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MASTER

The acute alerting effects of light during daytime

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Eindhoven, August 2016

The Acute Alerting Effects of Light During Daytime

by S.T. Peeters

identity number 0722883

in partial fulfilment of the requirements for the degree of

Master of Science
in Human Technology Interaction

Supervisors:
dr. ir. K.C.H.J. Smolders
prof. dr. ir. Y.A.W. de Kort

PREFACE

This thesis is my final part for the Master Human Technology Interaction at the Eindhoven University of Technology. In 2009 I started studying the Bachelor Industrial Design here in Eindhoven, which I completed in 2013. I have always liked the human centered approach at Industrial Design, but wanted to focus more on the background and research behind it. So in September 2013 I started with the pre-master program at Human Technology Interaction and continued with the Master itself.

Throughout my Bachelor I had done several projects involving light, however during my Master I hadn't done much work involving light. That's why I really wanted to work on the subject for my thesis. Luckily I was able to find this great project supervised by Karin Smolders and Yvonne de Kort. I have genuinely enjoyed working on the project, throughout the whole process. It has been challenging at times, but I was always happy when we got through it and were able to move on to the next step in the project. For me it was the first time to perform such a big experiment that was highly structured and used multiple measurements before and during the experiment. It was a big challenge, but I truly enjoyed performing the experiment. Thank you Karin and Yvonne, for your enthusiastic and helpful supervising throughout the project, I really liked working together.

Furthermore I would like to thank Wout van Bommel for all his help with setting up the lab for the experiment and Laura Huiberts, for providing me with help and advice to analyze the data.
Thank you John, Antoinette and Ashley, my dear parents and sister, who have always supported me throughout my whole study in Eindhoven. Thank you my dear Jasper, who has always supported me and helped me whenever needed.

ABSTRACT

In this thesis the acute alerting effects of light have been investigated during daytime. In literature, a large amount of research has been conducted towards the acute alerting effects of light. However, often these studies are performed during nighttime, when stronger effects are already expected. Additionally, most of these experiments either use a limited amount of light levels (often only two or three) or have highly controlled conditions. Therefore, in this thesis, the acute alerting effects of light intensity on alertness and arousal are investigated during daytime, employing a large range of illuminance levels (20-2000 lux). One of the main objectives is to investigate if it is possible to create a dose-response curve for daytime light exposure, similar to the dose-response curve for nighttime. A realistic setting was created, where participants come in during daytime. The results showed no significant main effects or interaction effects for the effect light on subjective and objective indicators of alertness. The results suggest that the dose-response curve for nighttime can't simply be translated one-to-one to for daytime situations and it might be necessary to use personally tuned lighting systems. Future studies are necessary to learn more about the non-image forming effects of light, and how these could eventually contribute to intelligent lighting systems for example in offices and schools.

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1. INTRODUCTION

Light is an integral part of our everyday life, light is almost always present. The moments that it is completely dark are rare. In the past, when there was no artificial light, humans got up during sunrise and stopped being active at sundown. But nowadays with electric light, light can be produced whenever required. During the day and in the evening when it gets dark outside, we switch on the lights and look at the screens of our televisions, laptops and phones. Light during the day and night, has a great influence on us, something we are not always aware of.

Humans are a diurnal species, meaning that they are active during daytime and inactive during the night. This activity-rest cycle is controlled by the circadian system, for which light is an important Zeitgeber or time cue. But light doesn't only influence the sleep-wake cycle. It has the ability to influence our well-being, health and performance, through two different pathways: the image forming pathway and the non-image forming pathway. Figure 1 provides an overview of the two different pathways.

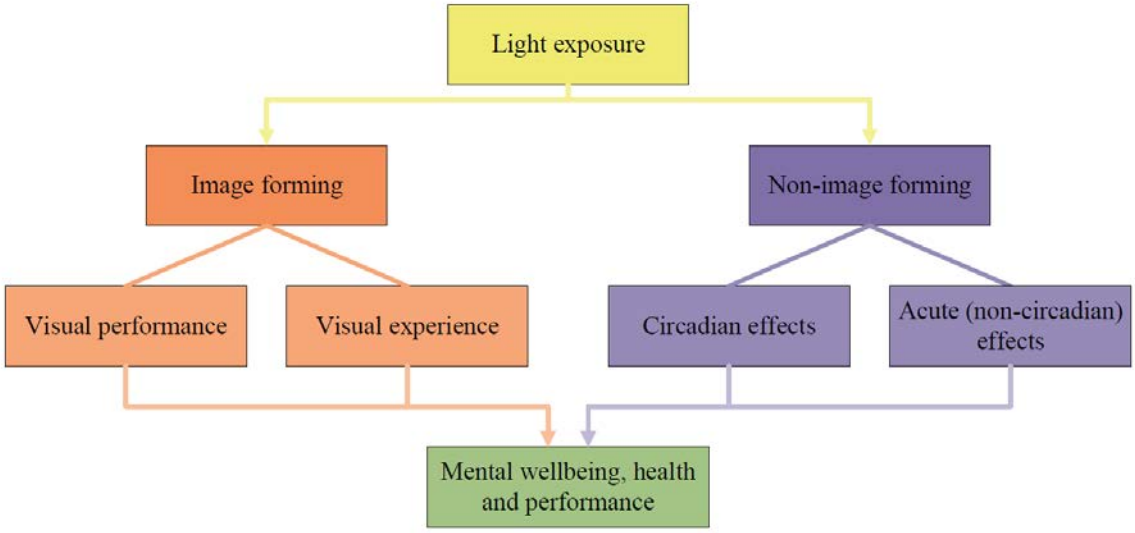


Figure 1.1. The pathways through which light can impact human functioning (Source: Smolders, 2013)

