MASTER

Exploration of asthenopia due to the ratio of direct/indirect light in office environments

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Award date: 2014

Link to publication
EXPLORATION OF ASTHENOPIA DUE TO THE RATIO OF DIRECT/INDIRECT LIGHT IN OFFICE ENVIRONMENTS.

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Identity number: 0804651

in partial fulfilment of the requirements for the degree of

Master of Science

in Human Technology Interaction

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ABSTRACT

Light is responsible for making environments visible to the eyes; it can modify the appearance and appraisal of the room and even increase the vitality of people. Nonetheless, high levels of light are prone to cause glare, creating visual discomfort or even visual disability. Previous research showed that different ratios of direct and indirect light (reflected from the ceiling) create a different perception of light comfort in the room, creating the greatest comfort perceived when combining direct and indirect light. The current study aims to explore further effects of light ratio of direct and indirect light on the levels of asthenopia, which represents the level of exhaustion of the eye.

The experiment in this thesis used a simulated office environment with controlled light settings that varied on their ratio of direct and indirect light while keeping a constant illuminance of 700 lux on the working area. Repeated experimental sessions presented different light settings to participants during long periods of time; using a single light setting for every session. The experiment explored the light appraisal and the level of asthenopia (i.e., both, visual fatigue and visual discomfort) on people; the former via subjective questionnaires and the latter via the accommodation facility, visual acuity and the headache and eye strain scale. As suggested by the main hypothesis, results showed that the light ratio of direct and indirect light has indeed an effect on asthenopia, particularly on the measures of accommodation facility and headache and eye strain scale. As predicted by the positive affect theory, the light settings formed by a combination of direct and indirect light were evaluated with the greatest light appraisal and created the lowest levels of visual fatigue and visual discomfort on participants. Furthermore, it appeared that specific zones of the room (i.e., room in general, ceiling or luminaires) were perceived with different brightness and light comfort, depending on the ratio of direct and indirect light. Based on these findings, we encourage the combination of direct and indirect light in office environments in order to minimize the effect of asthenopia on people.
1. INTRODUCTION

Human’s general performance is largely dependent on our capability to see. Historically, humans performed most of their activities during daytime and slept during nighttime; thus, our visual system developed itself to perform best in well-illuminated environments (Mather, 2009). When designed properly, artificial lighting may also enhance our performance (Shlaer, 1937; Van Nes & Bouman, 1967; Rea and Oullette, 1991), may affect us psychologically by changing our mood (Veitch, Newsham, Boyce and Jones, 2008), and may even affect our sleep cycle (Czeisler & Wright, 1999) and make us more alert (Smolders, de Kort, & Cluitmans, 2012). Hence, although often taken for granted, light has a bigger impact on our well-being (Veitch et al., 2008) than just allowing us to see what is in front of us. Some of these examples explain the great interest of literature on light.

Many of the examples mentioned above benefit from high light intensities. However, increasing light intensity also has its limits. Light with a large difference between the source and the background may trigger negative effects, such as glare (Saunders, 1969). A simple example of glare can be observed on highways. In a dark environment, lights of upcoming vehicles may produce huge annoyance to drivers; in the worst case, temporally blind the driver. Depending on the extent of the effect, glare is mainly classified as disability glare or discomfort glare; the former represents situations where a person is temporally blinded, whereas the latter mainly causes uncomfortable feelings (Vos, 1999; Vos, 2003).

Fischer (1991) has observed that glare has been studied for more than 50 years. The resulting knowledge is of great interest to light designers that aim at creating light environments that increase the capability of their occupants without having the drawback of glare. Several solutions to this problem have been proposed in the past (Shemitz & Stahlheber, 1980; Gordin, 1989; Fischer, 1991), e.g. the use of parabolic luminaires, or diffusing materials (details of these developments are described further in section 1.3 of this thesis). Some of these solutions, however, may become superfluous or impractical, because of the newly upcoming light technology, namely LED (Light Emitting Diodes).

LED lighting has many benefits over the more traditional lighting technologies, such as low energy costs, large range of colors that can be rendered, smaller emitting area, and so, more design freedom, longer life-time, more ecologically friendly, and fast switching characteristics (Schubert & Kim, 2005). Because of these advantages LED lighting is on its way to replace the more traditional lighting technologies. However, LED lighting also has disadvantages. One of these disadvantages is that LED lighting systems create high light intensities from a small emitting area, which makes them prone to glare (Kasahara et al., 2006).

The malleability and low price of LEDs allow light designers to approach the issue of glare at a system level, addressing the light distribution in the room. Literature has started to explore light systems that, besides emitting light towards the floor, also emit light towards the ceiling (Veitch et al., 2008; Boyce, Veitch, Newsham, Jones, Heerwagen, Myer, & Hunter, 2006; Eklund, Boyce, & Simpson, 2000; Hedge, SIMS JR & Becker, 1995). By simultaneously illuminating the ceiling and room in general, the contrast between the light source and the background illuminance is minimized. This approach has been proven to be clearly noticeable to people, even for small changes (Houser et al., 2002). Furthermore, this approach creates better light comfort (Geerdinck, 2002; Boyce et al., 2006) and was shown to be more pleasant, likeable and satisfying for people (Houser et al., 2002). These so-called back-illuminated light systems also resulted in faster learning curves in typing tasks (Boyce et al., 2006). These first findings suggest that the light distribution in a room clearly impacts people’s perception of comfort. To what extent improvements in visual comfort also contribute to a reduction in visual fatigue is not yet well-understood and, therefore, is the aim of the current study. Given the nature of discomfort glare that tends to build up over time, we hypothesize that a clear improvement in visual comfort, as a consequence of the light distribution in the room, also reduces visual fatigue for people performing tasks for a moderate period of time. To address this hypothesis, we will focus our study on lighting designed for office applications. In addition, we will extend findings of Geerdinck (2012) on light comfort for different distributions of light to ceiling and room to also include visual fatigue measurements.
Before discussing the actual experimental design and set-up, we will first summarize the relevant background information for the study. This background information includes a description of the distinction between visual comfort and visual fatigue, as used in the rest of the thesis, and a deeper exploration of the visual and non-visual effects of light on people. Based on that information, this chapter will end by presenting the hypothesis and related expectations.

1.1 ASTHENOPIA: VISUAL DISCOMFORT AND VISUAL FATIGUE

It is known from nature that the use of a system leads to depletion of its resources and, in more extreme cases, to exhaustion. The visual system also follows this trend and experiences a drain of resources over time. The long-term effect of this depreciation is noticeable when comparing the viewing capabilities of elderly people to those of younger people (Mather, 2009). Furthermore, wearing out of the visual system can also be observed on a daily basis. For example, the reader may have experienced some feelings of malaise after being behind a computer screen for most of the day. Typical symptoms of an exhausted visual system are double vision, perception of flicker, lack of focus, and black vision, and these negative effects may even result in neck pain, headache or muscle pain. All these symptoms together are part of a phenomenon called asthenopia (Sheedy & Bailey, 1995; Sheedy, Hayes, & Engle, 2003).

Asthenopia actually means “the eye without strength” (Lambooij et al., 2009), and its effects have been vastly explored in literature. The phenomenon is more commonly described by the name of visual fatigue or visual discomfort. While these two terms refer to the same phenomenon, there is an intrinsic difference between them; visual fatigue refers to the objective measurement of asthenopia, while visual discomfort refers to its subjective evaluation (Lambooij et al., 2009). A similar relationship can be observed with the measurement of illuminance and brightness, being brightness the subjective counterpart of the physical measurement of illuminance. The distinction between visual fatigue and visual discomfort is greatly overpassed and ignored in literature, making the use of both terms interchangeable (Lambooij et al., 2009). For this study, however, the distinction between both terms will be made constantly throughout the entire thesis.

Visual discomfort is often utilized to evaluate lighting systems, basically due to its ease of extraction. Literature reports several questionnaires to measure people’s opinion regarding the degree of visual discomfort. For instance a very popular scale is the multi-criterion scale of Hopkinson (Hopkinson, 1950) illustrated in figure 1. This method evaluates light discomfort on a scale going from “imperceptible” to “intolerable”. Improvements on this scale have been presented over time. For instance, Geerdinck (2012) created a variation of the scale that allowed a clearer distinction between the acceptance and the comfort of the brightness of the luminaires. As a result, the scale is suggested to be split in two different scales to measure each value independently. Furthermore, Houser and colleagues (2002) created a different questionnaire of visual discomfort, which could obtain perception of brightness for different parts of the room. This questionnaire consisted of several items, scored on a 7-points scale, used to extract the score on the perception of eye-discomfort, glare and quality. Another alternative is the headache and eye strain scale (HES), which semantically evaluates different symptoms of asthenopia independently (Gobba, Broglia, Sarti, Luberto & Cavalleri, 1988; Saito, Sotoyama, Saito & Taptagaporn, 1994); again, items on the subjective perception of double vision, headache, dry eyes, etc., are scored on 7-point scales.

![Figure 1: Multi-criterion scale (Hopkinson, 1950) used to connect the physical aspect of a stimulus (i.e., illuminance) with the subjective aspect (i.e., brightness).](image-url)
Similar effort has been devoted to develop measurement tools for the objective evaluation of asthenopia and to compare their outcomes with their subjective counterpart (i.e., visual discomfort). A well-documented comparison of these measurements is provided by Chi and Lin (1998). In their study, the authors compared accommodation power, visual acuity, critical flicker frequency (CFF), pupil diameter and eye movement speed against the subjective rating of visual fatigue, and evaluated the sensitivity of these objective measures to determine visual fatigue. All techniques were able to objectively measure visual fatigue for the three different visual tasks used in the experiment (i.e., reading, tracking and monitoring). Notice that some of these techniques require optometric equipment to perform the measurements.

In most cases the effects of asthenopia have been explored in both an objective and subjective manner simultaneously. For instance, 3D display systems that were perceived as more comfortable also showed a lower level of objective visual fatigue (Lambooij et al., 2010). Not only research on 3D display systems provided a clear relation between visual comfort and visual fatigue, also studies in related fields have proven such relationship: for example, effects on visual discomfort and visual fatigue have been observed while reading text on differently colored backgrounds (Matthews, 1987), and while reading text with different pixel representations (Sheedy and McCarthy, 1994).

### 1.2 BENEFITS OF BRIGHT LIGHT ON PEOPLE

It is well-known that people perceive electromagnetic waves with frequencies between 400 and 700 nm as light (Mather, 2009). Light is absorbed by the cells at the retina in the eyes, and the resulting signals are transmitted to different parts of the brain via two different pathways (Boyce, 2013; Veitch et al., 2008): the image forming visual path representing the pathway that creates an image-like representation of the environment; while the non-image forming pathway is responsible for the stabilization of our awake-sleep cycle (Czeisler & Wright, 1999). A commonly used visual representation of both pathways is given in figure 2. Both pathways have a completely different impact on people's life. While the image forming pathway has been explored in literature already for a long time, the non-image forming path has been discovered more recently, and therefore currently attracts lot of interest of scientists. In this chapter, both pathways and their effects on people are described in more detail.

![Figure 2: Graphical representation of the two pathways of the effect of light on people. The image forming pathway creates an image-like representation which affects the performance and the appraisal of people. The non-image forming path does not result in an image-like representation of the environment to create an effect on people; its effects are both immediate and cyclical. (Veitch et al., 2008).](image)
1.2.1 IMAGE FORMING PATH

The image forming pathway starts when light falls on the photoreceptors at the retina. The two most commonly known receptors are the so-called rods and cones; the former are very sensitive at low light levels, while the latter become sensitive at higher light levels (Wald, 1945) and deliver important information from which color perception can be extracted (Mather, 2009). Subsequently, these receptors send signals to the section of the brain in charge of visual perception, the so-called visual cortex. The relation between the photoreceptors and the visual cortex shows great similarity in its organization; for instance, each cell in the visual cortex is in charge of receiving signals from a limited area on the retina (Boyce, 2003). In addition, the visual cortex is responsible of more complex functions, performed in the higher areas of the visual cortex, like analyzing color, motion and even human faces observed from particular angles (Desimone, 1991).

The most obvious way in which light affects people is by improving their performance. In a very dark environment, visual tasks like reading or detecting small targets are difficult to achieve, while brighter environments facilitate the performance of such tasks. Moreover, light may also affect the way people interpret and experience an environment. As such, the visual pathway contributes to the visual performance and the visual experience; both aspects are described in more detail below.

