 5^Q)* businesslike (3^Q)

In general, participants found the atmosphere of the cool settings cold, chilly, detached and unpleasant atmospheres. These settings were associated with a hospital, an office, a laboratory and the dentist. The warm settings were found to be warm, pleasant, and cheerful. These settings were mostly associated with pleasant and relaxing environments like twilight, living room and bed room. The high intensities, especially at high CCT, were associated with functional situations, for example working and hospital.

The results of the time of day questionnaire are displayed in Figure 25. The figure shows the number of participants that indicated that the particular light setting was associated with the morning, afternoon, evening or night. In order to define whether a setting is associated with a part of the day a criterion of 50% (16 people) was used. Hence, a setting is defined to be associated with a time of the day if more than 50% of the participants choose for that time of the day. Based on this criterion, a 95% confidence interval can be calculated, indicated as the area within the dashed lines. The bars that lie outside this area differ significantly from this criterion. For bars below the area the number of participants is significantly less than 50%, so people do not associated the light setting with that part of the day. For bars above the area the number of participants is significantly larger than 50%, so people do associate the light setting with the part of the day (see: appendix 4 for more information).

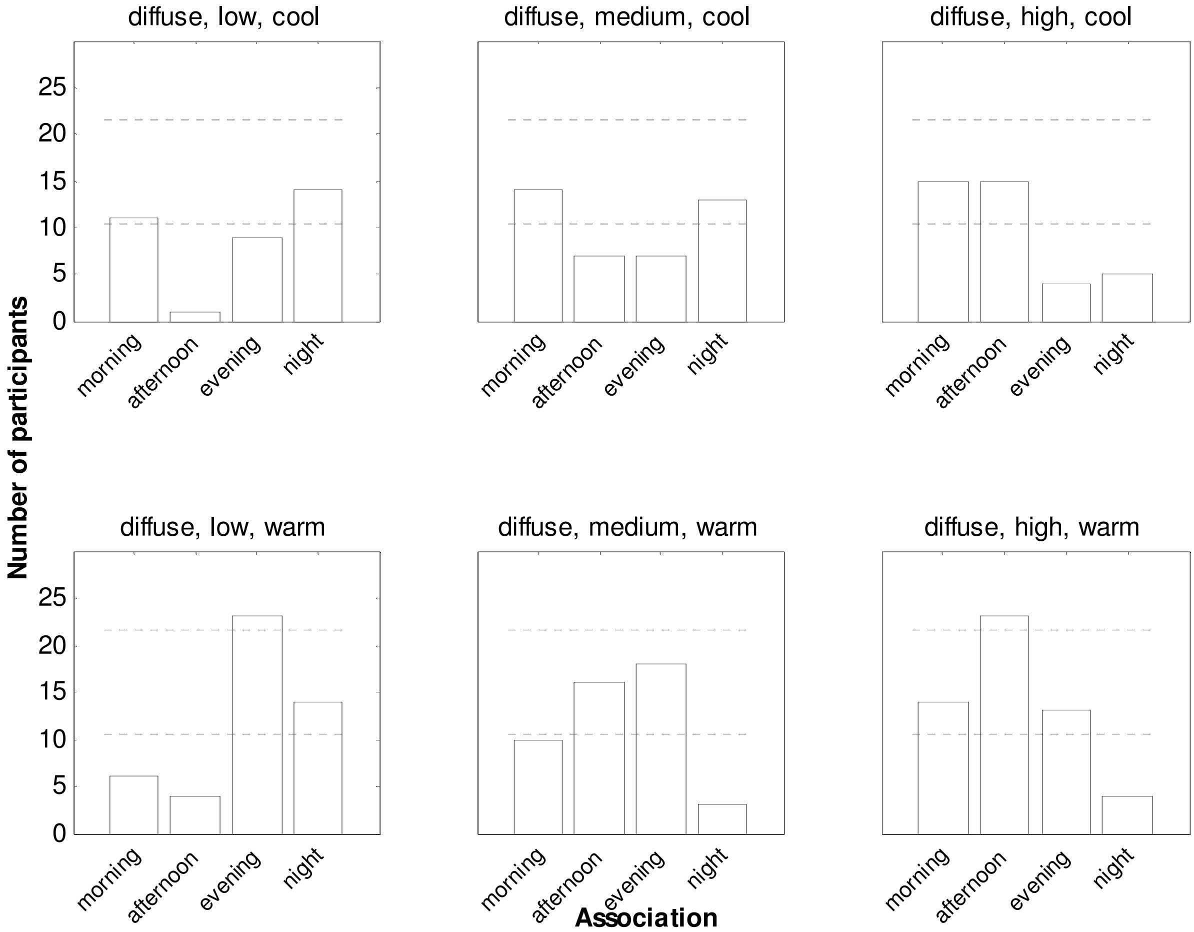


Figure 25: The number of participants that indicated that the particular light setting was associated with the morning, afternoon, evening or night for each light setting of design 1. The dashed lines represent the 95% Confidence Interval of the criterion of 50% (16 persons).

The figure shows that the setting at low intensity and low CCT is associated with evening by more than half of the participants and the setting at high intensity and low CCT is associated with afternoon. None of the cool settings was associated significantly with any time of the day. However, a trend is visible. For both CCT levels, associations with morning and afternoon appear to increase with intensity, and associations with evening and night appear to decrease with intensity.

The difference between the scores of the four associations was tested with a Cochran test for each setting. The score between the association words differed significantly for the cool settings with low and high intensity (respectively: $\chi 2(3, N = 32) = 13.1$, $p = 0.004$ and $\chi 2(3, N = 32) = 16.0$, $p = 0.001$); and the warm settings with low, medium and high intensity (respectively: $\chi 2(3, N = 32) = 25.2$, $p < 0.001$, $\chi 2(3, N = 32) = 16.6$, $p = 0.001$, and $\chi 2(3, N = 32) = 22.2$, $p < 0.001$). The difference between the association words was not significant for the cool setting with medium intensity ($p>0.05$). This means that, for five of the settings, participants associated some words more often than other words. However, as indicated by the confidence intervals, for most of the settings none of the association words were selected by more than half of the participants.

For each of the four association words a Cochran test was conducted to evaluate score differences among the six settings. The score on afternoon differed significantly among the light settings ($\chi 2(3, N = 32) = 48.2$, $p < 0.001$). This was also the case for the score on evening, ($\chi 2(3, N = 32) = 31.7$, $p< 0.001$) and night ($\chi 2(3, N = 32) = 23.4$, $p < 0.001$). This means that changes in intensity and CCT had an effect on the association score of afternoon, evening and night. No significant differences were found for morning ($p > 0.05$), which means that intensity and CCT had no effect on associations with morning.

Design 2: Directional light

The associations mentioned by the participants are summarized in Table 10. Both settings were associated with a pleasant, warm, cozy and relaxed atmosphere. Most people associated both settings with a living room or home situation. However, the low intensity setting was associated with more relaxing situations like watching television and a pleasant situation, whereas the high intensity setting was associated more with functional situations like a shop, work and a museum.

Table 10: First impressions and associations for each light setting of design 2. The associations mentioned in the questionnaire are displayed with a 'Q' as subscript. Only the most frequently mentioned words are displayed.

directional, low, warm	*directional, high, warm*
Atmosphere	**Atmosphere**
gezellig/pleasant (11)	warm/warm (7)
knus/cozy (6)	gezellig/pleasant (6)
warm/warm (6)	ontspannen/relaxed (6)
rustig/quiet (3)	rustig/quiet (5)
rustgevend/tranquil (3)	sfeervol/pleasant/cozy (3)
ontspannen/relaxed (3)	vriendelijk/friendly (3)
sfeervol/pleasant/cozy (3)	
Association	**Association**
living room (5)	living room (6, 4^Q)
evening (4)	shop ($5,3^Q$)
home (4)	home (3)
watching television (3)	work (3)
no answer (4)	museum (3)
cozy (5^Q)	no answer (3^Q)
pleasant (4^Q).	

Figure 26 shows the number of participants that indicated that the particular light setting was associated with the morning, afternoon, evening or night. Again a criterion of 50% was used (see: appendix 4).