The process starts with the initial light exposure at the eye, after which there are the two pathways: image forming and non-image forming. The image forming pathway is used for conventional vision where the rods and cones, which are found in the outer layer of the retina, are particularly involved with processing the light and forming an image. The image forming pathway influences both the visual performance and visual experience. Visual performance

means being able to see a visual task properly, such as reading a book. Visual experience refers to how the lighting or environment is evaluated, about creating an ambience, and involves light appraisals (finding the light warm/cold, pleasant/unpleasant). People might use a certain light setting in their room when they want to relax, and another when they want to concentrate on a task. Both visual performance and visual experience contribute to our mental wellbeing, health and performance.

The second pathway is the non-image forming pathway. In the non-image forming pathway, the recently discovered intrinsically photosensitive retinal ganglion cells (ipRGCs) are particularly involved in processing light (Berson, 2002). The ipRGCs are located in the inner layer of the retina and, together with the rods and cones, receive information about the light which falls upon the eyes. This information is projected to the suprachiasmatic nucleus (SCN), which is the main circadian clock. Through this mechanism, the circadian system can be influenced by the light/dark cycle and artificial light. A circadian rhythm is a biological process which is about 24 hours, and comes from the Latin words Circa and Dies, meaning about and day, hence about a day. The non-image forming pathway can cause a circadian effect. Light can modify the phase of the system that synchronizes circadian rhythms in humans. Light is used to entrain the circadian rhythm to environmental demands and makes sure that, when entrained to the natural light/dark cycle, we are awake during daytime and sleep during nighttime. A circadian effect caused by light is phase shifting, due to the influence of the light/dark cycle or artificial light on our sleep/wake rhythm. This is important because our circadian rhythm is about 24 hours, so it needs to be entrained every day to make sure we don't become desynchronized. For example, when traveling to a different time zone, the circadian clock and the light-darkness rhythm are not synchronized. This leads to a jetlag, which is a temporary effect. Another well-known example of external desynchronization is shift work. Shift workers often work during the night and sleep during daytime, causing their internal clock and external light/dark cycle to be desynchronized. Such circadian effects can influence our well-being as well as our performance.

Other effects of the non-image forming pathway are the acute (non-circadian) effects. These acute effects have the ability to influence alertness, vitality and performance during the actual light exposure. These acute effects will be the focus in this study. In the current study we want to investigate at what light intensities such acute alerting effects occur during daytime. To do so, we aim to establish dose-response curves for different indicators of alertness by assessing the diurnal effect of a large range of light intensities on subjective alertness and vitality, task

performance and physiological arousal. Such dose-response curves will describe the magnitude of the effect of different light intensities on different indicators of alertness during daytime.

A large amount of studies have been conducted, investigating the acute effects of light. Most of these studies have been conducted during nighttime. At night, homeostatic sleep pressure (process S) is generally high and the circadian drive for arousal (process C) is low as illustrated in Figure 1.2. When the circadian drive for arousal is low and sleep pressure is high, this often coincides with the start of melatonin production. The start of the melatonin production is influenced by the biological clock.

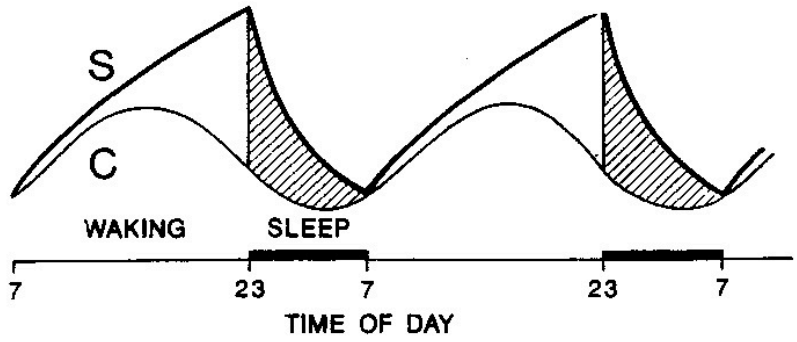


Figure 1.2. S stands for sleep pressure, C stands for circadian drive for arousal (both represented on the y axis). (Source: Borbely & Achermann, 1999)

Most of the studies where acute alerting effects have been found, have been performed during nighttime. Badia, Myers, Boecker, Culpepper and Harsh (1991), for example, compared 5000 lux vs 50 lux and found bright light effects on several indicators of alertness and arousal. Cajochen, Krauchi, Danilenko and Wirz-Justice (1998) investigated a combination of administrated melatonin and bright light (5000 lux) and found acute effects of bright light on subjective sleepiness compared to a placebo group without bright light. Campbell and Dawson (1990) studied the acute effects of light during simulated night shifts using three lighting conditions (10-20 lux, 100 lux and 1000 lux). Their results revealed that participants in the 1000 lux condition maintain higher alertness during their night shift. Foret, Daurat, Touitou. Aguirre and Benoit (1996) exposed participants to 100 lux or 1000 lux in the night. They found that exposure to 1000 lux suppresses melatonin and improves alertness.