1.2.1.1 VISUAL PERFORMANCE

Visual performance describes the capabilities of people to perform tasks that require a visual component. Or more specifically, visual performance “refers to the process of extracting information relevant to the performance of the task using the sense of sight” (Boyce, 2011). Literature has delimited four parameters that contribute to visual performance: i.e., age of the viewer, task size, contrast between the task and the background and general task illuminance (Veitch, 2006; Rea and Ouellette, 1991).

Rea and Oullette (1991) performed a study, in which participants were presented with a visual performance test under different conditions that varied along the latter three dimensions. They found that visual performance increased in a logarithmic manner when increasing either the task size, contrast or task illuminance. After reaching a certain level, called the saturation level, further increase on any of the parameters resulted in a minor increase of the visual performance. This level was considered to indicate the minimum light requirements in order to perform visual tasks. To easily represent visual performance, Rea and Oullette (1991) created the so-called relative visual performance (RVP) model. It is a three-dimensional shape that represents for a task of a given size visual performance scores as a function of contrast and illuminance of the task, an example of which is given in Figure 3. By making these graphs for different task sizes, visual performance could be characterized in all three dimensions. For light designers, these findings imply that beyond a threshold, there is a broad range of light levels that provide sufficient light for office environments.
1.2.1.2 VISUAL EXPERIENCE

Apart from affecting the objective visual performance, light can also affect the general perception of the environment by affecting people's mood and/or motivation (Boyce, 2011). Such perception is sometimes referred as ‘the message’ that light creates in an environment (Boyce, 2011). This message is known to be different for different people, and to depend on situation and/or period of time. A clear example can be deduced from everyday life; office workers prefer to have well-distributed bright light when performing their tasks, while at the same time, they prefer a dimmer and variable light when visiting the local bar. Under both lighting conditions, people are satisfied while the parameters in each condition differ largely.

A model to entirely represent the preferences of people on light levels would be very complex. The preferences show a great variation depending on factors like current location (inside a building), usage of blinds on the window, time of the day, and season of the year (Begemann, 1996). For instance Begemann (1996) observed that even on the same day, the preferred light level increased in the morning, remained stable during the afternoon and decreased by the end of the day. The study also showed that months with greater natural light, prompted higher levels of artificial light; on the other hand, months with lower natural light, prompted lower levels of artificial light. Further, the perception of the light has been observed to be different per gender. Knez (1995) observed that women perceived the light in an office environment as significantly glarier, more intense, less dim and less soft than men. These differences also had an interaction with the color temperature; a ‘warm’ light induced a more positive mood on women than on men. The results show that there is no general trend towards a light setting that produces the most pleasant visual experience in all situations.

Despite the variations, researchers continue to explore the effects that light appraisal has on people; in particular on the effect that light appraisal can produce on working environments. Based on the positive affect theory that predicts that working conditions influence well-being and work behavior of people (Isen & Baron, 1991), Veitch and colleagues (2011) have developed and proved a model that predicts the work satisfaction and the work engagement of people based on the light appraisal. A general overview of the model can be observed in figure 4. In their research, Veitch and colleagues (2011) observed that “people who appraise their lighting as good will also appraise the room as more attractive, be in a more pleasant mood, be more satisfied with the work environment and more engaged in their work” (Veitch et al., 2011). These findings prove that light designers should not only take care that the lighting system is able
to allow people to observe the environment, but it should also prompt people to have a positive interpretation of the environment.

**Figure 4:** Hypothesized Model of the effect of light on work satisfaction and work engagement. Continues lines represent the visual experience pathway and dotted lines represent the visual performance pathway. Copied from Veitch et al., 2011.

### 1.2.2 NON-VISUAL FORMING PATH

The non-image forming pathway refers to light that reaches our brain without a visual representation of the environment (Veitch et al., 2008). Since recently discovered, this pathway still gets lots of attention in current literature. The non-image forming pathway creates two types of effects on people depending on the duration and rhythm of the lighting: the circadian effect and the acute effect. Both effects are briefly described below.

#### 1.2.2.1 CIRCADIAN SYSTEM

Recent literature has showed that the retina of our eyes contains an additional type of light receptor (besides the rods and cones); the so-called Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs) (Berson et al., 2002). When light falls onto the ipRGCs, electric signals are sent to the thalamus and hypothalamus, which are parts of the brain in charge of the awake and sleep cycle (Berson et al., 2002). This cycle is called the circadian rhythm or also the biological clock, due to its duration of approximately 24 hours, as the duration of an entire day. During a circadian cycle, several hormones are naturally released by the body in order to achieve activation or relaxation along the day (Cajochen, 2007).

Cajochen (2007) observed that a lack of synchrony between our internal biological clock and our daily required activities, as a consequence of a lack of sufficient light at the right moments of time, can lead to cardiovascular diseases, sleep disorders, and depression. Some of these negative effects are largely observed in countries located close to the poles, where the winter drastically limits the amount of natural light. These conditions are generally referred to as Seasonal Affective Disorder (SAD) (Rosenthal et al., 1984), also called ‘winter depression’ or ‘winter blues’.

Artificial light offers a plausible solution for environments that lack sufficient natural light. Bright sources of light, in the form of bright light therapy or dawn simulation therapy, have the ability to shift the biological clock back in synchrony with the daily cycle of activities and counteract the negative effects of SAD (Golden et al., 2005). It has been demonstrated that the effect of bright light therapy creates a positive response even on people with non-seasonal depressions (Golden et al., 2005).
1.2.2 ACUTE SYSTEM

Effects of light through the non-image forming pathway have also been observed on single exposure to different amounts of light. Campbell and Dawson (1990) recruited participants to work on a night shift while measuring their performance and alertness. Participants that were in the brighter light condition (i.e., 1000 lux) showed higher levels of alertness and better performance compared to participants in the lower light conditions (i.e., 10 or 100 lux). This effect was observed and retained during the entire progress of the night.

Similar effects have also been observed during daytime. Smolders and colleagues (2012) observed that exposure to higher light levels (i.e., 1000 lux vs 200 lux) induce higher alertness during office hours. The effects were measured both subjectively (i.e., by means of self-reporting scoring scales) and objectively (i.e., via auditory PVT, heart rate variability), both in the morning (i.e., 09:00) and around noon (i.e., at 11:00). The results showed that higher levels of light increased subjective alertness, subjective vitality and heart rate variability of the participants at any time of the day, while the PVT scores showed such difference only in the morning session.

1.2.3 SUMMARY OF BENEFITS OF BRIGHT LIGHT

In summary, high intensities of light produce great benefits to people in terms of performance, mood, alertness and general well-being. It is evident that dark environments may greatly reduce the performance of people, thus minimal standards for required light intensities for different activities have been established. As a consequence, different standards of light have been created where minimum light levels should be met in order to have proper lighting (CIE, 2011). Generally, a specified minimal horizontal illuminance level is required by law in European office environments to ensure that light levels are above the visual performance threshold. In practice, often higher light illuminance levels are used because of their beneficial effects on general comfort, vitality and alertness. At the same time, these higher levels of light intensity may help to reduce depressive seasonal and non-seasonal effects (i.e., as described in the previous sections). Nonetheless, bright light does not only have benefits; several parameters need to be taken into account when designing a bright light system, since too bright light may also harm people. The next section describes different problems that light designers encounter when trying to design optimal light.

1.3 NEGATIVE EFFECTS OF BRIGHT LIGHT

Office environments are of great importance to people, as many people spend a large amount of their daytime in these indoor spaces. While the use of windows for offices is greatly adopted, office workers still have to rely on artificial light sources as the constant source of light to create sufficient illuminance in many occasions. Increasing light levels generally increases the capability of people to observe the world and perform their activities; nonetheless when the light intensity reaches very high levels, it may create annoyance, discomfort and disability to people. For instance, the brightest source of natural light, i.e., the sun, may create huge discomfort, may impair visibility and may even permanently damage the visual system. Such extreme effects are hardly ever achieved in office environments; nonetheless, higher luminance levels from the luminaires may produce discomfort in everyday office conditions. The general goal of light designers shall aim to create lighting systems that enhance the capabilities of people without hindering them by creating discomfort.

1.3.1 CAUSES OF DISCOMFORT AND FATIGUE

Asthenopia, observed in the form of visual fatigue or visual discomfort, may be triggered by a large number of causes. For instance, Sheedy and others (2003) classified from literature that asthenopia can be created by glare from lighting, anomalies in binocular vision, accommodative dysfunctions, uncorrected refractive errors, compromised quality of the viewed image, less than optimal gaze angles, flickering stimuli and dry eyes. While these causes can be attributed to many different physical phenomena, only phenomena related to high light intensity levels are interesting for the
remainder of this study. As such, in the rest of this chapter we focus on asthenopia related to light uniformity, glare and veiling reflections.

### 1.3.1.1 UNIFORMITY

A sufficiently high illuminance in an office is commonly generated by a combination of light sources. When adding more than one light source to a room, light designers need to be careful that the variation in illumination over different zones of the room remains relatively small. Saunders (1969) studied the variation in light uniformity expressed as the ratio between the lower and higher illuminance levels in a room. In his study, participants observed two light levels falling on adjacent desks and reported their perception of the non-uniformity. His results determined that a ratio of 0.7 provides the ‘minimum illuminance uniformity’; larger variations in light uniformity were perceived as unreasonable.

### 1.3.1.2 GLARE

An extreme situation of light non-uniformity may create the feeling of glare. Glare occurs when large sources of light create some sort of veil over the retinal image, or on parts relatively close to it, making the contrast difference of the observed image much smaller (Boyce, 2003). As such, this veil over the image may reduce the visual capabilities of the eye. Literature has established eight different types of glare, all varying in their intensity and consequences. According to Vos (1999) the types of glare are: flash blindness, paralyzing glare, retinal damage (as when looking directly into the sun), distracting glare, saturation glare, adaptation glare, disability glare and discomfort glare. The last two types of glare are most important for office environments.

Disability glare, as the name suggests, refers to a situation where a relatively bright light source in an otherwise dark background hinders the performance of the visual system. A clear example occurs in the situation where upcoming traffic on a road at night reduces the visibility of a driver. Although glare most frequently occurs for small light sources that emit light at very high intensity, light sources with a large emitting area may also create disability glare. For instance, before entering a dark tunnel, the bright light of the sky prevents the driver to see details inside the tunnel. Disability glare affects the visual performance of humans; as such, it can be objectively measured with performance related methods (i.e., visual acuity).

Discomfort glare, on the other hand, is more difficult to assess. Even though no immediate performance effects have been observed, discomfort glare may add up over time to negatively affect people (Boyce, 2003). A reason why effects of discomfort glare are harder to measure may be a lack of sensitivity in the measuring methods. Basically discomfort glare is usually measured subjectively, by means of scoring scales. Despite the limited understanding of discomfort glare, researchers developed guidelines that can predict the amount of perceived glare sensation. The estimation of glare created by a single source of light can generally be described by the following formula (Fischer, 1991):

$$\text{Glare sensation} = \frac{L_s w_s^b}{L_b P^d}$$

where $L_s$ is the luminance of the source, $L_b$ the luminance of the background, $w_s$ the solid angle subtended at the eye by the glare source (in steradians) and $P$ the deviation of the position of the glare source from the line of sight. So, in order to avoid glare, three general principles must be pursued: avoiding large light sources, keeping light sources far from the line of sight and keeping a small luminance difference between the light source and the background.

To estimate glare perception for combinations of light sources, even including the position of furniture and windows, several models have been created. Clear (2013) made a nice overview of the comparison of different models that estimate discomfort glare to the data of Luckiesh and Guth (1949), on which the development of most models is based. The results showed that, in general, there is big variation between the models, with some having a better performance than others, as illustrated in figure 5. Especially the Visual Comfort Probability (VCP) model and the Unified Glare Rating
(UGR) model were able to predict perceived glare for the data of Luckiesh and Guth reasonably well. This finding supports the use of UGR in the current European standard for estimated glare (CIE, 2011).