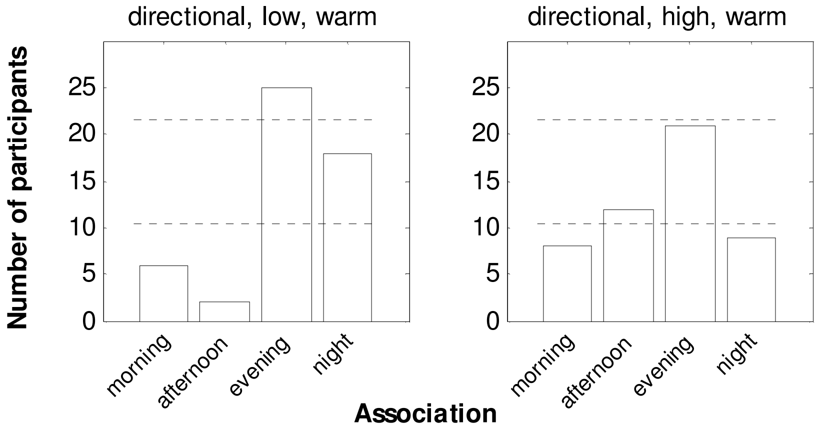


Figure 26: The number of participants that indicated that the particular light setting was associated with the morning, afternoon, evening or night for each light setting of design 2. The dashed lines represent the 95% Confidence Interval of the criterion of 50% (16 persons).

The figure shows that only the setting with a low intensity setting is associated with evening by more than half of the participants. However, again a trend is visible. The number of associations with evening and night decreases with intensity, whereas the number of associations with morning and afternoon increase. It is interesting to see that the results look similar to those of the diffuse settings with a low CCT at low and medium Intensity.

A Cochran test revealed that there was a significant effect of association words. The associations differed significantly from each other for the low intensity setting ($\chi2(3, N = 32) = 36.0, p < 0.001$) and for the high intensity setting ($\chi2(3, N = 32) = 11.7, p = 0.009$). This means that, for the two settings, participants associated some words more often than other words. However, as indicated by the confidence intervals, almost none of the association words were selected by more than half of the participants.

A McNemar test was conducted to test, for each of the four association words, for differences between the two light settings. A McNemar test tests the difference between two conditions. Only the association with afternoon differed significantly between the two settings ($p = 0.002$). The other association words with the other day parts did not differ significantly among the two settings ($p > 0.05$). This means that a change in Intensity mainly affects the association with afternoon.

Design 3: Diffuse versus directional light

The associations mentioned by the participants are summarized in Table 11. The atmosphere of the directional lights was considered to be quit, relaxed, cozy and warm. The atmosphere of the diffuse settings was judged differently among participants: some participants considered the atmosphere as pleasant and warm, whereas other participants also mentioned unpleasant boring and musty. Participants associated the directional setting with living room, evening, twilight and home. The diffuse setting was associated with situations as twilight, calmness and boring.

Table 11:First impressions and associations for each light setting of design 3. The associations mentioned in the questionnaire are displayed with a 'Q' as subscript. Only the most frequently mentioned words are displayed.

directional, low, warm	*diffuse, low, warm*
Atmosphere gezellig/pleasant (11) knus/cozy (6) warm/warm (6) rustig/quiet (3) rustgevend/tranquil (3) ontspannen/relaxed (3) sfeervol/pleasant/cozy (3)	**Atmosphere** gezellig/pleasant (6) warm/warm (5) ongezellig/unpleasant (5) saai/boring (4) bedompt/musty (3) *no answer (3)*
Association living room (5) evening (4) home (4) watching television (3) *no answer (4)* cozy (5^Q) pleasant (4^Q)	**Association** *no answer (7, 2^Q)* twilight (4) calmness (3^Q) boring (2)

The results of the time of day questionnaire for the directional versus diffuse settings are displayed in Figure 27. The bars that lie outside the confidence intervals differ significantly from chance (see: appendix 4).

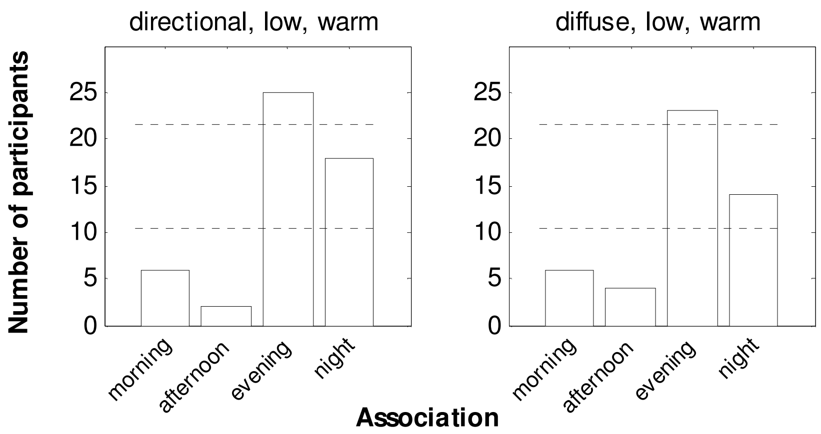


Figure 27: The number of participants that indicated that the particular light setting was associated with the morning, afternoon, evening or night for each light setting of design 3. The dashed lines represent the 95% Confidence Interval of the criterion of 50% (16 persons).

Both the directional and the diffuse settings at low intensity were associated with evening by more than half of the participants. It is interesting to see that the score on associations have the same pattern for both settings. This indicates that associations with a time of the day is not strongly dependent on the spatial distribution of the light.

For each setting a Cochran test was conducted to test for differences between the association words. An effect was found both for the directional light ($\chi2(3, N = 32) = 36.0, p < 0.001$) and for the diffuse light ($\chi2(3, N = 32) = 25.2, p < 0.001$). This means that, for the two settings, participants associated some words more often than other words. However, as indicated by the confidence intervals almost none of the association words were significantly selected by more than half of the participants.

A McNemar test was conducted to test for differences between the two settings for each word. This test revealed no significant differences ($p > 0.05$), indicating that the associations were not affected by a change in spatial distribution.

4.2.5. Applications

In the first part of the experiment participants were asked to mention what application would be suitable for each of the presented light setting.

Later, in the application questionnaire participants were asked to indicate how suitable the light setting would be for six applications. For each design a repeated measures ANOVA was conducted to test for the complete design and gender. We report the results of the multivariate analyses. If the results of this analysis deviate from the results of the univariate method, we will report the results from the univariate method in the footnote A contrast analysis was conducted for design 1 to test for significant effects between the three levels of intensity and interaction effects between intensity and CCT. Only the significant effects are reported. The statistics for these effects can be found in appendix 2.

Design 1: Diffuse light

Table 12 shows the results of the applications that were spontaneously mentioned by participants. Remarkably, a lot of the participants could not think of a suitable application. However, waiting room and bathroom were mentioned most. It is interesting to see that the cold settings were especially associated with functional situations when the intensity was medium or high. In general, participants found more applications suitable for the higher intensities.

Table 12: Suitable applications that were spontaneously mentioned for each light setting of design 1

diffuse, low, cool	*diffuse, low, cool*	*diffuse, high, cool*
Application *no answer (20)* mortuary (3)	**Application** *no answer (13)* hospital (6) waiting room (3) train station (3)	**Application** *no answer (9)* laboratory (6) hospital (3)
diffuse, low, warm	*diffuse, medium, warm*	*diffuse, high, warm*
Application *no answer (16)* waiting room (3)	**Application** *no answer (14)* bathroom (5)	**Application** *no answer (17)* waiting room (3)

The results of the application questionnaire are displayed in Figure 28. Participants found the cool settings, at medium and especially high intensity, suitable for the functional environments: study room, office and shop. The cool settings at low intensity were not considered to be applicable to any of the asked environments. The warm settings were found to be suitable for the relaxing environments: bed room, living room and hotel room, especially at the medium intensity level. The functional settings were considered to be more applicable when intensity increases.

A repeated measures ANOVA was conducted to test whether suitability for an application is dependent on Intensity, CCT and Gender. The results for the significant main and interaction effects are displayed in Table 13.

Table 13: The significant main and interaction effects of Intensity and CCT on suitability for an application, for design 1.