In addition to these studies testing acute effects of light intensity on alertness and arousal, generally employing a limited set of lighting conditions (often two or three), the most relevant research for this thesis is the study by Cajochen, Zeitzer, Czeisler and Dijk (2000), providing

insights in the dose-response relationship between light intensity and various indicators of alertness. This study was performed during the biological night. In total they had 23 participants, who were exposed to a single illuminance level for 6.5 hours. The illuminance range they used was 3- 9100 lux. During the light exposure, participants were required to remain seated and alternate their gaze between a fixed spot on the wall and a free gaze for 6 minutes every hour (to assess EEG during Karolinska drowsiness test protocol). At 30 minute intervals, participants reported on their subjective sleepiness by means of the Karolinska Sleepiness Scale. Before and after the 6.5 hours of light exposure, participants were exposed to an illuminance of about 3 lux for 4.75 hours. Prior to the study, participants had to keep up with their habitual sleeping pattern for 2 weeks before entering the laboratory and underwent a constant routine of about 50 hours in the lab, followed by a recovery night of 8 hours. In this study, Cajochen et al. (2000) found effects for a reduction in slow-eye movements (SEMs), a reduction of the EEG activity in the theta-alpha range and a reduction in self-reported sleepiness, as can be seen in Figure 1.3. For the analysis, the illuminance range was divided into three groups; low, middle and high intensity. All indicating an acute alerting effect of light. When plotting the data for each intensity level separately, it is consistent with a logistic dose-response curve as shown in Figure 1.4.

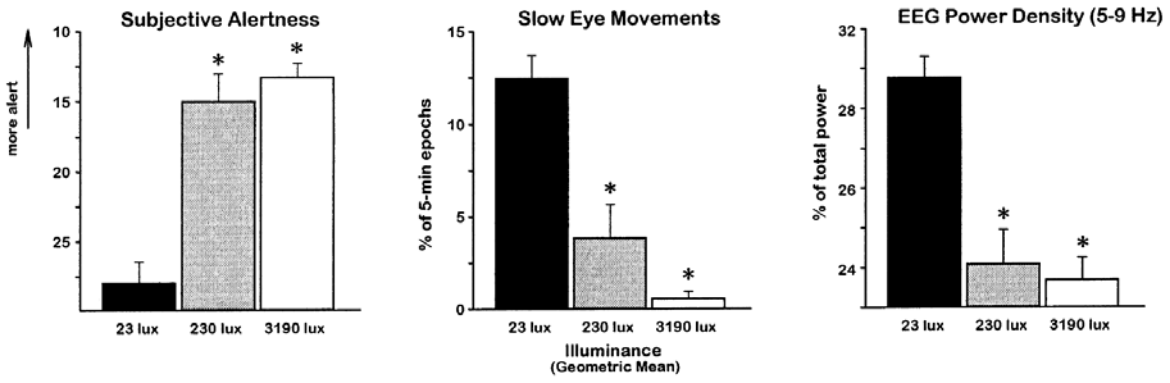


Figure 1.3. Illuminance dependent effects for low, middle and high intensity light groups on subjective alertness, slow eye movements and EEG power density in the theta-alpha range. (Source: Cajochen et al, 2000)

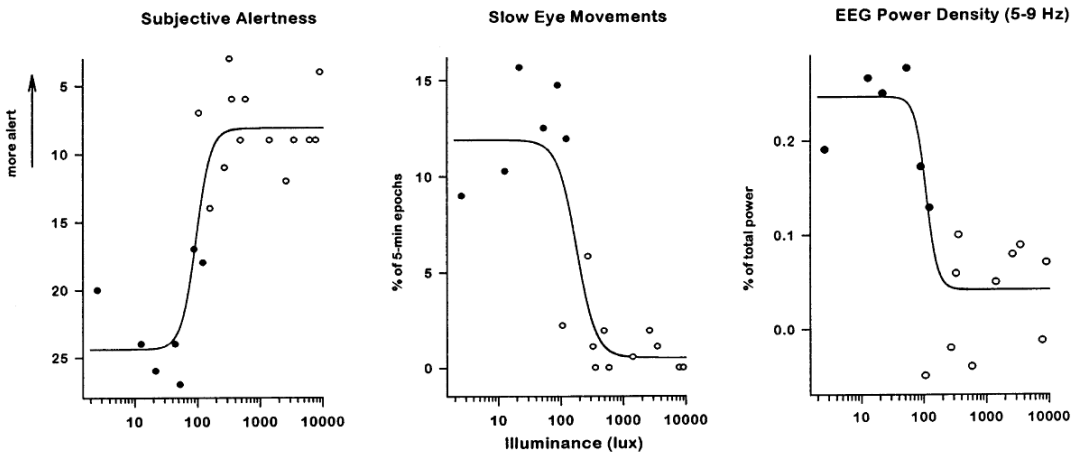


Figure 1.4. Dose-response relationship between illuminance and subjective alertness, slow eye movements and EEG power density in the theta-alpha range. (Source: Cajochen et al, 2000)

Investigating the curve for subjective alertness, it becomes evident that about 50% of the maximum alerting effect is already reached at 100 lux (at the eye). This suggests that light intensity and subjective alertness happen in a dose-responsive manner at night, and relatively low intensity levels can induce an alerting effect.

It is, however, still unclear what such a dose-response relationship would look like during daytime. Most of the research performed towards the acute (non-circadian) effects have been conducted at night, because this is where you would expect the strongest effects. Furthermore at night melatonin possibly is an underlying mechanism in the acute alerting effects of light. Melatonin itself is a very robust and sensitive biomarker, showing the effects of light exposure very clearly.