![Figure 5: Estimation Border between Comfort and Discomfort (BCD) luminance for a certain background luminance measured by a large variety of glare models compared with the original data of Luckiesh and Guth. Copied from Clear (2013)](image)

Figure 5 also shows the general relationship between background luminance and the border between comfort and discomfort (BCD) glare (i.e., the threshold luminance for which perceived glare changes from comfortable to uncomfortable). Clearly for a higher background luminance, also the luminance of the light source may be higher before the BCD is reached. This relation seems logical, as the perception of glare is trigged by large differences in light intensity within the field of view. The latter also implies that for the same luminance of the light source, a higher background luminance reduces the luminance difference in the field of view, and thus reduces the perception of glare.

### 1.3.1.3 VEILING REFLECTIONS

A simple activity as reading a magazine in a park on a sunny day is a nice illustration of the discomfort that veiling reflections may induce. Just like glare, veiling reflections greatly reduce the contrast in the retinal image. Specifically, veiling reflections largely increase the luminance surrounding the viewing objective; this in turn reduces the luminance contrast between the objective and the surrounding and, finally, largely hinders the task of viewing the objective image. Veiling reflections typically occur under specific geometrical conditions between observer, reflecting surface and light source, and require some specularity of the surface, i.e., fully mat surfaces do not create veiling reflections (Boyce, 2003). Making changes in the geometry between viewer, surface and light source, even small changes, immediately affects the magnitude of the veiling reflections. This magnitude usually is characterized in terms of the contrast rendering factor (CRF), expressing the ratio of the luminance constant of the target under a certain light against the luminance constant of the same target under a completely diffuse light; note that diffuse light sources produce the smallest veiling reflections.

### 1.4 (CURRENT) SOLUTIONS TO NEGATIVE EFFECTS OF BRIGHT LIGHT

Creating a glare free environment is not straightforward, since it requires considering parameters related to the light sources involved, windows, material reflections, the position of furniture, and so on. Yet, simple solutions to avoid glare are already used in several environments. A basic example used in most households is a desk lamp. If observed with curiosity, the mechanism behind a desk lamp consists of a light source surrounded by a darker, non-transparent material. While common, this technique prevents the user to look straight into the light source, and thus prevents glare. A similar principle, though implemented with different techniques, is commonly used in office environments. Parablic
louver luminaires use blades/shields along the length of the fluorescent tube(s) to reduce direct visibility into the light source. Especially, the part of the light tube farthest away from the viewer, and thus closest to the line of sight, is no longer visible to the user. This technique does not reduce the amount of light coming from right above the user; light coming from this direction is far from the line of sight, and thus, produces very little glare. A different solution is the use of diffusing lenses to cover small, sharply edged light sources. This technique diffuses the light coming from the light source and spreads it over a bigger area, thus reducing the amount of perceived glare.

A different approach, more interesting for our current study, is the use of back-illuminated luminaires. These types of luminaires utilize a new technique that emits light upwards (i.e., creating indirect light via the ceiling) as well as downwards (i.e., creating direct light towards the user). Using this technique, where the background of the luminaire gets illuminated, reduces the luminance difference between the source and the background, and thus reduces the perception of glare. Some beneficial effects of this technique have already been proven by Geerdinck (2012). In this study, several light settings were observed and rated by the participants. Each light setting consisted of a different percentage of light that was emitted downwards and upwards, while keeping the horizontal illuminance on the desk of the participants constant. The author measured light acceptability and light comfort for each of these light settings, via subjective scoring scales. The results, summarized in Figure 6, showed that light distributions that included a contribution of indirect light (i.e., emitted upwards) were evaluated as more comfortable up to a level of about 70%; at higher percentage of indirect light, the perceived comfort decreased.

![Figure 6: Frequency graph of binomial scores of acceptability (Y/N), comfort (Y/N) and Hopkinson (below or above BCD) scale. Copied from Geerdinck (2012)](image)

The findings of Geerdinck (2012) confirmed earlier findings by Houser and colleagues (2002). In their study participants evaluated multiple aspects of light, among which comfort, for eleven light settings formed by different distributions of direct and indirect light. The authors found that participants were able to distinguish small variations in light distribution among all the light settings. Light distributions consisting of both upward and downward light were rated as more comfortable, though the differences were not significant. Nonetheless, participants rated light distributions formed by only indirect light, or close to it, as significantly more unpleasant, more dislikeable and more unsatisfying.

An extended study performed by Boyce and colleagues (2006) showed that light systems formed by upward and downward light not only improved light appreciation, but also performance. In their study, participants were presented with two light conditions: only direct light (i.e., called the base case) and a combination of direct and indirect light (i.e., called the best practice). Participants rated the light significantly less uncomfortable, better distributed, with less reflections that hindered their work, and as less excessively bright in the best practice scenario compared to the base case scenario. Furthermore, the participants had a faster learning curve in a typing task and in general typing was better for the best practice scenario compared to the base case scenario. It is worth to notice that this study measured the
effect of cognitive performance, visual performance and motor performance together, as can be observed from the nature of their measurements.

The last three studies point to an intriguing trend of beneficial effects of light systems that use both direct and indirect light. These studies, however, mainly focus on subjective assessment of the lighting conditions using scoring scales; how the combination of direct and indirect light affects objective measures is not yet fully explored. Hence, there still is a lack of knowledge on how back-illuminated luminaires affect performance on the short term and asthenopia on the longer term.

1.5 RATIONALE

It is of great interest to further explore techniques that create bright illuminated environments while taking care of the negative effects of bright light. Newly adopted technologies, such as LED, become commonly available and offer great potential in design freedom. But, to take advantage of all the capabilities of LED, it is necessary to overcome some of the disadvantages, such as perceived glare and/or uncomfortable lighting.

Recent literature has started the exploration of techniques that may prevent the negative effects of LED light systems. Using the malleability and design freedom in LED-based luminaires, adding upwards emitted light to the more common downwards emitted light may help to reduce glare. Several studies have explored this technique and indeed observed positive effects on the subjective scale of asthenopia, i.e., on visual comfort. In order to have a deeper understanding of the benefits of the combination of upwards and downwards light, the current findings on subjectively perceived visual comfort needs to be extended with objective measures related to visual fatigue. Hence, the current study shall investigate the impact of the combination of upward and downward light with objective measures that characterize asthenopia. The study will make a systematic exploration of light designs based on different ratios of upward and downward light aiming at determining the optimal ratio of upward and downward light for office environments in terms of visual fatigue.

1.5.1 RESEARCH QUESTION

As a whole, the main research question of this thesis is:

Does the ratio between direct and indirect light has an effect on asthenopia in office environments?

To have a deeper understanding of the possible beneficial effects of adding indirect light to the current direct light systems, several sub questions are also explored:

1- Does the brightness, comfort and acceptability of light (i.e., light appraisal) are perceived to be different for different ratios of direct and indirect light?
   - It is expected that the perception of brightness, comfort and acceptability of light vary according to the ratio of direct and indirect light, as has been observed in previous literature (Geerdink, 2012; Houser, 2002). Appraisal of light is expected to increase as the light settings further include indirect light; having a maximum level before the light setting is formed only by indirect light.

2- Does the development of visual fatigue and visual discomfort differ for different ratios of direct and indirect light?
   - It is expected that visual fatigue and visual discomfort are leaded by the already known effect of visual appraisal, implying that visual fatigue and visual discomfort shall vary in synchrony with the perceived visual appraisal. This relation is expected to have a negative direction, such that visual discomfort increases for decreased visual appraisal

3- Is there a correlation between the scores of visual comfort and visual fatigue for the different ratios of direct and indirect light?
As described previously, the measures of visual fatigue and visual discomfort represent the objective and subjective counterparts of the same phenomenon, asthenopia. Thus, the scores of visual fatigue and visual discomfort are expected to be very similar.
# 2. Method

The research questions of this study were addressed with an empirical study in which participants were requested to perform visual tasks under different light conditions. The light conditions varied in their contribution of direct versus indirect light, while keeping the illuminance level on the working area constant. Measures of visual appraisal and asthenopia were presented to the participants at different times during the experiment. A more detailed description of the methodology of this empirical study is given in the different sections of this chapter.

## 2.1. Design

The experiment followed a Balanced Incomplete Block Design (BIBD), meaning that some conditions were measured within subjects, but that not all conditions were seen by all subjects. The BIBD divided participants into subsets, called blocks. Each block of people attended the experiment four times; each time in a different test condition. By presenting a different combination of four conditions to each block (i.e., represented by each participant), the score of the fifth condition could be estimated from the interaction of the missing condition with other blocks. By using this design, the experiment received the statistical advantages of a repeated-measures design without requiring each participant to attend all the conditions. At the end, this design allowed the experiment to have sufficient power ($\alpha = 0.76$) while keeping the cost of the experiment low.

The experiment used a single independent variable named light distribution, represented by the ratio of direct and indirect light. The light distribution had 5 levels (hereafter referred to as light settings) evenly distributed between, on the one hand, using only direct (downward) lighting, and, on the other hand, using only indirect (upward) lighting via the ceiling.

The effect of the independent variable was measured with two dependent variables, namely light appraisal and level of asthenopia. Light appraisal refers to the perception of brightness, comfort and acceptability of the lighting for an office environment. This measurement was presented once at the beginning of every session. The measurement of asthenopia represented the negative effects that light could induce on the visual system. The score of asthenopia was formed by the difference of individual tests at the beginning and the end of each session.

In order to induce asthenopia, participants were required to engage in visual fatigue induction tasks that were presented between the two measurements of asthenopia. The visual fatigue induction tasks required the visual attention of the participants without mentally depleting them. These tasks had the same difficulty level for all the conditions.

## 2.2 Participants

Participants were recruited via the recruiting agency CG Selections. In total 39 participants (51.3% women) took part in the experiment; from 40 recruited participants (i.e., one participant didn’t show up for any of the sessions). The participants were young adults between 18 and 40 years old (mean age = 30.23 years, SD = 6.401). They were required to have normal or corrected to normal vision (i.e., via glasses or contact lenses) and to have experience working in an office environment. They were prevented from drinking caffeine beverages (coffee and tea) before and during the experiment. Participants received a monetary compensation when attending the entire experiment.

A detailed representation of the way participants were organized for the BIBD is displayed in table 1. The table shows the light settings presented to each participant, including the order, day and time of presentation. In addition, the table shows the sessions for which the participant didn’t show up and it presents the light settings that were intentionally not shown to the participants (i.e., following the BIBD).
2.3 SETTINGS AND APPARATUS (SET UP)

The experiment took place in a simulated office environment located in Eindhoven, The Netherlands. The simulated office represented an open plan office environment of rectangular shape (6.80m x 3.60m x 2.60m). The walls of the office were white with small calendars attached to the walls. The smaller walls of the office had two ‘outdoors’ images, surrounded by a frame and some blinds, in order to simulate a window. Furthermore, the office was equipped with an air-conditioning system that allowed the temperature to remain constant at 20°C. Four participants took place in the office at the same time. Hence, the office contained four individual desks, each with a PC, a chair, a production calendar, a cabinet and some small decorations. A small extra desk was placed so that the test leader could sit down while running the experiment.

The light system was formed by two large floating luminaires, located parallel to each other, running along the longer axis of the office. The luminaires were capable of emitting light downwards and upwards and the output was highly controllable. As such, the office environment and its lighting were very symmetric from the center. Taking advantage of the shape of the office, the experiment used a standing board placed in the middle of the room. The standing board allowed the positioning of charts for the diverse tasks and tests that were required during each experimental session. For each task or test, four A3-sized charts were placed on the board, i.e., two on each side of the board. All the charts received the same illuminance in all conditions. A picture of the office, together with a blueprint, is presented in figure 7.
2.3.1 LIGHT SETTINGS

The light system used two rows of suspended luminaires, formed by five consecutive independent LED luminaires, each located at 2.1m above the floor. Each LED luminaire was formed by a combination of commercially available Philips LED fixtures. A PowerBalance fixture emitted light downwards (i.e., towards the desk); while Maxos panels were placed right on top of each PowerBalance fixture aiming at creating light upwards (i.e., towards the ceiling). In this form, the light emitted from the Maxos panels was nowhere directly visible for the user. At the same time, by positioning the luminaires parallel to the walls, the lighting system prevented the creation of scallop shades on the walls.