Intensity	*df*	*F*	*p*	*partial η^2*
Study room	2,29	103.02	< 0.001	0.88
Office	2,29	73.72	< 0.001	0.84
Shop	2.29	68.74	< 0.001	0.83
Bed room	2,29	3.55	0.042	0.20
CCT	*df*	*F*	*p*	*partial η^2*
Office	1,30	14.03	0.001	0.32
Bed room	1,30	109.82	< 0.001	0.79
Living room	1,30	103.75	< 0.001	0.78
Hotel room	1,30	88.28	< 0.001	0.75
Intensity x CCT	*df*	*F*	*p*	*partial η^2*
Office	2,29	3.49	0.044	0.19
Shop[10]	2,29	3.51	0.043	0.20
Bedroom[11]	2,29	4.33	0.023	0.23

Suitability for a study room increases significantly with Intensity. A contrast analysis revealed only a significant difference between the low and medium Intensity. Suitability for office increases significantly with Intensity. A contrast analysis revealed a significant difference between the low and medium Intensity and the medium and high Intensity. A high CCT was found to be significantly more suitable for an office application. The interaction effect between Intensity and CCT was significant. A contrast analysis revealed a significant difference between the low and medium Intensity. Suitability for office increases with Intensity, however this increase was larger for a high CCT compared to a low CCT. The suitability for a shop increases significantly with Intensity. A contrast analysis revealed a significant difference between the low and medium Intensity and the medium and high Intensity. Additionally, a significant interaction effect was found between Intensity and CCT. A contrast analysis revealed a significant difference between the medium and high Intensity. For bedroom a significant effect of Intensity was found. A contrast analysis revealed a significant difference between the medium and high Intensity. Furthermore a significant effect of CCT was found, and an interaction effect between Intensity and CCT. A contrast analysis revealed a significant difference between the medium and high Intensity. Suitability for bedroom decreases for the low CCT high Intensity. Finally, for living room and hotel room only a significant effect for CCT was found

[10] The univariate test was only marginal significant using the Greenhouse-Geisser correction, ($F(1.8, 54.4) = 2.61$, $p<0.08$, partial $\eta^2 = 0.08$)

[11] The univariate test was only marginal significant using the Greenhouse-Geisser correction, ($F(1.8, 55.0) = 3.13$, $p<0.056$, partial $\eta^2 = 0.094$)

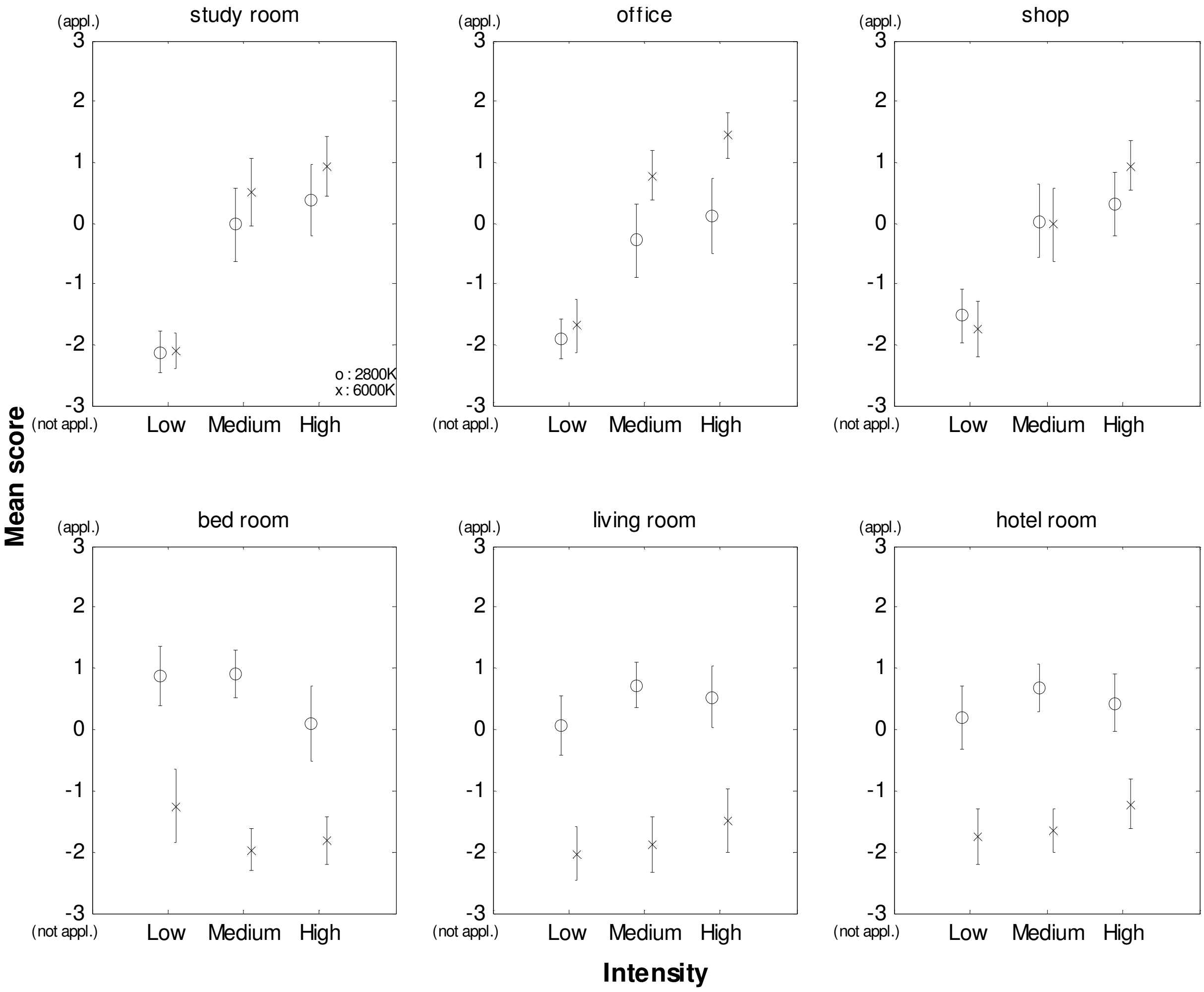


Figure 28: The effects of different levels of intensity and CCT on the suitability of six different environments for the light settings of design 1. The error bars indicate the 95% confidence intervals of the mean.

Design 2: Directional light

The results for the applications that were spontaneously mentioned by participants are displayed in Table 14. Again, many participants could not think of a suitable application. However, the same amount of participants found both settings suitable for a bathroom. Additionally, the setting with low intensity was thought to be suitable for a restaurant or lounge bar.

Table 14: Suitable applications that were spontaneously mentioned for each light setting of design 2

directional, low, warm	*directional, high, warm*
Application *no answer (17)* restaurant (5) bathroom (3) lounge bar (3).	**Application** *no answer (12)* bathroom (3)

Figure 29 shows the results of the application questionnaire for the directional settings. Both settings were considered to be suitable for the relaxing environments: bed room, living room and hotel room. The low intensity settings was considered less suitable for the environments: study office and shop compared to the high intensity setting. To test whether suitability for an application is dependent on Intensity and Gender, a repeated measures ANOVA was conducted (Table 15).

Table 15: The significant effects of Intensity on suitability for an application, for design 2.

Intensity	*df*	*F*	*p*	*Partial* η^2
Study room	1,30	8.51	0.007	0.22
Office	1,30	20.89	< 0.001	0.41
Shop	1,30	30.30	< 0.001	0.50
Bed room	1,30	4.51	0.042	0.13

Intensity had a positive effect on the suitability of study, office, and shop, and a negative effect on the suitability of bed room. No significant effects were found for living room and hotel room (p > 0.05).