There are several studies which have been performed during the day, investigating the acute alerting effects of light. For example, the study performed by Phipps-Nelson, Rednam, Dijk and Rajaratman (2003) investigated the effects of bright light during daytime. They used two light conditions: bright light (1000 lux) and dim light (<5 lux). In the bright light condition, participants were exposed to 1000 lux from 12.00-17.00. From 09.00-12.00 and 17.00-21.00 they were exposed to <5 lux. The control group was exposed to <5 lux from 09.00-21.00. The participants were allowed to sleep from 01.00-06.00 for two nights prior to the laboratory session, in order to increase the baseline daytime sleepiness levels. The measurements they used were: subjective sleepiness, psychomotor vigilance task (PVT), incidence SEMs and salivary melatonin levels. Compared with the baseline, effects of bright light were found for subjective sleepiness, PVT and SEMs, as shown in Figure 1.5. The graphs show that bright light decreased

the subjective sleepiness, improved performance on the PVT and reduced the occurrence of SEMs. These results indicate an acute alerting effect of bright light during daytime.

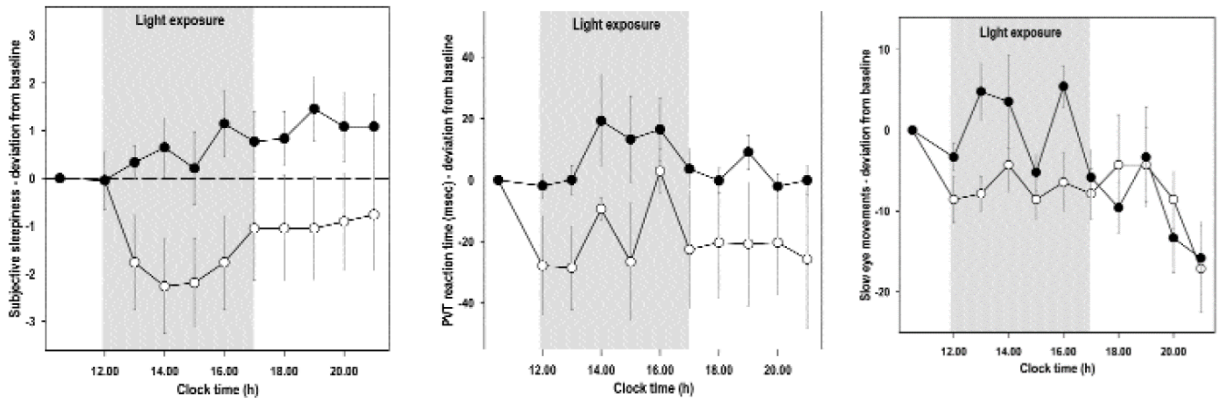


Figure 1.5. Graph 1 is subjective sleepiness, graph 2 is PVT reaction time, and graph 3 is SEMs. The open dots are the bright light condition, the black dots are the dim light condition. (Source: Phipps-Nelson, 2003)

Another example of a daytime study, is the study by Smolders and de Kort (2014). In this study 1000 lux vs 200 lux (at the eye) was used during daytime. The results show that participants were less sleepy, more vital and happier in the 1000 lux condition. Rüger, Gordijn, Beersma, de Vries and Daan (2005) compared bright light (5000 lux) with dim light (<10 lux) during daytime and nighttime. They found significant effects for sleepiness, fatigue and energy, which differed for daytime and nighttime. Huiberts, Smolders and de Kort (2015) looked at the effect of bright light on working memory performance and if this was dependent on task difficulty and time of day. They used 200 lux vs 1000 lux at eye level in two 60-min sessions. The study shows that variables such as the difficulty of a task and time of day can influence the effects of light and are variables to take into account in future studies. Smolders & de Kort (2012) also investigated the effect of 1000 lx vs 200 lux at eye level, and their results indicated that a higher illuminance induces alertness during office hours. For the PVT they found delayed effects. Another study by Vandewalle et al. (2006) compared <0.01 lux against >7000 lux, 5 hours after wake-up time and it was shown that bright white light during daytime affects brain functions and has an alerting effect compared to darkness, shown by fMRI.

The aforementioned studies, show us that acute alerting effects of light occur both during daytime and nighttime, though during nighttime the effects are often stronger. However, most of the studies use a limited intensity range or highly controlled conditions. A lot of the studies compared two or three illuminance levels to each other. But when doing so, it is not possible to

know what happens in between those levels. This makes it difficult to tell where the acute alerting effects will occur, e.g., is it really necessary to use 1000 lux or will a lower illuminance do as well? In some studies they used highly controlled conditions and some used a constant routine. For example participants were placed in darkness beforehand or sleepiness/fatigue was induced. These circumstances are not a good representation for day to day situations. It is unknown if the acute alerting effects still occur when participants are not fatigued or placed in the dark. A translation to realistic daytime situations is necessary and will be the focus of this thesis.

There are indications from the aforementioned studies that yes, bright light can have an alerting effect during daytime. It is however unclear which illuminance and setting would be most suitable to achieve acute alerting effects during the day. It is important and crucial information to have in order to design intelligent lighting systems and apply it to a realistic daytime situation.

Therefore, in the current study, we want to investigate the acute alerting effects of light intensity on alertness and arousal during daytime, employing a large range of illuminance levels. One of our main objectives is to investigate if it is possible to create a dose-response curve for daytime light exposure, similar to the dose-response for nighttime by Cajochen et al. (2000). We want to create a realistic setting, where participants will come in during daytime. These results could potentially be used for the design of intelligent lighting systems to support individuals. This leads to the following research question for this thesis:

What is the optimal light intensity to induce non-image forming acute effects of white light during the day in terms of subjective and objective indicators of alertness and vitality?