All light settings created a vertical illuminance of 700 lux at 3800 K on the charts of the standing board, with a maximum error of ± 2%. What varied between the light settings was the amount of direct versus indirect light on the charts. The first light setting used only direct light, meaning that the 700 lux on the charts was generated with downwards light only. The second light setting existed of 75% of the 700 lux illuminance on the charts (i.e., 525 lux) resulting from downwards illumination, while the rest (i.e., 25% or 175 lux) resulted from upwards illumination. For the third and fourth light setting the contribution of upwards illumination was further increased till 50% and 75%, respectively. Finally, the fifth light setting used no downwards light; thus, the 700 lux illuminance on the charts was entirely generated with upwards illumination. An overview of the illuminance values measured in the middle of each chart is given in table 2.

Table 2: Illuminance (in lux) measured on the four A3 charts for each of the light settings used in the experiment.

<table>
<thead>
<tr>
<th>Illuminance Values (lux)</th>
<th>Light Setting 1</th>
<th>Light Setting 2</th>
<th>Light Setting 3</th>
<th>Light Setting 4</th>
<th>Light Setting 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remarks</td>
<td>Only Direct</td>
<td>75% - 25%</td>
<td>50% - 50%</td>
<td>25% - 75%</td>
<td>0% - 100%</td>
</tr>
<tr>
<td>Ratio Direct - Indirect</td>
<td>100% - 0%</td>
<td>75% - 25%</td>
<td>50% - 50%</td>
<td>25% - 75%</td>
<td>0% - 100%</td>
</tr>
<tr>
<td>Chart 1 (North A)</td>
<td>706</td>
<td>712</td>
<td>716</td>
<td>715</td>
<td>704</td>
</tr>
<tr>
<td>Chart 2 (North B)</td>
<td>716</td>
<td>720</td>
<td>723</td>
<td>720</td>
<td>706</td>
</tr>
<tr>
<td>Chart 3 (South A)</td>
<td>695</td>
<td>702</td>
<td>706</td>
<td>706</td>
<td>694</td>
</tr>
<tr>
<td>Chart 4 (South B)</td>
<td>714</td>
<td>720</td>
<td>722</td>
<td>722</td>
<td>709</td>
</tr>
</tbody>
</table>
The resulting luminance distribution in the experimental room was further characterized using the luminance camera LMK 5 Color with no additional lenses. The images were obtained from the viewpoint of a participant sitting on desk 3 while observing the charts of the tasks (i.e., charts A and B north; used by participants on desks 3 and 4). The view of each chart was measured for the five light settings. The resulting images are shown in figure 8; each row of pictures represents a single viewing angle for the five different light conditions. When observing the results, the measurements confirm the constant illuminance level on the chart for all light settings used in the experiment. Furthermore, these measurements illustrate the large changes in illuminance on the wall in the immediate background of the chart. As expected, these luminance levels largely vary over the different light settings used because of the different contribution of direct and indirect illumination on these walls.

![Figure 8: Luminance images of the two charts (i.e., A & B north) observed from the viewpoint of a participant sitting behind desk 3; the five images in a row present the five light settings (i.e., marked as LS1-5). [Upper row] Luminance images of chart A north (left). [Lower row] Luminance images of chart B north (right). [Right] Common luminance scale for all the luminance images](image1)

Similarly, we took images of the luminance distribution in the field of view when looking directly to the luminaires and the surrounding ceiling. These luminance pictures are shown in figure 9, where the black corner in all five pictures represents the top part of the standing board. The large changes in luminance that occur in the upper part of the office are directly related to the mixture of upwards and downwards light, as used in the various light settings. The smallest contrast between luminaire and ceiling is created with an almost equal contribution of upward and downward light.

![Figure 9: Luminance image of the luminaires and surrounding ceiling for the five different light settings (i.e., LS1-5). All the images were taken from the viewpoint of a participant sitting behind desk 3. [Right] Common luminance scale for all the images](image2)

### 2.4 MEASURES

The measures used in this experiment consisted of both subjective questionnaires and objective measurements. All the assessments of these measures were presented to the participants on paper, in order to avoid external sources of light from additional display screens. Between the assessments, visual fatigue was induced to the participants by means of visually demanding tasks. It is important to notice that the tools for the objective measures and the tasks to induce fatigue were placed vertically on the standing board, making the illuminance for these tests and tasks constant at 700 lux. On the other hand, filling in the subjective questionnaires on paper didn't require having constant illuminance, and thus, they were evaluated in a natural way at the desk.
As mentioned before, the experimental design used two dependent variables: light appraisal and the level of asthenopia. Light appraisal was measured subjectively (i.e., with subjective questionnaires on brightness, comfort and acceptability of light), while the level of asthenopia was measured subjectively (i.e., via a questionnaire) and objectively (i.e., via accommodative facility and visual acuity). All measures are explained in more detail below. At the end of this subsection, a more detailed explanation of the visual fatigue induction tasks used in between the measurements is given.

### 2.4.1 LIGHT APPRAISAL

Light appraisal of the room was measured with subjective scales, as described before in literature (Geerdinck, 2012; Houser et al., 2002). The measurement addressed different parts of the room, since responses were expected - based on existing literature - to vary depending on the part of the room that was considered (Houser et al., 2002). More specifically, participants were asked to assess three zones of the room: (1) the room in general, (2) the ceiling, and (3) the luminaires.

The first zone embraced the evaluation of the room in general; this zone was evaluated using two items. The first item measured light comfort on a bipolar semantic 7-point scale, as used before in the study of Geerdinck (2012). The second item requested participants to give a score for the general grade of the lighting in the office. Both items are graphically represented in figure 10.

![Figure 10: Subjective questionnaire measuring light appraisal for the room in general.](image)

In general, to what extent do you experience the lighting in this room as comfortable?

<table>
<thead>
<tr>
<th>very uncomfortable</th>
<th>uncomfortable</th>
<th>slightly uncomfortable</th>
<th>not uncomfortable, not comfortable</th>
<th>slightly comfortable</th>
<th>comfortable</th>
<th>very comfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please, could you judge the lighting in this office with a grade between 1 and 10, where 1= very bad and 10= excellent

My grade for the lighting in this office (1-10):

The light appraisal of the ceiling was assessed with three items. First, the amount of brightness coming from the ceiling was evaluated using a bipolar semantic 7-point scale. Second, light comfort related to the brightness of the ceiling was assessed using a bipolar semantic 7-point scale; the same scale as used for the room in general. Third, a dichotomous semantic scale was used to ask the acceptability of the brightness of the ceiling. All three items are graphically shown in figure 11. Note that the assessment of the luminaires was exactly the same as the assessment of the ceiling. Hence, the same three items were used; though, the word "ceiling" was replaced by the word "lamps".
2.4.2 ASTHENOPIA

As remarked earlier, this thesis makes an explicit difference between visual fatigue (measured objectively as suggested by Lambooij (2012)) and visual discomfort (measured subjectively); both representing asthenopia. Visual fatigue was measured by means of eye accommodation facility and visual acuity (Chi and Lin, 1998). Visual discomfort was measured using the Headache and Eyestrain Scale (HES) (Saito et al., 1994; Chi and Lin, 1998). In general, all three measurements obtained their results by evaluating participants at two different times during the experiment; i.e., at the beginning and at the end of each experimental session. The difference in scores was taken as measure for visual fatigue or visual discomfort.

2.4.2.1 ACCOMMODATIVE FACILITY

The difference in accommodative facility was used as the first measure of visual fatigue. Accommodative facility is defined as the “rate at which (eye) accommodation can be stimulated and inhibited repeatedly during a specific period of time” (Zellers et al., 1984). It is an optometric clinically based measurement used as a score of the accommodation speed of the eye. The difference in accommodation facility before and after a task was previously used to measure visual fatigue (Chi & Lin, 1998).

The measurement of accommodative facility uses a lens-like device called “accommodative lens flipper”, a picture of which is shown in figure 12. This device is formed by two different pairs of lenses, each pair attached at one side of a plastic spatula. Each pair of lenses has a different optical power; each pair is meant to be placed in front of the eyes, at the same position as normal lenses. While grabbing the device from the spatula, participants are able to flip the device back and forth (i.e., from one set of lenses to the other) in order to continuously change the optical power in front of their eyes. Several authors have used different values for the optical power of the lenses, varying between ±1 and ±2.5 Diopters. In our study we used an optical power of ±2 Diopters to allow a comparison with the findings of Zellers and others (1984).
Figure 12: Accommodative lens flipper device. Each pair of lenses has a different optical power (i.e., ±2 Diopters)

To measure accommodative facility, participants were requested to use the lens flipper while observing a segment of pseudo text printed with a Calibri 20 font. The text was placed on the standing board in the center of the office and participants were asked to stand at a fixed distance of 40 cm in front of the board. Each participant had its own chart placed on the standing board. When in position, participants were asked to use the lens flipper on the plus side and aim to fixate their vision on the text. Instantly after participants were able to fixate their vision on the text, they could flip the lens flipper and try to fixate their vision again. This repetitive process continued for a period of 30 seconds, when the test leader announced the end of the measurement time. Each participant counted individually the amount of flips made and, immediately after the 30 seconds, wrote down that number as the score.

2.4.2.2 VISUAL ACUITY

The difference in visual acuity was used as a second measure of visual fatigue. Visual acuity is defined as “a measurement of the ability to resolve detail for a target with a fixed illuminance contrast” (Boyce, 2003). It is an optometric clinical measurement used in the medical profession. Similar to the accommodation facility, the difference in score of visual acuity is reported in literature to measure visual fatigue (Chi &Lin, 1998).

The visual acuity test consists of measuring the capability of participants to identify specific figures called optotypes. Optotypes are figures that can be distinguished from each other in a simple way. For instance, letters or rings are commonly used optotypes. The score is represented by the size of the optotype that can be identified in 50 percent of the occasions. Usually, the size of the optotype is measured in terms of the visual angle observed by the viewer, making the size independent of the viewing distance.

The optotypes used for our study were the Landolt rings, which are rings with a small opening towards any of four sides; being up, down, right or left. The test sheet used in the measurement was formed by 96 Landolt rings with different sizes of the opening randomly placed in a grid of 8 x 12 rings (as can be seen in figure 13). The 8 different sizes of the Landolt rings varied from 0.847 to 4.233 mm. Subjects were requested to view the sheet of Landolt rings from a distance of 2.70m (using a chinrest to keep the distance constant); thus, the size of the Landolt rings, in terms of visual angle, varied between 1.078’ (min arc) and 5.39’. These visual angles represent a visual acuity between 4.638 and 0.928 (i.e., in the decimal scale), which include and overpass the nominal correct vision value of 20/20. To avoid a learning effect of participants memorizing a fixed sequence of rings, the order in which participants had to read the rings changed randomly from session to session. As can be seen in figure 13, the randomization of the sequence was achieved by means of a red LED light, indicating which Landolt ring had to be read at a given moment in time.
2.4.2.3 VISUAL DISCOMFORT

Visual discomfort was measured with a questionnaire that was reported to indicate effects of visual fatigue on people (Chi & Lin, 1998; Saito et al., 1994). The questionnaire consisted of eight items that explore different symptoms of asthenopia. The different items used in this questionnaire were: “my eyes felt tired”, “my eyes are dry”, “my eyes are irritated or burning”, “I have eye pain”, “It is hard to focus my vision”, “I have double vision”, “I have flicker vision” and “I have a headache”. Each item was evaluated on a 7-point scale that varied from ‘totally disagree’ to ‘totally agree’. A graphical representation of one of the questions is given as an example in figure 14 (the entire list of questions is presented in Appendix 1).

![Figure 14: Example of an item of the HES questionnaire used to measure visual discomfort.](image)

2.4.3 VISUAL FATIGUE INDUCTION

With the aim to enhance the possible effect of the light distribution in the room on visual fatigue, different visually demanding tasks were created for this experiment. The goal of these visually demanding tasks was to direct the visual attention of the participants to the standing board in the middle of the room, while at the same time presenting the largest possible view of the room in the visual field of the participants by asking them to perform the tasks sitting behind their desk. The illuminance level of the charts on the standing board was strictly controlled to 700 lux vertically in order to eliminate the effect of illuminance on task performance, but the luminance distribution in the rest of the visual field was largely affected by the light setting, as was already shown in figure 8. It was our goal to direct the visual attention of the participants constantly to the charts for 35 minutes, so that a possible effect of light distribution in the
room on asthenopia was sufficiently large to be measured. As with the other measurement tools, the fatigue inducing tasks needed to be paper based.