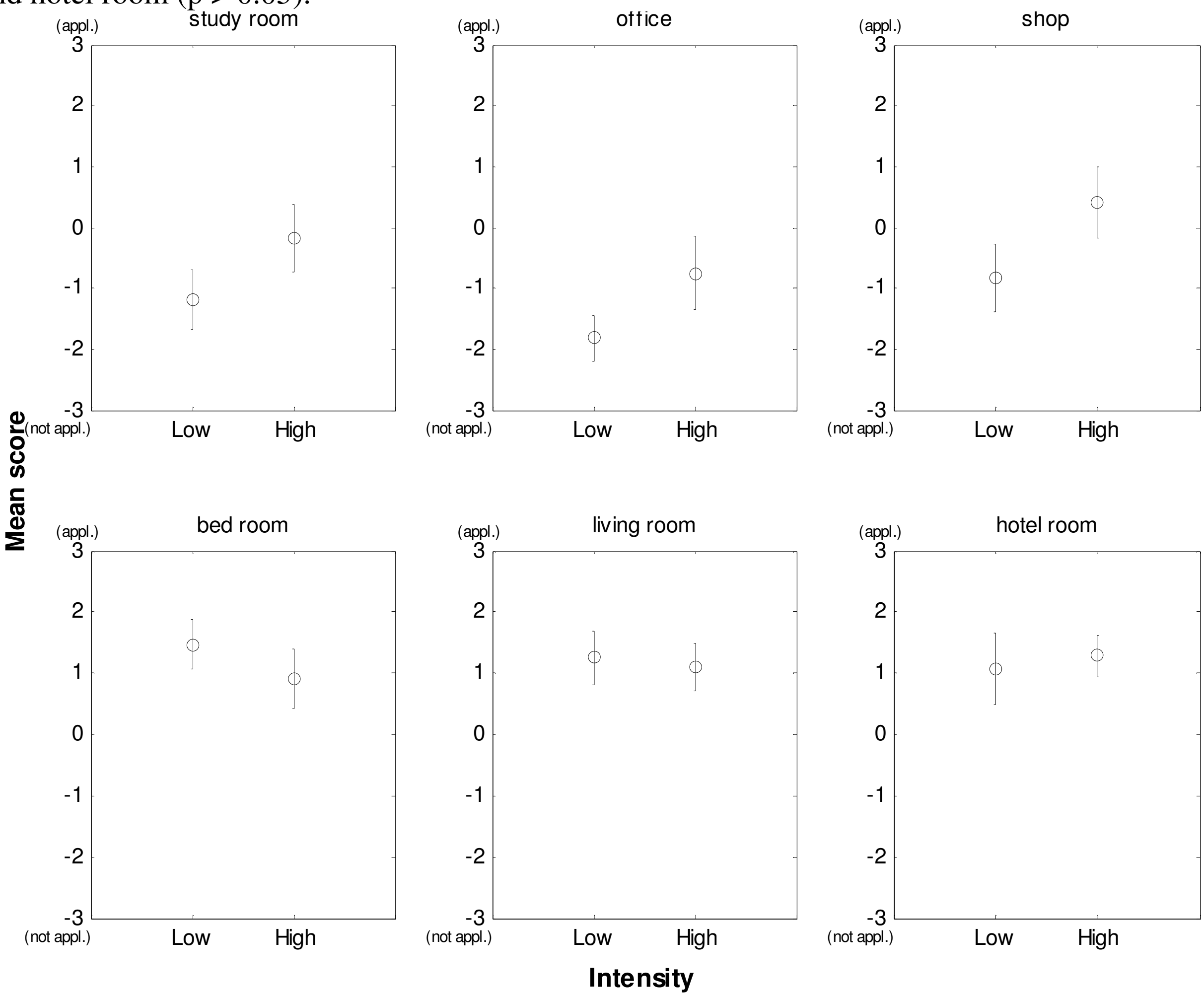


Figure 29: The effects of different levels of intensity on the suitability of six different environments for the light settings of design 2. The error bars indicate the 95% confidence intervals of the mean.

Design 3: Diffuse versus directional light

Table 16 shows the results for applications that were spontaneously mentioned, for the directional versus the diffuse settings. Again, a lot of participants could not think of a suitable application for the two settings. However the directional lights seem more suitable for relaxing applications, whereas the diffuse lights seem slightly more suitable for a more functional application.

Table 16: Suitable applications that were spontaneously mentioned for each light setting of design 3

directional, low, warm	*diffuse, low, warm*
Application *no answer (17)* restaurant (5) bathroom (3) lounge bar (3).	**Application** *no answer (16)* waiting room (3)

The results of the application questionnaire are displayed in Figure 30. Both settings were, according to the participants, not suitable for the functional applications study room, office and shop. Both settings were more suitable for the applications bed room, living room and hotel room. The diffuse settings were in general less suitable for all of the applications.

Table 17: The significant effects of spatial distribution on suitability for an application, for design 3.

Intensity	*df*	*F*	*p*	*Partial* η^2
Study room	1,30	12.91	0.001	0.30
Living room	1,30	12.91	0.001	0.30
Shop	1,30	4.27	0.048	0.12

To test the effect of Spatial Distribution and Gender on suitability, a repeated measures ANOVA was conducted. Table 17 shows the results of the application questionnaire for the directional and diffuse settings. The directional settings were significantly more suitable for the applications: study room, living room and shop.

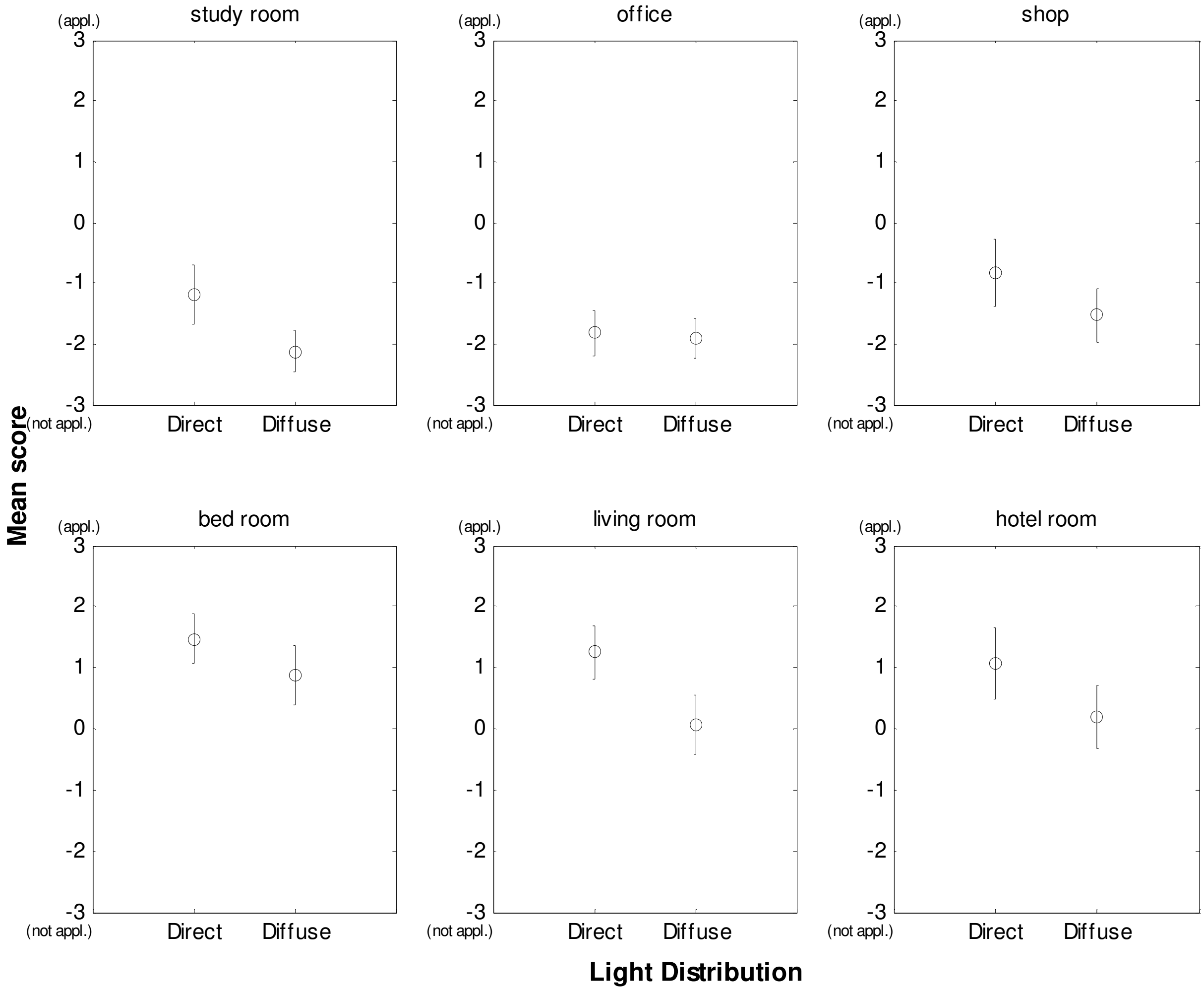


Figure 30: the results of the application questionnaire. The effects of two different spatial distributions on the suitability of six different environments are displayed for design 3. The error bars indicate the 95% confidence intervals of the mean.