To answer this question, we designed an experiment to investigate the effects of a varied range of light intensities on both subjective and objective indicators of alertness and vitality during daytime. By using a range of light levels, the current study will provide more insight into the potential non-linear relationships between various light intensities and alertness, and which light intensities are most suitable to implement.

The results of this study will contribute to the scientific knowledge about the effect of white light on alertness, vitality and performance during daytime. And potentially insights into suitable light intensities to support an individual in sustaining attention and performance on

cognitive tasks. The current study also provides a higher level of ecological validity than the aforementioned studies. Healthy participants, who are not exhausted beforehand, will come to the lab; it is a closer reflection of how they feel and behave in daily life.

2. METHOD

2.1 Experimental Design

In this study, participants were exposed to a single illuminance (manipulated between subjects) for 1 hour after an initial baseline exposure of 100 lux for 30 minutes. The illuminances ranged from 20-2000 lux (at the eye), of which each participant was exposed to a single illuminance. Per illuminance level, two participants were assigned. Both subjective (self-reports) and objective (performance and physiological) indicators for alertness and vitality were used. The timing of the light stimulus (morning vs afternoon) was manipulated within participants. Each participant was exposed to the same illuminance in the morning as in the afternoon (9:00/11.00 and 13.00/15.00) on two separate visits to the laboratory.

2.2 Participants

Thirty-eight Dutch speaking subjects participated in this study, of which 14 were male and 24 female (mean age 21, SD = 3.75, range 18 to 38). Each participant filled out a questionnaire regarding their Chronotype (mean Chronotype 4.55, SD = 1.12). Participants were randomly assigned to a lighting condition. The participants were compensated €30, - for participating.

Recruitment

A proposal was written for the experiment which was approved by the HTI Daily Management Board and the Ethical Review Board of the Eindhoven University of Technology. Participants were recruited by sending an email to participants in the J.F. Schouten School for User-System Interaction Research database. The selection criteria were Dutch speaking, healthy and between the age of 18 and 45. In the email the procedure was explained, including the distribution of materials beforehand.

2.3 Procedure

After participants registered for the experiment, they were sent an email to plan appointments for picking up the materials and a link to the Munich Chronotype Questionnaire (Zavada, Gordijn, Beersma, Daan, & Roenneberg, 2005). The participants who registered for the experiment, were invited to come to the Eindhoven University of Technology. Three days before the start of the experiment, participants had to pick up a lightlogger, Actiwatch and sleep diary. They received an explanation about the materials and how to use them, as well as an

explanation about the sessions in the lab. Additionally they received a flyer with the information about the materials. After the explanation, the participants were asked to sign the informed consent form. After wearing the lightlogger, actiwatch and completing the sleep diary for three consecutive days, participants came to the Vertigo building located on the campus of the Eindhoven University of Technology. Here they took part in a 90 minutes session in the lab. At the start of the experiment, participants had to register their participation in the Archie system on a laptop. The participants were told they would perform 3 different tasks, with a questionnaire after each 3 tasks. First participants had to attach the sensors for the physiological measurements through the use of an instruction sheet. After attaching the sensors, the participants were asked to wear the headphones, read the explanations on the laptop and start the trial tasks. After the trial versions of the different performance tasks, the participants had the opportunity to ask questions. After this, the actual experiment started, which lasted 75 minutes. A complete session lasted 90 minutes. After the first session, the second sessions was confirmed with the participant and arrangements were made for the actiwatch, sleep diary and lightlogger: when do they need to pick up the materials and when do they have to wear it. At the end of Session 2, participants were thanked for their participation, debriefed and were paid €30,-. They signed a list, confirming they had received the compensation.

2.4 Apparatus / Materials

Setting

The experiment was conducted at the Eindhoven University of Technology in a light lab in the Vertigo building. The dimensions of the lab are 3.60 m x 4.80 m. In the room there were surface-mounted Philips Strato luminaires (Philips TPH710). There are 11 luminaires located on the sides and 12 on the ceiling, each luminaire measured 1.20 m x 1.20 m. To accommodate the room for our experiment, white divider walls were placed to create two separate cabinets with a surface-mounted light panel in the gazing direction of the participants.

Cabinets

In total, two cabinets were created. Per session it was possible for two participants to participate at the same time, each seated in a cabinet. The dimension of the cabinets were 1.20 m x 2.50 m. At the end of each cabinet there was a small desk (55 cm x 40 cm) with a laptop, mouse, headphones and Mobi8, placed 55 centimeters from the light panel on the wall. The setup is shown in Figures 2.1, 2.2 and 2.3.

Figure 2.1. Setup in cabinet, participant wearing headphones

Figure 2.2. Cabinet with the lightpanel, table, laptop, headphones, mouse and Mobi8

Figure 2.3. The two cabinets in the light lab on the left and right side of the room

Light Panels

As mentioned before, the light panels are 1.20 m x 1.20 m in size. With the current placing of the desks, a light intensity range from 100 – 2000 lux with a correlated colour temperature (CCT) of around 4000 Kelvin can be administered. For the 20 – 100 lux range, a neutral density filter was used, which will be explained in more detail later. Each light panel contained six fluorescent tubes of 28W, of which three tubes of 2700K (TL5-28W/827) and three tubes of 6500K (TL5-28W/865). Each light panel has a translucent cover with an integrated diffuser which blends the two lamp types and creates a homogeneous luminous surface.