To fulfil the above requirements, we created four different types of visually demanding tasks: ‘Letter search’, ‘Figure search’, ‘Word search’, and ‘Difference search’. An example of the different tasks is given in table 3. The ‘Letter search’ task required participants to search for the letters ‘r’ and ‘d’ in a pseudo text; the text was divided in 10 paragraphs and participants needed to report the number of occurrences for each paragraph separately. The ‘Figure search’ task required participants to identify 15 objects in a larger image, in which these objects were camouflaged; a grid was used to facilitate participants to report the location of the detected object. The ‘Word search’ task used a simple world puzzle with 15 words; participants needed to draw a line in the direction, in which they found the word in the puzzle. Finally, the ‘Difference search’ task required participants to identify 15 differences between two images; also here a grid was used to let participants indicate where they saw the differences. As such, all four tasks required concentrated visual attention on the chart, but low cognitive power, to avoid mental depletion of the participants. The tasks were presented in such a way that participants could write their responses individually on paper. They were required to provide an answer to all tasks in order to keep their attention on the charts, but their answers were not further analyzed, since measuring performance was not the main purpose of this study. Each task was estimated to take about 7 to 10 minutes (based on a short pilot study), but nonetheless, all tasks (except the letter search task) were modified to make them unsolvable, in order to prevent that participants started looking around in an uncontrolled way after finishing their tasks.

Table 3: Examples of the four fatigue inducing tasks. Each example has a visible mark to present one of the several possible answers.

<table>
<thead>
<tr>
<th>Visual Demanding Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Letter Search</strong></td>
</tr>
<tr>
<td>Count the ‘r’/’R’ and the ‘d’/’D’.</td>
</tr>
<tr>
<td>1. <em>Cu idam officiis nam, audire eligendi eam an, vel ad video discipulam silenti. Et est prius nominati, an nec dicam deleniti judicabit. Quam pecusia nel ne, integra locundia has an? Leudem admodum te vim, iBiue.</em></td>
</tr>
<tr>
<td>2. <em>Vel et erant marmorum, singularis nominati</em></td>
</tr>
<tr>
<td><strong>Figure Search</strong></td>
</tr>
<tr>
<td><img src="image1" alt="Figure Search Example" /></td>
</tr>
<tr>
<td><strong>Word Search</strong></td>
</tr>
<tr>
<td>Animals:</td>
</tr>
<tr>
<td>1. Bear</td>
</tr>
<tr>
<td>2. Butterfly</td>
</tr>
<tr>
<td>5. Chicken</td>
</tr>
<tr>
<td>7. Bird</td>
</tr>
<tr>
<td>8. Wolf</td>
</tr>
<tr>
<td>9. Lion</td>
</tr>
<tr>
<td>10. Elephant</td>
</tr>
<tr>
<td><strong>Difference Search</strong></td>
</tr>
<tr>
<td><img src="image2" alt="Difference Search Example" /></td>
</tr>
</tbody>
</table>

2.5 PROCEDURE

The whole experiment consisted for each participant of four experimental sessions distributed over two days. Participants were requested to come back on the second day at the same time as they performed the experiment on the first day. Each day, each participant performed two sessions with a 15-minutes break in between. Each session showed a different light setting to a group of four participants. The light setting was kept constant during the entire
participants were blind to the experimental conditions. In some cases, however, participants were able to see noticeable changes in the light settings; when this occurred, participants were instructed to focus their judgments only on the light setting that was displayed at that particular moment in time.

When arriving, participants were welcomed to the simulated office environment. They were guided to a specific desk, which they used for the entire experiment (i.e., the same desk for each participant over the four experimental sessions). Each participant had on his/her desk the informed consent form, an accommodative lens flipper and an instruction set; the latter contained 83 pages with clear instructions and illustrations that guided the participants along each day of participation.

The first session started with the participants reading and signing the informed consent form. Afterwards, participants received a small introduction to the instruments and measurements used during the experiment. To get acquainted with the different measurement tools, participants were requested to exercise them. For the accommodation facility test, participants were asked to stand up, go to the board and use both sides of the lens flipper until vision through both lenses was sharp. This procedure was done at the beginning of each day to let the eyes of the participants adapt to the optical power of the lens flippers. For the visual acuity test participants were asked to position the chin-holder such that it fitted the size of their head and to place their keyboard at a convenient distance. The scores of the visual acuity test were stored via a computer, though the computer monitors were off during the whole experiment to avoid extraneous light sources. The subjective measurements required no further action at the start of the experiment.

When all four participants understood and practiced the different measurements, the actual experimental session started. Participants were first asked to fill in the comfort questionnaire; they were instructed to take their time and look around before making a judgment. Next, participants engaged in the first measurement of visual fatigue, including three methods. They started with the accommodation facility measurement, then performed the visual acuity measurement, and finally filled in the visual discomfort questionnaire. After this measurement of visual fatigue, participants performed the visual fatigue inducing tasks for 35 minutes. During this time, participants observed 7 different tasks in fixed periods of 5 minutes. After every five minutes, the test leader quickly announced the time to the participants and changed the tasks on the charts. After 35 minutes (i.e., immediately after the last visual demanding task) participants engaged in the second measurement of visual fatigue, following the same order (i.e., accommodation facility, visual acuity and visual discomfort questionnaire).

After the first session, participants were able to take a 15-minutes break. During that break, participants could relax their eyes and their body. They were also offered a beverage (without caffeine) and/or a cup of soup. The group of participants remained together during the entire relaxation time. Right before the end of the break, the test leader returned to the office environment to change the light setting, preventing participants to observe this change. Eventually, the test leader called the participants and the group returned to the simulated office, to engage in the second session of the day.

The second day of experimental sessions was similar to the first one, except for the start. On the second day, participants didn't need an introduction to the measurements. They still were asked to exercise the visual fatigue measurements. So, they were asked to approach the standing board and practice the lens flipper, until they were able to see sharply through both lenses. In addition, they were requested to adjust the length of the chin holder to the size of their head.

The debriefing session took place at the end of the second day, after participants had finished the entire experiment and their responses could no longer be biased. Participants received debriefing information on the purpose of the experiment and the different light settings were displayed to them.
2.6 DATA ANALYSIS

For an easier interpretation and comparison, all scores were re-coded to the same direction, meaning that higher values of the score represented higher levels of the measured characteristic. For instance, the scores of lighting appraisal were easily interpreted, since the higher values in the scoring scale already corresponded to higher levels of light appraisal. The various scores of asthenopia, on the other hand, provided a different interpretation.

The three scores of asthenopia represented the difference between two measures at different times of the test, namely before and after the fatigue induction. In order to make all the scores representing the level of asthenopia, the differences of the scores were calculated in different ways. First, the measure of accommodation facility expressed higher visual fatigue when the score decreased over time. As a consequence, the corresponding score was obtained as:

\[ VF_{AF} = AF_{Before} - AF_{After} \]  

The score of visual acuity (VA) was actually represented by the smallest size of the optotype that the participants were able to distinguish. Hence, smaller numbers in this measure represented higher visual acuity. So, an increase of the minimum distinguishable size of the optotype over time represented an increase in visual fatigue, which resulted in the equation:

\[ VF_{VA} = VA_{After} - VA_{Before} \]  

Lastly, the HES score before and after the experiment was first determined as the averaged score over the 8 items of the questionnaire to form a single score for further data analysis. Due to the presentation of the test (i.e., presented on paper), it was impossible to control that all participants answered all items. Thus, a couple of participants accidently left some sporadic items unanswered. For those participants, the overall score of visual discomfort was obtained by averaging only the answered items. The resulting HES score represented visual discomfort (VD), such that an increase of the HES score over time represented an increase in visual fatigue. Thus, to calculate visual discomfort the following equation was used:

\[ VD_{HES} = HES_{After} - HES_{Before} \]  

In order to take full advantage of the BIB design that was used in the experiment, the data were analyzed using linear mixed models. These models extend the capabilities of linear models by allowing the analysis to use two types of effects, i.e., fixed and random effects, to predict the observed score of the dependent variable. In comparison, classic linear models only use fixed effects. By adding specific effects as random effects in the model, it is assumed that the scores of those effects have different “baseline” values. This assumption allows the model to explain interpersonal variability with random effects, which, as a consequence, explains part of the “error term”, and eventually makes the model more accurate.

All data analyses used the ID of the participants as a random effect in the model. This variable fitted well the description of a random effect, since the ID of the participants was not idiosyncratic, nor systematic, it did not exhaust the population of interest, and, most importantly, the effect of the ID of the participants was not of interest for this study (Winter, 2011). In contrast, the fixed effects of the model should represent the effects that the study was interested in, which basically was the light setting. Where appropriate, several control variables were added to the model, in the form of fixed effects, to have a better understanding of the results.

The type of dependent variables used for the data analysis varied greatly. The scales used to measure asthenopia were all continuous. The measures of visual comfort were ordinal, though they were treated as continuous scales for the entire data analysis. Only the light acceptability scale was dichotomous; this special case was analyzed using a repeated measures logit regression. The data analyses were performed using the language and environment for statistical computing called “SPSS”. The algorithm for the linear mixed models assumed linearity, homoscedasticity, normality of residuals and normality of betas. These properties were visually controlled before proceeding with reporting the
results. All data analysis, that showed significant differences, were further analyzed in a pairwise comparison (i.e., contrast analysis) while controlling for the overall significance level using the Bonferroni correction.

To clearly understand the data, graphical representations were created. By using the “multcomp” package in R (Hans-Peter, 2004), a graphical estimation of the linear predictor separated by the variable of interest (i.e., light setting) could be plotted. These graphs indicated the estimated scores taking into account the fixed and random scores of the model.
3. RESULTS

This chapter first reports the results on light appraisal, obtained at the beginning of each experimental session. Then, the results on the measured asthenopia are reported; note that these measures were formed by the difference in scores between the evaluations at the start and end of the experiment. The fatigue inducing tasks were only meant to facilitate the measurement of visual fatigue; as such, their results are not reported.

3.1 LIGHT APPRAISAL

Each zone of the room (i.e., room in general, ceiling and luminaires) was analyzed separately, as mentioned before. Further, each zone of the room was evaluated by one or more evaluations of light appraisal (i.e., grade, brightness, comfort, acceptability); the results for each zone are presented separately in this thesis.

3.1.1 ROOM IN GENERAL

Two measures evaluated the light appraisal of the room in general. First, according to the 7-point scale of comfort (see figure 10), participants perceived the room as comfortable (mean=5.23, SE = 0.1). The linear mixed model analysis showed that the comfort of the room was not significantly affected by the light setting (F(4,92.25) = 0.5, p = 0.736); the estimated scores of comfort in the room for every light setting, together with the standard error and confidence interval, are presented in Table 4. The score of light comfort in the room was lowest for the light setting formed only by direct light, but this tendency should be interpreted with care since there was no significant difference in the perception of light comfort between the different light settings.