5. Discussion

In this study, the effects of several lighting characteristics on (1) the perceived atmosphere of an environment (2) the appearance of light and (3) the preferences of the light were investigated. Additionally, participants were asked to provide associations with the lighting and to come up with suitable applications for each light setting. The results of the experiments are summarized and discussed in this chapter. This chapter will end with the limitations of this study, suggestions for further research, and a general conclusion.

5.1. Light appearance

The light appearance questionnaire showed that the light characteristics intensity, CCT and spatial distribution had an effect on the corresponding perceptual attributes. This means that people were able to discriminate between the different levels of intensity, CCT and spatial distribution. This is an important result, because if people could not distinguish between the different levels of an attribute, we would probably not find an effect of the attribute on perceived atmosphere. The observation that brightness is affected by intensity, perceived color temperature is affect by CCT and perceived uniformity is affected by spatial distribution are in line with previous research, e.g., Davis and Ginthner (1990), Loe, Mansfield and Rowlands (1994), and Manav (2007).

Some perceptual attributes were also influenced by non-corresponding light characteristics. However, it should be noted that these effects were much smaller compared to the effects of the corresponding light characteristics. Brightness was affected by intensity and, at a high intensity, it was also affected by CCT. The cool light appeared to be brighter at high intensity compared to warm light. Perceived color temperature was only affected by CCT. Uniformity perception was affected by both the spatial distribution and intensity of light, but not by CCT; light settings with a high intensity were perceived as more uniform compared to light settings with a low intensity. In addition, an effect of gender was found. Females perceived a directional light setting as more uniform than males, whereas male participants perceived diffuse settings as more uniform than female participants.

The results that diffuse lights with a high CCT look brighter than lights with a low CCT at high intensity do agree with the study of Harrington (1953) and Knez (1995a). Harrington found, in a matching task, that an illuminated projected field with a high CCT needs less illuminance than a field with a lower CCT in order to appear equally bright. However Davis et al. (1990) and Knez (1995a) only found effects of intensity on brightness while using lamps with a high CRI. Possibly the interaction effect between intensity and CCT only occurs for large extreme differences in CCT. The studies used moderate CCT differences. Davis et al. (1990) used CCT levels between 3200K and 5400K, and Knez used a CCT level 3000K and a level of 4000K. In contrast, the current study used more extreme differences in CCT; the CCT ranged between 2800K and 6000K.

The finding that uniformity perception is dependent on the intensity of light cannot be explained by Weber's law: $\Delta I = k \cdot I$. Weber's law states that the smallest detectable change in intensity (ΔI) is a constant fraction (k) of the level of stimulation (I). Given the fact that the ratio between minimum and maximum luminance and illuminance values is constant for the diffuse lights, Weber's law would predict a constant score on the uniformity scale. The results are also not in agreement with studies on the spatial contrast sensitivity. DeValois, Morgan and Snodderly (1974) found that the sensitivity to sinusoidal light patterns increases with an increase in average luminance level. This means that $\Delta I/I$ decreases with intensity and, hence, the pattern would look less uniform. De Valois et al. (1974) used gratings and looked for thresholds, whereas we illuminated a room and asked for uniformity. Further research is needed to clarify on the effects of intensity on uniformity perception in a space.

No literature has been found that reports an effect of gender on perceived uniformity in a space. Also in studies on spatial contrast sensitivity (e.g. Higgins, Jaffe, Caruso & deMonasterio, 1988) no gender effects were found. As mentioned earlier, studies on spatial contrast sensitivity have used a different stimulus and a different response compared to our experiment. In order to clarify the effect of gender on uniformity perception in a space further research is necessary.

5.2. Preference

Participants had clear preferences for certain levels of intensity, CCT and spatial distribution. In general, high intensities were preferred over low intensities and light with a low CCT was preferred over light with a high CCT. Therefore, a low CCT with medium or high intensity levels was most preferred, whereas a high CCT at a low intensity level was the least preferred light setting. Furthermore, directional light was slightly more preferred over diffuse light.

The results on preference for CCT and intensity are in line with the Kruithof curve (Boyce, 2003). The curve predicts that light is perceived as pleasing when the intensity lies between a maximum and minimum level, which depends on the CCT of the light. High CCT levels are already preferred at a low intensity level, whereas the intensity level of high CCT levels should be much higher to be preferred. This trend is visible in the data of the current experiment. As intensity increases, preference of a setting increases, irrespective of CCT. However a low CCT was preferred over high CCT at the same intensity. This means that a low CCT was already preferred at lower intensity levels, and that the intensity of light with a high CCT should be higher to be equally preferred.

This experiment was performed in an empty experimental room. Literature has shown that context plays a role in the preference of intensity and CCT. Also the suitability questionnaire shows that people prefer certain applications for certain light settings. Therefore, it would be interesting to repeat this experiment in different contexts by furnishing this room as e.g. an office, or a living room.

From the current experiment it can be concluded that that directional lights are slightly more preferred over diffuse lights. This is in line with findings from the Bartlett research group (see: Veitch, 2001). The Bartlett group found that settings with a non uniform luminance distribution are preferred over uniform distributed settings. Loe et al. (1994) found similar results: preference increases when the ratio between maximum and minimum luminance increases, i.e. when the light becomes less uniform.

5.3. Atmosphere

A factor analysis on the data of the atmosphere questionnaire revealed that perceived atmosphere can be described with four factors: *coziness, liveliness, tenseness* and *detachment*. It was found that exposure to different levels of lighting characteristics has an effect on each of these four dimensions. A high intensity was perceived as more *lively*, less *tense* and less *cozy* at a low CCT level. A high intensity was perceived as more *detached* for the diffuse light at high CCT and for the directional lights. For the diffuse settings a low CCT was perceived as more *cozy,* less *tense*, and less *detached* than a high CCT. In addition, for a medium and high intensity a low CCT was perceived as more *lively*. At low intensities both CCT levels are perceived as equally *lively*. Directional light was perceived as more *cozy,* more *lively,* and less *tense* compared to diffuse light at the same brightness.

Notice that these results can be intuitively understood. This experiment shows that the atmosphere questionnaire of Vogels (2007) is a sensitive tool to measure environmental experience. Lighting characteristics cannot only change the perception of the room, but also the perceived atmosphere. The tool is able to distinguish differences in atmosphere between moderate light settings in an empty room.

The results of the atmosphere experiment are first discussed in the context of previous research on atmosphere. Subsequently, the results are compared with results of research on emotion. The results of the factor analysis in the current experiment are similar to the results of Vogels (2008) and De Vries and Vogels (2007). In these two studies a factor analysis was conducted, using only the data of the particular study. In both studies two factors were found. Vogels (2008) found with a rotated (Varimax) method the factors *coziness* and *liveliness*. De Vries et al. (2007) found two unrotated factors which she called *pleasure* and *arousal*. However, a closer look to the rotated (Varimax) analysis reveals two factors that could be interpreted as a *tenseness* (relaxed vs. tense) and *liveliness* (lively vs. bored) factor. Furthermore two clusters of words that could be interpreted as *coziness* and *detachment* can be distinguished. This trend is in line with the results of the current study where four factors were found. The appearance of the additional factors in the current study might be attributed to the fact that this factor analysis was conducted on the combined data of Vogels (2008), De Vries et al. (2007) and this study.