Light range and calibration

For the current study we used a 20 – 2000 lux (at eye level) light intensity range with a CCT of 4000 K, of which 100 lux (at the eye) is the baseline. To determine the levels for each light condition in the 20-2000 lux range we used a logarithmic distribution. For the experiment we expect a non-linear logarithmic relationship between the logarithmic light intensity and the subjective and objective indicators of alertness. In the study by Cajochen et al (2000), half of the maximal alerting effect of light was measured around 100 lux and saturation was reached around 500 lux. However, because we perform our experiment during daytime, we expect these points to be at a higher illuminance level. Our range is from 20-2000 lux, but we don't want too many levels at the low illuminances (<100 lux) nor too many towards the end at the very high illuminances as the largest differences would, based on the results by Cajochen et al. (2000), be expected in the middle of the range. Although it is difficult to tell, the alerting effects are expected to occur somewhere in the middle of the logarithmic range. In order to avoid too many low illuminance levels and too many high illuminance levels we determined 40 equidistant point (on a logarithmic scale from 20 – 2000 lux) and subsequently selected 30 different intensity levels. The original idea was to have 60 participants and use 30 illuminance levels. In order to get to these levels, 5 points were removed alternately on each side, starting at the beginning (20) and the end (2000) (keeping the 20 lux and 2000 lux). However, because it is unclear where the acute alerting effect will occur, it was decided to first start with 40 participants, divided over 20 illuminance levels. Therefore, the alternate point removal process was continued to remove 10 more points. However, in the middle there is no point left which is in between, and we are left with 21 intensity levels. Because we do not expect an alerting effect in the lower illuminance ranges, it was decided to remove an extra value there and leave the two points in the middle. Figure 2.4 shows a graph with the resulting illuminance values used. The values can also be found for the 20 values in Table 2.1.

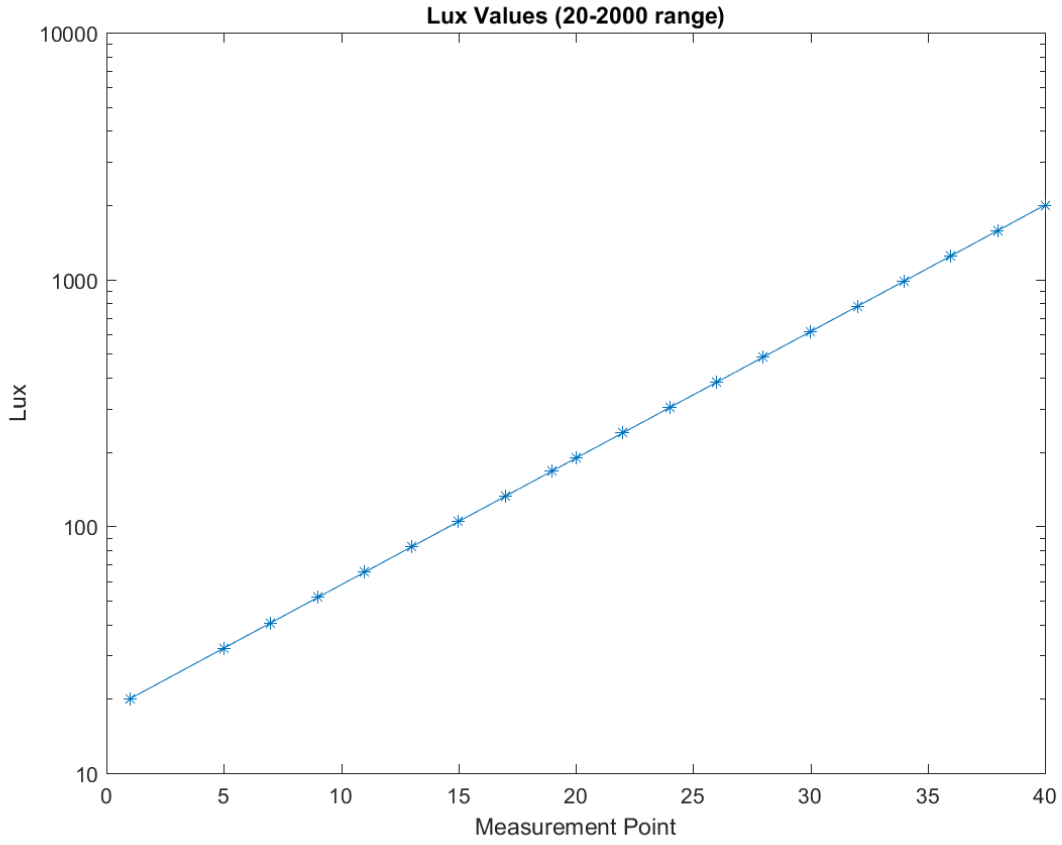


Figure 2.4: Graph of the measurement points in the intensity range (20-2000 lux)

Table 2.1. The specific intensity level for each condition

Condition	Illuminance (lux)	Condition	Illuminance (lux)
1	20	**11**	239
2	32	**12**	302
3	41	**13**	383
4	51	**14**	485
5	65	**15**	614
6	82	**16**	778
7	104	**17**	985
8	132	**18**	1247
9	168	**19**	1579
10	189	**20**	2000

Using the values specified in Table 3, the lamps were calibrated accordingly using a spectrometer. For the measurements a Specbos 1200 spectrometer was used in combination with the JETI LiMeS 4.0 software to measure the illuminance and CCT. The two light panels were calibrated individually. In Figure 2.5 an example of the spectral power distribution is shown, one for condition 7 which is 100 lux (the baseline), measured in the left cabinet.