Table 4: Estimated mean, standard error and confidence interval of the perceived comfort of the light in the room in general for each of the light settings

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>5.06</td>
<td>0.23</td>
<td>4.62 5.51</td>
</tr>
<tr>
<td>LS2</td>
<td>5.40</td>
<td>0.23</td>
<td>4.96 5.85</td>
</tr>
<tr>
<td>LS3</td>
<td>5.14</td>
<td>0.22</td>
<td>4.70 5.58</td>
</tr>
<tr>
<td>LS4</td>
<td>5.37</td>
<td>0.23</td>
<td>4.92 5.81</td>
</tr>
<tr>
<td>LS5</td>
<td>5.21</td>
<td>0.23</td>
<td>4.76 5.66</td>
</tr>
</tbody>
</table>

The second scale that evaluated the room was the grading for the lighting in the room (see also figure 10). This measure was generally rated with high values (mean=7.25, SE = 0.1). As expected when evaluating similar characteristics in the same zone of the room, the correlation between the perceived light comfort in the room and perceived grade of the light in the room was high (R=0.856). According to the linear mixed model analysis, the effect of the light setting on the grade of the light in the room was not significant (F(4,87.54) = 0.46, p = 0.764), meaning that the perceived grade of the light in the room in general was not perceived as significantly different for the different ratios of direct and indirect light. Table 5 shows the estimated score for every light setting, including the standard error and confidence interval. Once again, the lowest grade of light in the room was given to the light setting formed by only direct light, though this tendency should be considered with care since the difference was again not significant.
### Light grade of the room in general

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>7.08</td>
<td>0.23</td>
<td>6.63 - 7.52</td>
</tr>
<tr>
<td>LS2</td>
<td>7.43</td>
<td>0.22</td>
<td>6.99 - 7.88</td>
</tr>
<tr>
<td>LS3</td>
<td>7.31</td>
<td>0.22</td>
<td>6.88 - 7.75</td>
</tr>
<tr>
<td>LS4</td>
<td>7.27</td>
<td>0.22</td>
<td>6.83 - 7.72</td>
</tr>
<tr>
<td>LS5</td>
<td>7.20</td>
<td>0.23</td>
<td>6.75 - 7.65</td>
</tr>
</tbody>
</table>

#### 3.1.2 LUMINAIRE

The study used three different measures of light appraisal for the zone of the luminaires. The first one was the measurement of brightness (see figure 11). The result (mean=4.59, SE = 0.11) indicated that the perception of brightness of the luminaires was just above the middle of the scale (i.e., 'not low, not high'). The data analysis showed that the perception of brightness of the luminaires was significantly different for the different light settings ($F(4,82.85) = 10.52, p < 0.001$). Further, these effects remained significant when adding the control variables (i.e., day, session, age and gender) to the model ($F(4,78.07) = 10.30, p < 0.001$); table 6 presents the estimated mean, standard error and confidence interval of the perceived brightness of the luminaires.

#### Table 6: Estimated mean, standard error and confidence interval of the perceived brightness of the light of the luminaires for each of the light settings

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>5.20</td>
<td>0.22</td>
<td>4.77 - 5.63</td>
</tr>
<tr>
<td>LS2</td>
<td>4.96</td>
<td>0.22</td>
<td>4.52 - 5.39</td>
</tr>
<tr>
<td>LS3</td>
<td>4.90</td>
<td>0.22</td>
<td>4.47 - 5.33</td>
</tr>
<tr>
<td>LS4</td>
<td>4.47</td>
<td>0.22</td>
<td>4.04 - 4.91</td>
</tr>
<tr>
<td>LS5</td>
<td>3.51</td>
<td>0.22</td>
<td>3.08 - 3.94</td>
</tr>
</tbody>
</table>

By looking at the estimated mean for each light setting it can be observed that light setting 5 was graded as less bright compared to the rest of the light settings. This finding is in line with the physical measurements of the luminance in the room, meaning that the brightness of the luminaires was perceived lowest for the light setting with no direct light. Further, the contrast analysis (i.e., based on the Bonferroni correction) showed that light setting 5 was significantly different from the rest of the light settings. Table 7 presents the pairwise comparisons, whereas figure 15 gives a graphical representation of the scores on brightness of the luminaires. Note that all other mutual comparisons of perceived brightness of the luminaires between the different light settings (i.e., light settings 1, 2, 3 and 4) were not significantly different; and thus, they are not presented in the table.
Table 7: Results of the contrast analysis for the perceived brightness of the luminaires limited to those pairwise comparisons between light settings that were found to be significant

<table>
<thead>
<tr>
<th>Pairwise comparison of perceived brightness of luminaires</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) LS vs (J) LS</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>LS5</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 15: Boxplot of the estimated marginal means of the perceived brightness of the luminaires for each light setting. In addition, different colors indicate different significance levels.

The second measure of light appraisal for the zone of the luminaires was the perceived comfort of the light (see again figure 11). The average score (mean=4.79, SE = 0.12) indicated that the comfort of the light was perceived just above the neutral score (i.e., the center of the 7-point scale received the label ‘not uncomfortable, not comfortable’). The corresponding data analysis showed that the perception of comfort was not significantly different for the different light settings (F(4,82.75) = 0.46, p = 0.763); hence, no further analysis was done for this measure. The estimated scores of comfort in the room for every light setting, together with the standard error and confidence interval, are given in Table 8.
Table 8: Estimated mean, standard error and confidence interval of the perceived comfort of the light of the luminaires for each of the light settings.

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lower</td>
<td>upper</td>
<td></td>
</tr>
<tr>
<td>LS1</td>
<td>4.63</td>
<td>0.27</td>
<td>4.10 5.16</td>
</tr>
<tr>
<td>LS2</td>
<td>5.00</td>
<td>0.27</td>
<td>4.46 5.54</td>
</tr>
<tr>
<td>LS3</td>
<td>4.63</td>
<td>0.27</td>
<td>4.10 5.16</td>
</tr>
<tr>
<td>LS4</td>
<td>4.80</td>
<td>0.27</td>
<td>4.27 5.34</td>
</tr>
<tr>
<td>LS5</td>
<td>4.85</td>
<td>0.27</td>
<td>4.32 5.39</td>
</tr>
</tbody>
</table>

The third measure of light appraisal evaluated for the luminaires was the dichotomous acceptability of the brightness, and so, was analyzed with a repeated-measures logit regression. The Wald Chi-Square test showed that the different light settings produced no significant effect on the judgment of acceptance ($\chi^2(4) = 5.7, p=0.223$). To have a deeper understanding of the scores, table 9 presents the model estimated (normalized) scores of acceptability for each of the light settings, including their standard error and confidence interval. From these data, it can be observed that the acceptability of the light from the luminaires was high for all light settings. In addition, the estimated scores also were considerably spread (resulting in relatively large confidence intervals), which could give an indication on why the acceptability of the light from the luminaires was not significantly different between the different light settings.

Table 9: Estimated mean, standard error and confidence interval of the perceived acceptance of the light from the luminaires for each of the light settings.

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lower</td>
<td>upper</td>
<td></td>
</tr>
<tr>
<td>LS1</td>
<td>0.71</td>
<td>0.08</td>
<td>0.53 0.84</td>
</tr>
<tr>
<td>LS2</td>
<td>0.86</td>
<td>0.06</td>
<td>0.68 0.95</td>
</tr>
<tr>
<td>LS3</td>
<td>0.76</td>
<td>0.07</td>
<td>0.59 0.87</td>
</tr>
<tr>
<td>LS4</td>
<td>0.91</td>
<td>0.05</td>
<td>0.75 0.97</td>
</tr>
<tr>
<td>LS5</td>
<td>0.88</td>
<td>0.06</td>
<td>0.70 0.95</td>
</tr>
</tbody>
</table>

3.1.3 CEILING

Similar to the assessment of the luminaires, the zone of the ceiling was evaluated with three measures of light appraisal. The first measure represented the scale of perceived brightness from the ceiling. The ceiling was perceived similarly neutral in brightness (mean=4.41, SE = 0.1) as the luminaires; the average score was close to the center of the 7-point scale labeled as ‘not low, not high’, and so, representing a very mild perception of brightness despite the high luminance levels used in the experiment. The linear mixed model analysis showed that the perceived brightness of the ceiling was significantly affected by the light setting ($F(4,105.64) = 6.01, p < 0.001$). The brightness scores remained significantly different between the light settings after adding the control variables day, session, age and gender to the
model ($F(4, 106.89) = 6.06, p < 0.001$). The estimated mean of perceived brightness of the ceiling (including standard error and confidence interval) is presented for every light setting in Table 10.

Table 10: Estimated mean, standard error and confidence interval of the perceived brightness of the ceiling for each of the light settings

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>3.60</td>
<td>0.21</td>
<td>3.18-4.01</td>
</tr>
<tr>
<td>LS2</td>
<td>4.56</td>
<td>0.21</td>
<td>4.15-4.98</td>
</tr>
<tr>
<td>LS3</td>
<td>4.87</td>
<td>0.21</td>
<td>4.47-5.28</td>
</tr>
<tr>
<td>LS4</td>
<td>4.65</td>
<td>0.21</td>
<td>4.24-5.07</td>
</tr>
<tr>
<td>LS5</td>
<td>4.35</td>
<td>0.21</td>
<td>3.93-4.77</td>
</tr>
</tbody>
</table>

The estimated mean values of the perceived brightness of the ceiling showed the lowest brightness for the light setting formed only with direct light (i.e., light setting 1); which was expected, since light setting 1 had no contribution of light reflected on the ceiling (i.e., indirect light). The rest of the light settings were evaluated with a noticeably higher brightness; the difference in perceived brightness between light setting 1 and the other light settings was about 1 point on the 7 point scale. The contrast analysis showed that light setting 1 was indeed scored significantly different from most of the other light settings. The results of the contrast analysis are summarized in Table 11; which is limited to these comparisons that were found to be significantly different. In addition, Figure 16 gives a graphical representation of the results.

Table 11: Results of the contrast analysis for the perceived brightness of the ceiling limited to those pairwise comparisons between light settings that were found to be significant

<table>
<thead>
<tr>
<th>(I) LS vs (J) LS</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval for Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>LS1</td>
<td>LS2</td>
<td>-.97*</td>
<td>.25</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>LS3</td>
<td>-1.28*</td>
<td>.28</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>LS4</td>
<td>-1.06*</td>
<td>.29</td>
<td>.004</td>
</tr>
<tr>
<td></td>
<td>LS5</td>
<td>-0.75</td>
<td>.30</td>
<td>.119</td>
</tr>
</tbody>
</table>
From figure 16, it can be observed that the perception of brightness of the ceiling increased as the light settings continued to include more indirect light up to a level of 50% indirect light (i.e., light setting 3). Above this level the increase in perceived brightness stopped, while still more indirect light was added to the light setting. Eventually, light setting 5 (i.e., formed only by indirect light) was perceived with a brightness level very similar to light setting 1; the difference in perceived brightness between light setting 1 and 5 was no longer significant. A similar tendency in perceived brightness of the ceiling was also observed in the study of Geerdinck (2012).

The second measure of light appraisal for the zone of the ceiling was perceived comfort. Its mean value (mean=4.78, SE = 0.11) was evaluated slightly above the neutral level on the scale, towards the direction of comfort. The linear mixed model analysis showed that the perception of comfort of the ceiling varied significantly between the different light settings (F(4,87.75) = 2.99, p = 0.023). Again, this effect remained significant after adding the control variables day, session, age and gender to the model (F(4,87.19) = 3.18, p = 0.017). The scores on perceived comfort of the light from the ceiling, as summarized in table 12 (including also the standard deviation and the confidence interval), indicated that adding indirect light increased the perceived comfort when looking to the ceiling, at least to the level of some contribution of the indirect light.
The scores also show that the lowest perception of comfort was obtained for the light settings formed by light in only one direction (i.e., only direct or only indirect light). Once again, these findings are in line with existing literature (Geerdinck, 2012). However, not all differences in perceived comfort reached significance. The contrast analysis showed two important pairwise comparisons for the scores of perceived comfort. First, the comfort of the light of the ceiling in light setting 2 was rated 1.07±0.32 points more comfortable than light setting 1; this difference was significant (p=0.014). Second, the comfort of the light of the ceiling in light setting 3 was rated 0.9±0.34 points higher than in light setting 1; unfortunately, this difference only approached significance (p=0.086). A graphical representation of the results is given in figure 17.