There might be a relation between the four atmosphere factors and the emotion factors *pleasure*, *arousal* and *dominance* (see: Mehrabian and Russell, 1974). The diagonals of the *pleasure* and *arousal* dimensions are excitement versus bored and relaxed versus tense. Excitement versus bored might be the same as the *liveliness* dimension as found in the current study, and relaxed versus tense might be the same as the *tenseness* dimension. We expect that the *coziness* dimension that was found in the current study might be the *pleasure* dimension since words with a pleasure component, like *warm* (warm) and *behaaglijk* (cozy), score high on this dimension. Possibly the *detachment* dimension is related to the *dominance* factor. The dominance factor ranges from feelings of total lack of control to the opposite extreme of feeling influential and in control. The factor correlation matrix shows a low correlation between each of the four atmosphere factors, which indicates that they are unrelated to a large extend. A follow up study is necessary to investigate the relation between atmosphere and emotion.

Some differences between this study and studies on the effects of lighting on emotion can be observed. The effect of lighting on emotion is smaller and inconsistent compared to the effect on atmosphere perception. Additionally, complex interaction effects of lighting characteristics, gender and age on emotion have been found in these studies. Differences between the effects on atmosphere and emotion might be caused by differences in adaptation time, experimental design (within groups design vs. between groups design), stimuli, measurement method, and, of course, dependent variable.

In the study of McCloughan et al. (1999) participant's emotion was measured immediately after the exposure to the stimulus and after 40 minutes. They found short term effects of intensity on sensation seeking (a positive mood) and short term effects of CCT on hostility (a negative mood). After 40 minutes no differences were measured in sensation seeking, however, complex interactions with intensity, CCT, gender and anxiety and hostility were reported. Studies of Knez (1995 a; 1995b; 2001) and Knez & Enmarker (1998) show no direct effects of lighting on mood. Also Baron (1992) found no significant results of lighting on the PANAS scale. Additionally, studies of Knez (1995a; 1995b; 1997) revealed several complex interaction effects of intensity, CCT, CRI, gender and age on emotion.

In our study participants were asked to fill in the atmosphere questionnaire almost directly after the light stimulus was shown. Since participants had a very short time to adapt to the light setting, a setting might appear more extreme at first glance than it would after total adaptation. Consequently, perceived atmosphere might have been less extreme than in the current experiment when people would have stayed in the room for a long period of time. Because longer term effects of lighting on emotion are reported, it would be interesting to conduct a study on these long term effects.

The results on perceived atmosphere are larger than the effects on emotion. Although, compared to the current atmosphere study, the stimuli used in emotion studies are more extreme in intensity (ranging between 300lx and 1500lx), and slightly less extreme in CCT (ranging between 2875K and 5500K). Moreover, results in emotion research are difficult to compare with each other since they show inconsistent and complex effects. This implies that emotion might not be a useful dependent variable to determine the environmental effect on human beings. Because lighting can only change people's emotion if this light setting is personally meaningful (Lazarus, 1991), an emotion might simply not always change as a result of a lighting characteristic.

5.4. Associations

In the first impression part, light settings with a high CCT were judged as having a cold, chilly, detached and unpleasant atmosphere. The settings with a low CCT, on the other hand, were judged as having a warm, pleasant and cheerful atmosphere and were associated with pleasant and relaxing environments like twilight, living room, bed room or general home situation. The settings with a high intensity were associated with functional situations (e.g. working and hospital) for both CCT levels and both for the diffuse and directional settings. The associations that participants give were in line with the results of the atmosphere questionnaire. This shows that the atmosphere questionnaire is rather complete.

In the time of the day questionnaire the warm settings were associated most with evening at low intensity and with afternoon at high intensity. None of the cool settings was associated with any time of the day by more than half of the participants. For both

CCT levels, associations with afternoon increased with intensity, and associations with evening and night decrease with intensity.

It is remarkable to see that the score on associations have the same pattern for both spatial distribution settings, indicating that associations with a time of the day was to a less extend dependent on spatial distribution of light, and more on intensity and CCT.

5.5. Applications

In general people found it difficult to spontaneously mention a suitable application for a light setting in an empty room. Light with a high CCT at a medium or high intensity was mostly found to be suitable for a functional situation. Warm directional light was found to be suitable for a relaxing environment like a restaurant or a bathroom. Warm diffuse light was found to be more suitable for a waiting room.

Intensity and CCT is was an important factor in judging suitability for a functional application. The higher the intensity and CCT, the more suitable a setting was for a functional application. A low CCT was suitable for a relaxing application.

The results from the application questionnaire can be intuitively understood in combination with the results from the atmosphere questionnaire. For the application ‘study room’ and shop a high intensity light setting was preferred. A high intensity makes an atmosphere more *lively* and *detached* (at high CCT). The application ‘office’ was preferred at high intensity and high CCT level, these levels make an environment *detached* and somewhat *lively*. For the ‘bedroom’ application a low CCT was preferred in combination with lower intensity levels. These levels make an environment more *cozy*, less *lively* and less *detached*. For the applications ‘living room’ and ‘hotel room’ a low CCT and higher intensity levels were preferred, these settings makes an environment *cozy,* more *lively,* less *tense* and less *detached.*

It would be interesting to verify these results in a furnished room and to ask which light setting would be the most suitable for a certain type of furnishing.

5.6. Suggestions for further research

The study gives insight in the relation between lighting and atmosphere perception. However, some limitations and suggestions for further research have to be mentioned.

In the current study three designs were tested, whereas one full design was desired. It was desired to test all combinations of intensity, CCT and spatial distribution on two levels. Due to technical constraints it was impossible to change the directional luminaires on different levels of intensity and CCT independent of each other. Furthermore the range of intensity and CCT for the directional lights was rather small. It would be interesting to investigate the effect of directional lights for a wider range of intensity and CCT. This might be possible by using LED spots or spots with fluorescent lamps.

In order to investigate the effect of spatial distribution on atmosphere, settings with equal perceived brightness and color temperature have to be created. However, there is no physical measure known that is a good predictor for brightness impression of a room. We have shown that brightness perception has a high correlation with the luminance averaged across all room surfaces. It furthermore became clear that spatial light distribution plays a role. To gain insight in the exact mechanisms behind brightness perception, this topic should be investigated in more detail.

The current experiment was conducted in an empty room and therefore the ecological validity might be low. It is hard to generalize the effects of lighting on other environments. It would be interesting to investigate the effect of lighting characteristics on atmosphere perception for real life environments. Therefore, a follow up experiment should be conducted in a more realistic situation, e.g. a room furnished as a living room, or an office.

During the experiment participants were able to see the luminaires. They could possibly recognize the diffuse luminaries as fluorescent lamps and the directional luminaries as halogen lamps. It is possible that people have certain associations with each of the luminary types. It should therefore be taken into account that the results on atmosphere might be biased by the associations with a certain luminary type. Because of practical reasons it was hard to overcome the problem during this study. A suggestion for further research would be to use one luminaire type which can be varied in diffuseness.

The sample group as used in this experiments was homogeneous in age, professional background and nationality. As Vogels (2008) already mentioned it is very well possible that people have different opinions about atmosphere in an environment depending on culture, age and professional background. It would be interesting to investigate the effects of these variables on atmosphere perception.

During each light setting a neutral settings was used to eliminate adaptation effects. It is possible that people used this neutral setting as an anchor. Participants would then judge atmosphere of each setting with respect to this neutral setting. It should be taken into account that participants possibly scored the perceived atmosphere in this experiment relatively to this neutral setting. A way to deal with this is to make use of a between groups design. If each participant has to judge only one light setting, then it is expected that their personal experiences are used as an anchor.

The calculated factors in this experiment are based on a larger set of data, including 85 unique participants. However, in order to guarantee stable factors, a larger number of participants and applications should be tested. A larger number of applications might give rise to new factors and a larger number of cases guarantee factor stability.

This study gives valuable insight in the effect of different lighting characteristics on atmosphere perception. However, lighting can differ on more characteristics than intensity, CCT and spatial distribution. It would be interesting to investigate the effects of decorative lighting on atmosphere perception. This means for example the effects of color, dynamics and spatial configuration of the light sources.

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Appendix 1

Translation of the atmosphere, from Dutch to English.