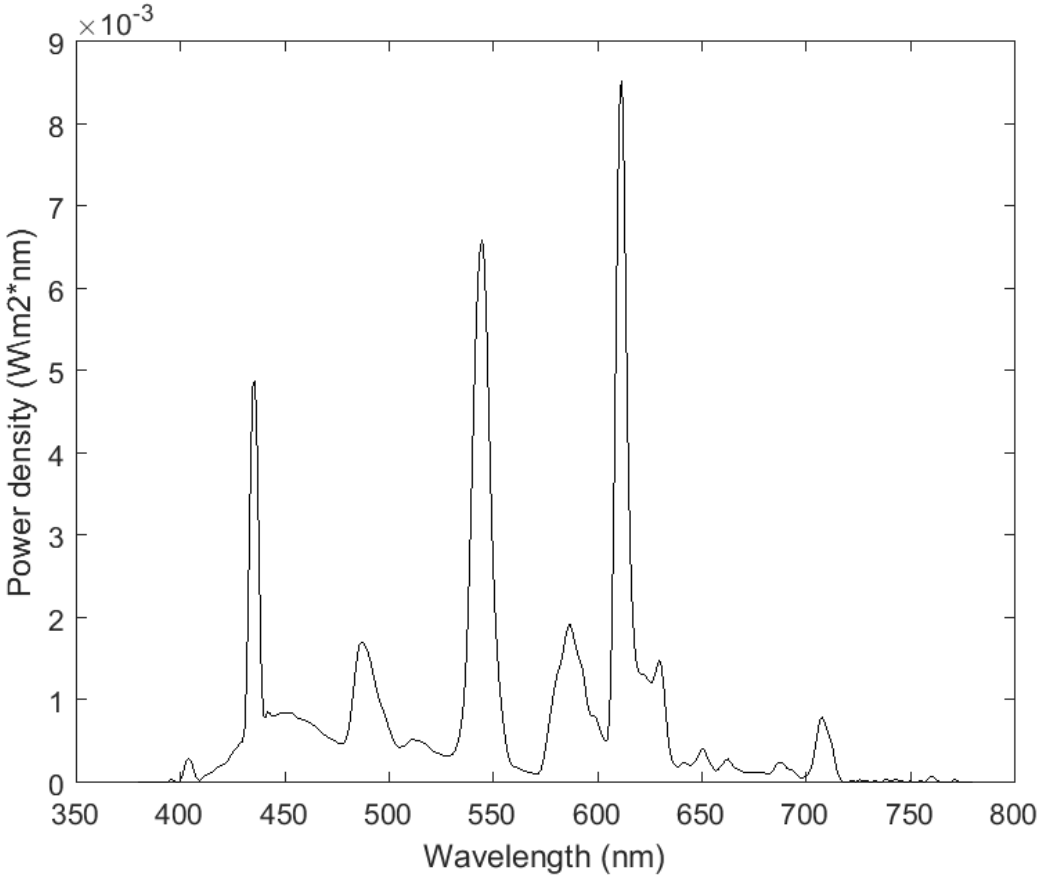


Figure 2.5. Spectral power distribution measured at eye level in the 100 lux (4000 K) condition

The light panels were not able to provide illuminances below 100 lux. For this reason a neutral density filter was used for all the values below 100 lux. In this condition, the baseline is also performed with the neutral density filter. The filter used was Rosco E-Colour+ #211: .9 Neutral Density, which reduces light with three stops (Transmission = 13%). The filter allowed for the lighting conditions below 100 lux.

Actiwatch

The type of actiwatch used was a Philips Respironics Actiwatch Pro which uses a MEMS type accelerometer. The actiwatch system is designed to provide accurate and objective activity, sleep, wake, and light-exposure data. Participants wore the actiwatch when they went to bed and removed the actiwatch when they got out of bed. Using the actiware software, data could

be extracted which provides an actography report, showing the sleep/wake cycle of the participant.

Lightlogger

A lightlogger was utilized to keep track of the light-levels of the environment of the participant. The LightLog device is designed and built by Gary Martin (Martin, 2015). It is based on the TAOS TCS34725 color sensor chip. It has an on board EEPROM memory of 64kB and is controlled by a programmable PICAXE 14M2 microcontroller. Serial communication to and from the device is established with an AXE027 USB to serial cable. The sample period was set to 60 seconds, allowing a logging period of 7.5 days. Data was extracted using LightLogControl, a windows application.

Physiological measurement

For the experiment the heartrate (HR), heartrate variability (HRV) and galvanic skin response (GSR) was measured. To measure these physiological variables, we used a Mobi8 device. The Mobi8 has 9 inputs: 4 bipolar channels (2 sockets with 2 inputs each), 4 auxiliary channels and 1 pulse-oximeter input and a separate ground socket. The maximum sample frequency for the Mobi8 device is 2057 Hz. For measuring GSR, a bipolar cable was used which could connect up to two bipolar electrodes. For the ECG measurements, HR and HRV, we used three sticker electrodes, two for the bipolar input and one for the participant's ground. Figure 6 shows how the electrodes were attached. An auxiliary sensor was used to measure GSR. The sensor consists of two electrodes that are attached to the soft part of the first phalanx of the middle finger and the ring finger.

Figure 2.6. Placing of electrodes. Green is the ground electrode.