The third measure of light appraisal for the ceiling area was the dichotomous acceptability of the brightness, which was analyzed with a repeated-measures logit regression. The Wald Chi-Square test showed that the acceptance of the brightness of the ceiling was not significantly different between the light settings ($\chi^2(4) = 5.67, p=0.225$). The estimated (normalized) scores of brightness acceptability (as summarized in table 13, including also the standard error and confidence interval) showed that the light of the ceiling was generally very well accepted. The lowest acceptance score was again obtained for light setting 1, which was noticeably different with the scores of the rest of the lights settings; nonetheless, the latter conclusion should be taken with care since the difference in acceptance did not reach significance.
Table 13: Estimated mean, standard error and confidence interval of the perceived acceptance of the lighting of the ceiling for each of the light settings

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>0.80</td>
<td>0.07</td>
<td>0.62 0.91</td>
</tr>
<tr>
<td>LS2</td>
<td>0.93</td>
<td>0.05</td>
<td>0.77 0.98</td>
</tr>
<tr>
<td>LS3</td>
<td>0.90</td>
<td>0.05</td>
<td>0.73 0.97</td>
</tr>
<tr>
<td>LS4</td>
<td>0.93</td>
<td>0.05</td>
<td>0.77 0.98</td>
</tr>
<tr>
<td>LS5</td>
<td>0.90</td>
<td>0.06</td>
<td>0.72 0.97</td>
</tr>
</tbody>
</table>

3.2 ASTHENOPIA

3.2.1 ACCOMMODATION FACILITY

The degree of visual fatigue as represented by the difference in accommodation facility showed an increase during the experiment (mean=0.61, SE=0.18). This increase corresponded to a small reduction in the number of cycles per minute (cpm) induced by the visual fatigue induction tasks. Further, this reduction was observed to have a significant variation depending on the light setting (F(4,98.87) = 4.01, p = 0.005). The effect of light setting on accommodation facility remained significant after adding the control variables session, gender, age and day (F(4,98.87) = 4.01, p = 0.005). The estimated mean, together with the standard error and confidence interval, are summarized in table 14. The estimated means show the highest visual fatigue for light setting 1 (i.e., formed only with direct light), followed by light setting 5 (i.e., formed only with indirect light). It should be noted that light setting 4 resulted in a negative estimated mean value, which indicates that the level of visual fatigue decreased along the experimental session.

Table 14: Estimated mean, standard error and confidence interval of the difference in accommodation facility before and after the experimental session (representing visual fatigue) for each of the light settings

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>1.28</td>
<td>0.37</td>
<td>0.54 2.02</td>
</tr>
<tr>
<td>LS2</td>
<td>0.73</td>
<td>0.38</td>
<td>-0.02 1.48</td>
</tr>
<tr>
<td>LS3</td>
<td>0.44</td>
<td>0.37</td>
<td>-0.29 1.18</td>
</tr>
<tr>
<td>LS4</td>
<td>-0.42</td>
<td>0.38</td>
<td>-1.17 0.33</td>
</tr>
<tr>
<td>LS5</td>
<td>1.04</td>
<td>0.37</td>
<td>0.30 1.77</td>
</tr>
</tbody>
</table>

A contrast analysis was used to further explore the differences in visual fatigue between the different light settings. For an easier interpretation, a graphical display of the scores in visual fatigue is given in figure 18. The contrast analysis showed two important results from all pairwise comparisons between the light settings. First, light setting 1 and light setting 4 were observed to be significantly different (p=0.004); the average accommodation facility in light setting 1 decreased by 1.7±0.46 cpm more than light setting 4. Second, the change in accommodation facility was significantly different between light setting 5 and light setting 4 (p=0.025). Light setting 5 was observed to decrease the
accommodation facility by $1.46\pm0.47$ cpm more than light setting 4. Altogether, light setting 4 showed the lowest visual fatigue.

![Accommodation facility](image)

**Figure 18**: Boxplots of the estimated visual fatigue (determined by means of the accommodation facility) for every light setting.

### 3.2.2. VISUAL ACUITY

The difference in visual acuity before and after fatigue induction resulted in small negative values (mean = $-0.057$ arcmin, SE = 0.02, as expressed in angular size of the optotypes), indicating a small decrease in visual fatigue by the end of the session. The magnitude of this difference in visual acuity is very small compared to the angle of the optotypes used for the test, which varied from 1.078 to 5.39 arcmin. As such, these small scores indicated a null effect of fatigue inducted on the visual acuity.

The linear mixed model analysis also showed no effect of light setting on the level of asthenopia ($F(4,105.47) = 1.05$, $p = 0.384$). The latter conclusion could be expected from the small values of the visual acuity differences. The estimated means in visual acuity difference for each light setting are summarized in table 15, and for comparison purposes, a graphical representation of the differences in visual acuity are also illustrated in figure 19.

**Table 15**: Estimated mean, standard error and confidence interval of the difference in visual acuity before and after the experimental session (representing visual fatigue) for each of the light settings.

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>-0.12</td>
<td>0.05</td>
<td>-0.23 to -0.02</td>
</tr>
<tr>
<td>LS2</td>
<td>-0.09</td>
<td>0.05</td>
<td>-0.19 to 0.02</td>
</tr>
<tr>
<td>LS3</td>
<td>0.01</td>
<td>0.05</td>
<td>-0.09 to 0.12</td>
</tr>
<tr>
<td>LS4</td>
<td>-0.06</td>
<td>0.05</td>
<td>-0.16 to 0.05</td>
</tr>
<tr>
<td>LS5</td>
<td>-0.02</td>
<td>0.06</td>
<td>-0.13 to 0.09</td>
</tr>
</tbody>
</table>
3.2.3. VISUAL DISCOMFORT

The only measurement of visual discomfort was done using the HES questionnaire; obtained (as explained before) from average of different elements of visual discomfort. In general, these scores showed small increases at the end of each session (mean=0.55, SE = 0.07). The difference in scores between the start and end of each session varied half a point of the original 7-point scale, making it a rather large difference. The linear mixed model analysis also showed a significant effect of light setting on the difference in visual discomfort score (F(4,111.12) = 3.88, p = 0.006). When adding the control variables session, day, age and gender to the model, several interesting effects were observed. First of all, the effect of light setting on visual discomfort remained significant (F(4,111.64) = 3.68, p = 0.007). Furthermore, with this full model, also the variable session (i.e., the dichotomous variable making a distinction between the morning and the afternoon sessions) had a statistically significant effect on the change in scores of visual discomfort (F(1,129.72) = 14, p < 0.001). A summary of the related estimated means (including standard error and confidence interval) is presented in table 16 and 17.

Table 16: Estimated mean, standard error and confidence interval of the difference in visual discomfort before and after the experimental session for each of the light settings.

<table>
<thead>
<tr>
<th>Light Setting</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1</td>
<td>0.38</td>
<td>0.14</td>
<td>0.10 – 0.65</td>
</tr>
<tr>
<td>LS2</td>
<td>0.63</td>
<td>0.14</td>
<td>0.36 – 0.91</td>
</tr>
<tr>
<td>LS3</td>
<td>0.38</td>
<td>0.14</td>
<td>0.10 – 0.65</td>
</tr>
<tr>
<td>LS4</td>
<td>0.47</td>
<td>0.14</td>
<td>0.20 – 0.75</td>
</tr>
<tr>
<td>LS5</td>
<td>0.97</td>
<td>0.14</td>
<td>0.69 – 1.24</td>
</tr>
</tbody>
</table>
Table 17: Estimated mean, standard error and confidence interval of the difference in visual discomfort before and after the experimental session for session in the morning compared to sessions in the afternoon

<table>
<thead>
<tr>
<th>Session of the Day</th>
<th>Estimated Mean</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>0.78</td>
<td>0.09</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>Midday</td>
<td>0.35</td>
<td>0.09</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.53</td>
</tr>
</tbody>
</table>

A contrast analysis was used to explore in which way the independent variables light setting and session affected the change in score of visual discomfort. First, and most interestingly, the contrast analysis was applied for the different light settings. A graphical representation of the difference in score of visual discomfort per light setting is given in figure 20. This graph shows the largest change in visual discomfort for light setting 5 (i.e., formed only with indirect light); for this light setting visual discomfort increased with almost one point on the original 7-point scale. The contrast analysis showed a significant difference between some levels of the light settings. Light setting 5 was significantly different from light setting 1 (p=0.029) and light setting 3 (p=0.02) in terms of increase in visual discomfort. Light setting 5 showed to be 0.59±0.2 points more uncomfortable than light setting 1, and 0.59±0.19 points more uncomfortable than light setting 3. Further, light setting 5 also showed a trend towards significance when compared to light setting 4 (p=0.054), where light setting 5 was 0.5±0.18 points more uncomfortable than light setting 4.

![Visual discomfort graph](image)

**Figure 20:** Boxplots of the estimated change in visual discomfort for every light setting. Different colors indicate different significance levels.

Second, the effect of the variable session on the change in visual discomfort was further evaluated. The difference in scores in visual discomfort showed that participants evaluated a larger visual fatigue along an experimental session in the morning compared to an experimental session in the afternoon. The morning sessions showed on average an increase in visual discomfort that was 0.44±0.12 points larger (again on the 7-point scale) as compared to the increase in visual discomfort for the afternoon sessions. The graphical representation of the effect of session on the change in visual discomfort is illustrated in figure 21.
Figure 21: Boxplots of the estimated change in visual discomfort comparing the time of the day when the experiment took place. Different colors indicate different significance levels.
4. DISCUSSION

4.1. SUMMARY OF THE FINDINGS

The goal of this study was to explore whether the ratio of direct and indirect light could create bright illuminated environments while controlling the negative effects of bright light. The research was based on three hypotheses: (1) are the brightness, comfort and acceptability of the light perceived to be different for different ratios of direct and indirect light?, (2) does the development of visual fatigue and visual discomfort differ between different ratios of direct and indirect light?, and (3) is there a correlation between the scores of visual discomfort and visual fatigue for the different ratios of direct and indirect light?. Using empirical research, the three hypotheses were addressed by varying the ratio of light emitted from floating luminaires that could emit light downwards and upwards while keeping the vertical illuminance on the working area fixed. The perception of brightness, comfort and acceptability, and the level of asthenopia, represented by visual discomfort and visual fatigue, were measured for the different ratios of downward and upward light.

4.1.1. FINDINGS ON APPRAISAL OF LIGHT

The appraisal of light was acquired separately for different zones of the room; namely, room in general, ceiling and luminaires. The room in general was perceived as comfortably illuminated, since participants evaluated the comfort in the room with a high grade, independent of the ratio of direct and indirect light. Hence, the light ratio does not seem to have an effect on the general impression of comfort in the room.

The brightness of the light emitting area of the luminaires was perceived highest for the light setting with only direct light and lowest for the light setting with only indirect light. This response corresponded very well to the physical measurements of the light settings, yielding the highest luminance emitted by the luminaires when all light was emitted downwards. Further, the light from the luminaires was perceived as slightly comfortable and well acceptable, again independent of the ratio of direct and indirect light. Hence, these results suggest that the ratio of direct and indirect light only affects the perceived brightness of the luminaires, but not the comfort and acceptability, at least not within the range of luminance of the luminaires used.

Finally, the perception of brightness of the ceiling did not entirely follow the physical luminance measurements of the zones above the floating luminaires, for which the luminance increased continuously with higher contributions of indirect light. The lowest score for brightness was given for the light setting formed by only direct light; as the light settings included more indirect light, the perception of brightness on the ceiling reached a maximum level (i.e., at the light setting formed by 50% direct and 50% indirect light), after which it started to decrease. Eventually, the light setting formed only by indirect light was perceived as having the second lowest brightness. The perceived comfort of the light on the ceiling was evaluated significantly different for the different light settings. The light setting formed with only direct light was perceived least comfortable. When adding some indirect light (i.e., 75% direct, 25% indirect), the comfort of the light of the ceiling increased; but for higher contributions of indirect light, the perception of comfort decreased. The setting with only indirect light was evaluated with the second lowest score on comfort of the light.

From this summary we may conclude that the findings regarding the ceiling of the room show a clear similarity between perceived brightness and perceived comfort of the light. Both measurements have their lowest score for the light setting formed by only direct light, and have their maximum score at an intermediate contribution of indirect light. Beyond this point, the scores on perceived brightness and comfort start decreasing again. These findings lead to two conclusions for the light at the ceiling: first, perceived comfort is affected by perceived brightness for the light at the ceiling. Second, the ratio of direct and indirect light has an impact on the perception of brightness and comfort, yielding the lowest appreciation of brightness and comfort for light at the ceiling generated by light sources in only one direction (i.e., only direct or only indirect light). Hence, our first hypothesis can only be partly accepted, i.e., referring to the perceived brightness and comfort only of the light from the ceiling.
4.1.2. FINDINGS ON ASTHENOPIA

In this study asthenopia was measured objectively (i.e., accommodation facility and visual acuity) and subjectively (i.e., visual discomfort questionnaire). Accommodation facility showed a general decrease of about half a cycle per minute during the experimental sessions. This decrease depended on the light setting; the highest level of visual fatigue was measured for the light setting formed by only direct light. By increasing the contribution of indirect light, visual fatigue decreased, reaching the lowest level (i.e., 1.5 cycles per minute higher than the minimum) for the light setting formed by 25% direct and 75% indirect light. The light setting formed by only indirect light, again, created substantial visual fatigue. Hence, the trend in visual fatigue follows a subtle U-shape, similar to the perceived brightness and comfort of the light at the ceiling. This finding suggests that the perception of comfort of the light from the ceiling may be a good predictor for visual fatigue; as measured by accommodation facility.