Dutch word	English word	Dutch word	English word
actief	active	koud	cool
afstandelijk	detached	levendig	lively
beangstigend	terrifying	luxueus	luxurious
bedompt	musty	mysterieus	mysterious
bedreigend	threatening	ongedwongen	uninhibited
behaaglijk	cozy	ongemakkelijk	uncomfortable
beklemmend	oppressive	onrustig	restless
deprimerend	depressed	ontspannen	relaxed
enerverend	exciting	persoonlijk	personal
formeel	formal	romantisch	romantic
gastvrij	hospitable	ruimtelijk	spatial
geborgen	safe	rustgevend	tranquil
gemoedelijk	pleasant	saai	boring
gespannen	tense	sloom	lethargic
gezellig	pleasant	stimulerend	stimulating
inspirerend	inspiring	toegankelijk	accessible
intiem	intimate	vijandig	hostile
kalm	calm	vrolijk	cheerful
kil	chilly	warm	warm
knus	cozy	zakelijk	business

Appendix 2

The results of the conducted contrast analyses. A contrast analysis was conducted to test for the effects of intensity and the interaction effects between intensity and CCT on the items of each questionnaire for design 1. Only the significant effects are displayed.

Lighting appearance questionnaire

Brightness

Intensity	df	F	p	partial η^2
low vs. medium	1,29	204.62	< 0.001	0.88
medium vs. high	1,29	26.52	< 0.001	0.48

Intensity x CCT	df	F	p	partial η^2
low vs. high	1,29	9.40	0.005	0.25

Perceived uniformity

Intensity	df	F	p	partial η^2
low vs. medium	1,30	5.77	0.023	0.16

Preference questionnaire

Intensity	df	F	p	partial η^2
low vs. medium	1,30	35.28	< 0.001	0.54

Atmosphere questionnaire

Coziness

Intensity	df	F	p	partial η^2
medium vs. high	1,30	4.41	0.04	0.13

Liveliness

Intensity	df	F	p	partial η^2
low vs. medium	1,30	89.23	< 0.001	0.75
medium vs. high	1,30	24.49	< 0.001	0.45

Intensity x CCT	df	F	p	partial η^2
low vs. medium	1,30	7.80	0.009	0.21

Tenseness

Intensity	df	F	p	partial η^2
low vs. medium	1,30	30.41	< 0.001	0.50

Detachment

Intensity	df	F	p	partial η^2
low vs. medium	1,30	21.39	< 0.001	0.42

Intensity x CCT	df	F	p	partial η^2
low vs. medium	1,30	6.30	0.018	0.17

Application questionnaire

Study room

Intensity	df	F	p	partial η^2
low vs. medium	1,30	143.74	< 0.001	0.83

Office

Intensity	df	F	p	partial η^2
low vs. medium	1,30	126.99	< 0.001	0.81
medium vs. high	1,30	6.62	0.015	0.18

Intensity x CCT	df	F	p	partial η^2
low vs. medium	1,30	5.90	0.021	0.164

Shop

Intensity	df	F	p	partial η^2
low vs. medium	1,30	60.56	< 0.001	0.67
medium vs. high	1,30	8.73	0.006	0.23