Visual acuity showed a general increase of 0.057 arcmin during the experimental sessions. Compared to the nominal corrected vision of 5 arcmin, the difference in visual acuity over the experimental sessions is very small. Evidently, this small difference in visual acuity was not significantly affected by the light settings used in this study. The small difference in visual acuity during the experimental sessions suggests that the visual fatigue induction tasks were not fatiguing enough to change the visual acuity of the participants. Hence, when comparing both measures of visual fatigue we may conclude that accommodation facility is more sensitive in measuring differences in ratio of direct and indirect light than visual acuity.

Finally, asthenopia was also measured with a questionnaire on visual discomfort. Its results showed that participants on average increased their score with half a point (on a 7-points scale) during the experimental sessions. More interestingly, this difference was significantly affected by the light setting. The largest score of visual discomfort was measured for the light setting formed by only indirect light. On the contrary, light settings formed by a mixture of direct and indirect light resulted in the smallest visual discomfort. Surprisingly, also the light setting formed with only direct light created a low level of visual discomfort. Based on these findings, we may accept hypothesis 2.

The subjective scores on visual discomfort had a peculiar relation with their objective counterparts, particularly considering accommodation facility. Both measures agree that light settings formed by a combination of direct and indirect light result in the lowest levels of asthenopia, while the light setting formed by only indirect light result in the highest level of asthenopia. Both measures don’t agree for the light setting formed by only direct light; accommodation facility reports substantial visual fatigue (in line with the low perceived comfort of the light at the ceiling), whereas the HES reports low levels of visual discomfort. Hence, hypothesis 3 cannot be accepted. This discrepancy prevents a straightforward interpretation of the results, since we do not have a clear explanation for this inconsistency in our findings apart from the fact that common office environments are formed with only direct light, and therefore, adaptation to this common situation may have affected the judgments of visual discomfort.

4.2. RELATION OF FINDINGS TO PREVIOUS RESEARCH

This section relates our findings to studies in literature that created light environments with direct and indirect light (i.e., Houser et al., 2002; Geerdinck, 2012; Boyce et al., 2006). In order to make an accurate comparison, this section first presents a comparison of the lighting systems used in the current study and similar studies in literature. To facilitate the discussion, this section then describes the similarities between the results of the current study and those of previous literature. Finally, this section discusses the discrepancies between the results of the current study and those of previous literature.

4.2.1. LIGHTING SYSTEM COMPARISON

Since the particular findings may be largely affected by the specific implementation of direct and indirect light, we first report the various techniques used in literature to create the light system. As previously described, the lighting system
of the current study used floating luminaires that were hanging from the ceiling. As a consequence, there was a very noticeable distinction between the luminance of the luminaires and the luminance of the ceiling between the five light settings used. Previous studies used different methods to adjust the contribution of upwards and downwards light. For instance, Geerdinck (2012) used a lighting system mounted in the ceiling and added mobile luminaires that were pointed towards the ceiling to generate indirect light (see figure 22a). A similar approach was used by Boyce and colleagues (2006); in their study the luminaires that emitted direct light were mounted in the ceiling, and they added floating luminaires for the indirect light (see figure 22b). Houser and colleagues (2002), on the other hand, created an environment with floating luminaires that were capable of emitting light upwards and downwards (see figure 22c), as in our study (see figure 22d).

![Image of lighting systems used in previous studies](image)

4.2.2. SIMILARITIES WITH PREVIOUS RESEARCH

In our study light appraisal only showed significant effects when considering the perception of the ceiling. In that case, the perceived brightness was lowest when only direct light was present. As the amount of indirect light increased, the perceived brightness also increased until it reached a presumably ‘saturation point’ where the perceived brightness remained constant regardless of the continuous increase of indirect light. This trend is very similar to what was found in the study of Houser and colleagues (2002). Since both studies used a very similar lighting system, though a largely different illuminance on the working area (i.e., 538 lux on the desk in the study of Houser et al., vs 700 lux on the vertical board with 1000 to 1500 lux on the desk in our study), the similarities in perceived brightness, including the observed saturation point, seem to be only caused by the ratio of direct and indirect light and independent of the absolute illuminance level.

The perceived light comfort of the ceiling as found in the current study has great similarities with trends found in previous studies. Similar to this study, the light setting formed with only direct light was perceived least comfortable in the study of Geerdinck (2012) and Boyce and colleagues (2006) (in the latter two studies, light comfort was measured for the luminaires while the luminaires were mounted in the ceiling). Light settings formed with a combination of direct and indirect light were perceived more comfortable in all studies. Finally, light comfort was slightly reduced for the light setting formed with only indirect light in our study and the one of Geerdinck (2012); Boyce and colleagues (2006) did not include this light setting in their study. In summary, these results suggest that light comfort can benefit from including indirect light regardless of the technique used to create that light.
Accommodation facility was used before in literature to measure visual fatigue (Chi & Lin, 1998); though, not in relation to the ratio of direct and indirect light. In the available studies accommodation facility showed a large spread. For instance, Zellers (1984) found that participants with normal vision had an accommodation facility of 7.7±5 cpm, whereas we measured accommodation facility of 10.11±4.6 and 9.5±4.7 cpm at the beginning and end of the experimental sessions respectively. Hence, the spread we measured is very similar to what was reported in literature. Regardless of this large spread, the effect of light ratio of direct and indirect light significantly affected accommodation facility, with the biggest difference between light settings being 1.5 cpm; implying a change of more than 10%. This finding shows that the effect of light ratio of direct and indirect light on visual fatigue is in line with the perceived light appraisal of the ceiling; suggesting that a combination of direct and indirect light is evaluated with the largest comfort and creates the lowest visual fatigue.

4.2.3. DISCREPANCIES WITH PREVIOUS RESEARCH

Acceptability of the brightness at the ceiling did not show significant differences among the different light settings in the current study. These results are in disagreement with previous findings in literature. Concretely, Geerdinck (2012) was able to measure an increase in acceptability as the amount of indirect light increased. This discrepancy is suspected to be caused by the big difference in design between the two studies. For instance, the study of Geerdinck (2012) presented each light setting to the participants for a small period of time, making it possible for participants to observe all the light settings in a single experimental session. On the contrary, the current study showed only one light setting per experimental session, but for a longer period of time. The ability to directly compare different light settings presumably allowed participants to create a more distinguishable perception of acceptability of the light in the different settings.

Visual acuity was not a useful objective measure of visual fatigue in the current study, since it only decreased around 0.03 points (expressed in the decimal scale of visual acuity, as used by Chi and Lin, 1998) during the experimental sessions. This decrease is particularly small when compared to the study of Chi and Lin (1998), who observed a decrease of visual acuity between .1 and .2. Both studies used a similar duration of fatigue induction (between 20 and 60 minutes), but differed substantially in illuminance level on the working area (i.e, 700 lux in our study versus 250 lux in the study of Chi and Lin, 1998). Based on the relative visual performance (RVP) model of Rea and Ouellette (1991), the high light level used in the current study had reached the saturation point of visual acuity, and so, may have prevented us from detecting possible differences in visual acuity.

4.3. LIMITATIONS OF STUDY

The results obtained from this study provide solid insights on how the ratio of direct and indirect light affects room appearance, visual fatigue, and the link between both of them. Nonetheless, the results should be interpreted cautiously considering the limitations of the current study. To start, the study took place in a very controlled laboratory environment, with limited ecological validity. This fact may limit the generalizability of the findings from this study to different rooms with different luminaires.

The results on light appraisal in this study were hard to compare to existing literature. The syntax of referring to different zones in the room was not directly translatable to the syntax of other studies (i.e., Geerdinck, 2012 and Houser and colleagues, 2002). Similarity in syntax is hard to achieve since previous studies used different layouts of the light system (i.e., mounted in the ceiling versus hanging from the ceiling). Similar results were found, but an accurate comparison cannot be entirely guaranteed.

In order to capture only the effect of light ratio of direct and indirect light, and avoid systematic biases, this study had a strict control on the luminance level in the working area. As a consequence, all the tasks were presented on paper (to keep the contrast between the task and the immediate background constant). Possibly, visual fatiguing tasks presented on visual display units (i.e., “monitoring task”, “reading task” and “tracking task”) may create more visual fatigue, as is
suggested by the study of Chi and Lin (1998). As a consequence, more visual fatiguuing tasks might be able to create bigger differences in visual fatigue for different ratios of direct and indirect light.

While in general our experimental design induced asthenopia on people, the effects remained modest. A longer period dedicated to induce asthenopia could provide larger effects on visual fatigue, thus amplifying the effect of different ratios of direct and indirect light. Longer periods (e.g., 60 min) of fatigue induction are feasible and have been already explored in literature (Chi & Lin, 1998). Further, the measurements of asthenopia did not all point in the same direction. Accommodation facility showed a response that was entirely in line with the expectations, but visual acuity did not show any effect of the fatigue inducing tasks, and so, also no effect of the ratio of direct versus indirect light. Finally, perceived visual discomfort showed scores roughly in line with the measured accommodation facility, thought the perceived visual discomfort for the light setting formed by only direct light was in disagreement with our expectations. Hence, the findings of this study are too limited to come to a clear conclusion.

4.4. SUGGESTIONS FOR FURTHER RESEARCH

To tackle several limitations of the study, it is suggested to further develop the findings observed in this study and explore them in an environment with larger ecological validity. In a nonintrusive experiment, for example in a real office environment, further research has the possibility to present tasks that more adequately resemble the everyday tasks of office workers. In addition, a real office environment would allow the light ratio to be perceived in the same way as office workers currently experience everyday lighting systems. Finally, the office environment would allow the experiment to extend the manipulation time (i.e., a full day of work); this might enhance the possible effects of light ratio on the levels of asthenopia.

Further, measurement of light appraisal could benefit from a standardized description of the different zones of a room. A clear description of what each zone represents delimits the evaluated area, and makes measures of such areas more specific. A similar description has been used by Houser and colleagues (2002) in order to describe what was expected to be evaluated when grading different parameters of light (i.e., brightness, visual comfort, spaciousness, etc.). If participants are aware and understand what the specific zone to be evaluated is, the results acquire better comparability among different studies.

Finally, it is suggested to explore the range of lower light levels on further studies on asthenopia. The current experiment opted for higher levels as a first attempt to increase the possibility of capturing an effect on asthenopia merely caused by the difference in ratio of direct and indirect light. As a consequence, the light levels used in this study were well above the minimum light levels required for office environments; this may have prevented measuring changes in visual acuity.

4.5. CONCLUSIONS

A Balanced Incomplete Block Design was used to explore the effects of light ratio of direct and indirect light on light appraisal and asthenopia; the former measured by means of the perception of brightness, comfort and acceptability and the latter by means of the accommodation facility, visual acuity and the Headache and Eyestrain Scale (HES). As expected, the ratio of direct and indirect light was observed to have an effect on the appraisal of light and on asthenopia of people. Remarkably, different zones of the room were perceived with different light appraisal. Light ratios formed by a combination of direct and indirect light (with contribution of indirect light between 25% and 75% of the total light) created the most beneficial effects of light on people; they were perceived with the greatest brightness and comfort, and induced the lowest visual fatigue and visual discomfort. The light setting formed with only indirect light induced the greatest visual discomfort and visual fatigue. Finally, the light setting formed only with direct light was perceived with the lowest brightness and comfort and, in turn, generated the greatest visual fatigue; as measured by the accommodation facility.
REFERENCES


APPENDICES:

APPENDIX 1: HEADACHE AND EYE STRAIN SCALE (HES)

This is the entire set of questions used in this study for the HES:

In this moment:

... my eyes feel **tired**:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

... my eyes are **dry**:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

... my eyes are **irritated or burning**:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

... I have eye **pain**:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

... it is **hard to focus** my vision:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>
... I have **double vision** on objects:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

... I have **flicker vision** (blinking fast):

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

... I have a **headache**:

<table>
<thead>
<tr>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Slightly disagree</th>
<th>Not Agree, Not disagree</th>
<th>Slightly agree</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>