Intensity x CCT	df	F	p	partial η^2
low vs. medium	1,30	4.04	0.05	0.12

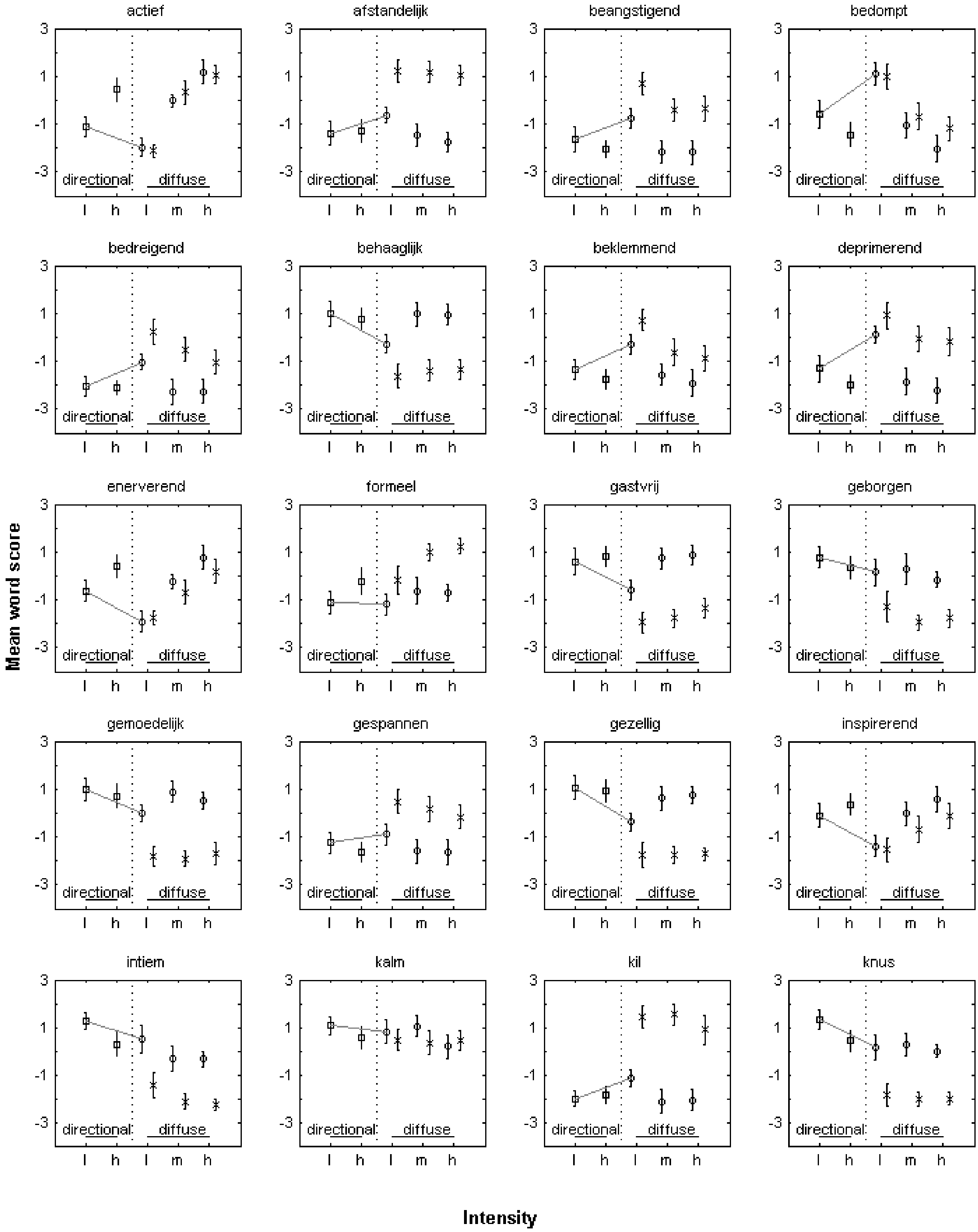
Bed room

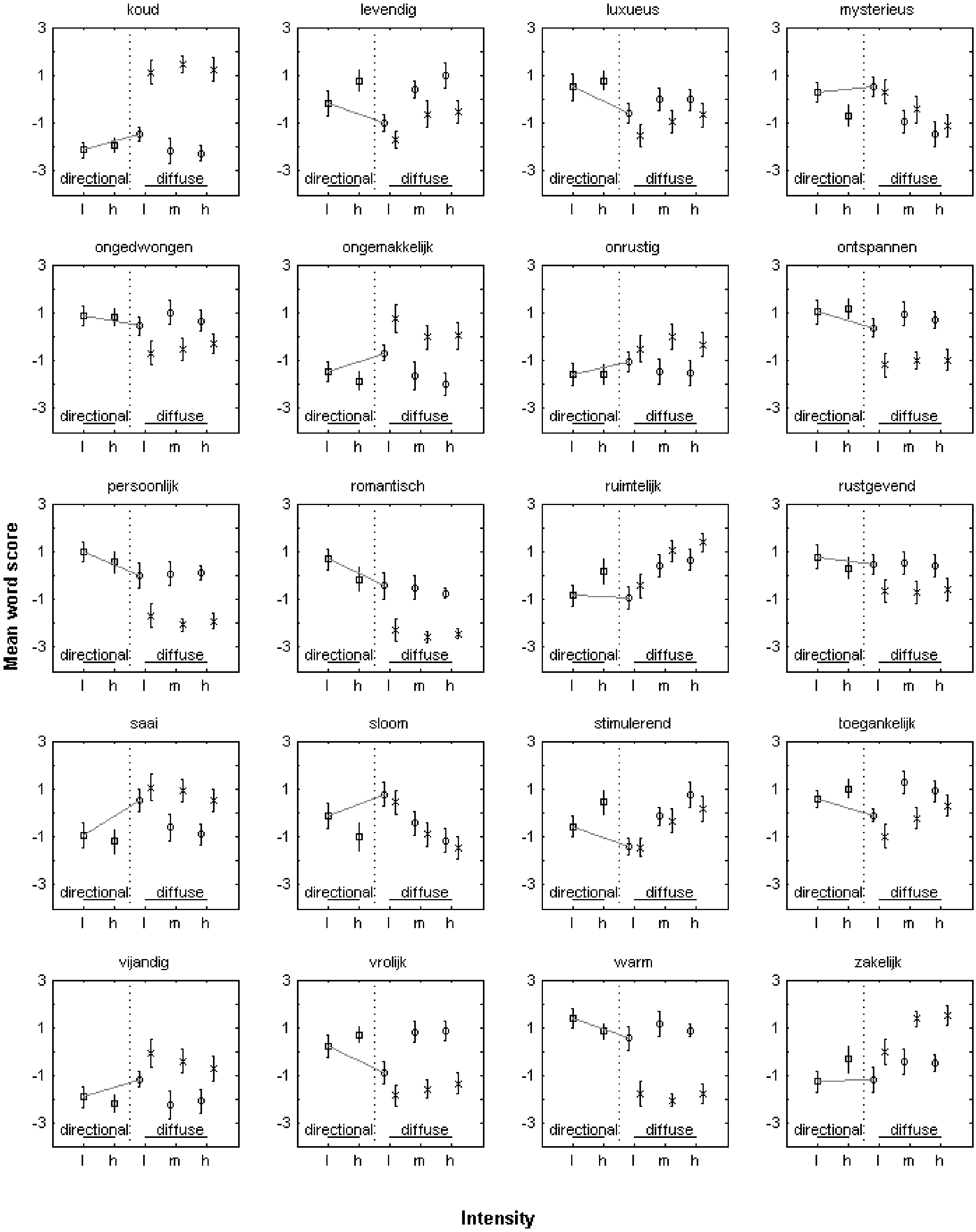
Intensity	df	F	p	partial η^2
low vs. medium	1,30	4.29	0.047	0.13

Intensity x CCT	df	F	p	partial η^2
low vs. medium	1,30	7.75	0.009	0.21

Appendix 3

The mean word scores, for each light setting, versus the intensity. The scores for design 1 (the diffuse light settings) are displayed in the right part of the figure, indicated with. In this part the warm settings are indicated with a ‘circle’, the cool settings with a ‘cross’. The scores for design 2 (the directional settings) are displayed in the left part of the figure. These settings are indicated with a ‘square’. The scores for design 3 are the two settings that are displayed as a ‘circle’ and a ‘square’ and connected with a grey colored line. The error bars indicate the 95% confidence intervals of the calculated means.




koud
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rustgevend
saai
sloom
stimulerend
toegankelijk
vijandig
vrolijk
warm
zakelijk
directional
diffuse
l h l m h
Mean word score
Intensity

Appendix 4

To test whether the results differ significant from the criterion, a binomial test was conducted. The number of participants that choose a particular association is assumed to be binomial distributed, with an expected value of np. With n=32 and p=0.5, np is calculated to be 16. Since np>5 and n(1-p)>5, the binomial distribution can be approached with a normal distribution with a confidence interval of:

$$np \pm 1.96 \cdot \sqrt{(np)(1-p)}$$

In this formula, 1.96 is the standardized score for a significance level 95%. The confidence interval is calculated to be 16±5.54.

Appendix 5

Woord atmosfeer vragenlijst

Geef voor elk woord uit de onderstaande lijst aan in welke mate dit woord van toepassing is op de atmosfeer van de ruimte, op een schaal van *absoluut niet van toepassing* tot *zeer goed van toepassing*.

	Absoluut niet van toepassing	Nauwelijks van toepassing	Niet zo van toepassing	**Neutraal**	Enigszins van toepassing	Goed van toepassing	**Zeer goed** van toepassing
Actief	0	0	0	0	0	0	0
Afstandelijk	0	0	0	0	0	0	0
Beangstigend	0	0	0	0	0	0	0
Bedompt	0	0	0	0	0	0	0
Bedreigend	0	0	0	0	0	0	0
Behaaglijk	0	0	0	0	0	0	0
Beklemmend	0	0	0	0	0	0	0
Deprimerend	0	0	0	0	0	0	0
Enerverend	0	0	0	0	0	0	0
Formeel	0	0	0	0	0	0	0
Gastvrij	0	0	0	0	0	0	0
Geborgen	0	0	0	0	0	0	0
Gemoedelijk	0	0	0	0	0	0	0
Gespannen	0	0	0	0	0	0	0
Gezellig	0	0	0	0	0	0	0
Inspirerend	0	0	0	0	0	0	0
Intiem	0	0	0	0	0	0	0
Kalm	0	0	0	0	0	0	0

	Absoluut niet van toepassing	Nauwelijks van toepassing	Niet zo van toepassing	**Neutraal**	Enigszins van toepassing	Goed van toepassing	**Zeer goed** van toepassing
Kil	0	0	0	0	0	0	0
Knus	0	0	0	0	0	0	0
Koud	0	0	0	0	0	0	0
Levendig	0	0	0	0	0	0	0
Luxueus	0	0	0	0	0	0	0
Mysterieus	0	0	0	0	0	0	0
Ongedwongen	0	0	0	0	0	0	0
Ongemakkelijk	0	0	0	0	0	0	0
Onrustig	0	0	0	0	0	0	0
Ontspannen	0	0	0	0	0	0	0
Persoonlijk	0	0	0	0	0	0	0
Romantisch	0	0	0	0	0	0	0
Ruimtelijk	0	0	0	0	0	0	0
Rustgevend	0	0	0	0	0	0	0
Saai	0	0	0	0	0	0	0
Sloom	0	0	0	0	0	0	0
Stimulerend	0	0	0	0	0	0	0
Toegankelijk	0	0	0	0	0	0	0
Vijandig	0	0	0	0	0	0	0
Vrolijk	0	0	0	0	0	0	0
Warm	0	0	0	0	0	0	0
Zakelijk	0	0	0	0	0	0	0

Vragen over het licht in de ruimte

Geef uw mening over het **licht** in deze ruimte door bij elk van de onderstaande woordparen een vakje in te vullen dat het meest van toepassing is op het licht.

Aantrekkelijk	0	0	0	0	0	0	0	Onaantrekkelijk
Mooi	0	0	0	0	0	0	0	Lelijk
Prettig	0	0	0	0	0	0	0	Onprettig

Vul bij elk van de onderstaande woordparen het vakje in dat het meest van toepassing is op het **licht** in deze ruimte.

Helder	0	0	0	0	0	0	0	Donker
Uniform	0	0	0	0	0	0	0	Niet-Uniform
Warm	0	0	0	0	0	0	0	Koud

Geef voor elke omgeving uit de onderstaande lijst aan in welke mate deze omgeving geschikt is voor **dit lichtscenario**, op een schaal van *absoluut niet geschikt* tot *zeer goed geschikt*.

	Absoluut niet geschikt	Nauwelijks geschikt	Niet zo geschikt	**Neutraal**	Enigszins geschikt	Goed geschikt	**Zeer goed** geschikt
Studeerkamer	0	0	0	0	0	0	0
Slaapkamer	0	0	0	0	0	0	0
Woonkamer	0	0	0	0	0	0	0
Kantoor	0	0	0	0	0	0	0
Hotelkamer	0	0	0	0	0	0	0
Winkel	0	0	0	0	0	0	0

Geef hieronder aan welke ruimtes, volgens u, nog meer geschikt zijn.

- -

- -

Waarmee associeert u het **licht** in deze ruimte?

Met welk dagdeel associeert u het **licht** in deze ruimte?

	Wel	Niet
Ochtend	0	0
Middag	0	0
Avond	0	0
Nacht	0	0

Hartelijk dank voor uw medewerking!