2.5 Measurements

During the experiment different types of measurements were used. Each measurement is described shortly. During the experiment participants performed three tasks; PVT, Go No Go and N-back. In this study all these tasks were auditory, since the focus of the study lies on non-image forming (NIF) effects of light. With a visual tasks, results might get affected by image-forming effects, such as visual comfort and visibility.

Prior measuring

Prior to the actual experiment, sleep quality and light history were measured. The sleep quality was measured with a combination of actiwatches and sleep diaries. The sleep diary was a simple pen and paper one, and functioned as a backup for when an actiwatch failed or wasn't available. Participants also completed the Munich Chronotype Questionnaire before the experiment. A lightlogger was utilized to keep track of the light-levels of the environment of the participant in order to determine the light history since sleep offset until the start of the experiment.

PVT

The first task in the experiment is the Psychomotor Vigilance Task (PVT), a performance task (Dinges & Powell, 1985). In this task an auditory version of the PVT was created and used. Participants need to press the spacebar as fast as possible when they hear a beep (400 hz). Each beep is generated at a random interval between 1000 and 9000 ms. For each block, the average reaction time was calculated. The PVT is widely used in the field of chronobiology and an objective measure for alertness and easy to use, this task measures alertness and sustained attention and lasted 5 minutes.

Go / No Go Task

The second task in the experiment is the "Go / No Go" task. This task is often used to study inhibitory capacity. Two types of beeps were presented to the user, one beep is the "target beep" (400 hz), which is the same frequency as the PVT beep, and the other is the "non-target" beep (600 hz), at a higher frequency. Participants should press the spacebar when they hear the target beep and should not respond when they hear the non-target beep. A target or non-target beep is generated randomly with at a random interval between 1000 and 9000 ms. The results from this tasks will provide information about inhibitory capacity.

N-Back Task

The third task in the experiment is the N-back task (Mackworth, 1959). In this study we use the 2-Back version of the task. In this task, participants are presented with an auditory sequence of one-syllable consonants (D, F, G, H, L, M, P, Q, S and W). Participants had to press the spacebar as fast as possible when the letter they heard at that moment was the same as the letter they heard 2 positions back. So for example when they heard the sequence G-L-F-L, they had to press the spacebar after hearing the second L. There was a1000 ms delay between each stimulus. Results from this task will provide information about working memory.

Subjective Sleepiness

The Karolinska Sleepiness Scale (KSS) (Åkerstedt & Gillberg, 1990) was used to measure subjective sleepiness. At the end of each block, this measurement was administered.

Participants had to indicate how alert/sleepy they felt on a 9-point scale. On the scale, response option 1 was labeled as “Extremely Alert” and option 9 as “Very Sleepy. Fighting Sleep.”

Subjective Vitality, Tension, Positive/Negative affect

The variables subjective vitality, tension and positive/negative affect were measured with 8 items from the activation-deactivation list (Thayer, 1967). After each block, participants had to indicate how they felt at that moment through the following items: Energetic, Sleepy, Sad, Calm, Alert, Depleted, Happy and Tense. They had to indicate how they felt for each item on a 5-point scale. On the scale 1 was labeled as “Not at all” and 5 was labeled “Totally”.

Lighting Appreciation

At the end of each session, participants were asked to evaluate the lighting in the room. They had to evaluate the lighting by means of six bi-polar scales: pleasant / unpleasant, comfortable / uncomfortable, warm light / cold light, disturbing / not disturbing, bright light / dim light, stimulating / calming. By using a 5-point scale they had to evaluate the lighting on each bi-polar scale.

Prior behavior experiment

To be able to evaluate other factors that might have influenced the participant’s results, they also completed a questionnaire at the end of each session asking about their behavior before the experiment. In this questionnaire, the participants were asked the following questions:

- How many cups of coffee did you drink the hour before the experiment?
- Did you drink soda or caffeinated drinks the hour before the experiment?
- How many cups of caffeinated drinks did you have today?
- How much did you eat the hour before the experiment?
- At what time did you have breakfast/lunch?
- What did you have for breakfast/lunch?
- How long have you been outside today? (daylight, no roof)
- How long did you travel to the experiment? (only outside)

General Vitality

At the end of the second session, we measured the general vitality or trait vitality of participants. Participants had to indicate for 7 items how it applied to them using a 5-points scale. The 7 items were: “I feel alive and vital”, “I don’t feel very energetic”, “Sometimes I feel full of energy”, “I’m full of energy and life”, “I look forward to each new day”, “I almost always feel alert and awake”, “I feel energetic”. On the 5-point scale, 1 was labeled as ‘Completely Incorrect” and 5 was labeled as “Completely Correct”.

Lighting Beliefs

At the end of the second session, we asked participants about their general beliefs on lighting. When participants have certain beliefs, this might have influenced their results. We asked them how much they thought light influenced the following variables: mood, performance, concentration problems, feeling energized, alertness and motivation. Each items was evaluated using a 5-points scale, where 1 was labeled “Not at all” and 5 was labeled “Completely”.

Light Sensitivity

At the end of the second session, participants had to answer questions regarding light sensitivity. If a participant is very sensitive to light, this might influence their results. Participants were asked the following three questions:

- How many problems do you have with your eyes when they are exposed to bright light?
- How much do you suffer from headaches when exposed to bright light?
- Do you use sunglasses because the light is too bright?

The questions were answered on a 5-point scale, where 1 was labeled as ‘None at all” and 5 was labeled as “A lot”.

2.6 Overview

To summarize, the following diagrams visually describe the setup of the measurement for each session, divided into individual blocks, describing the blocks in more detail.

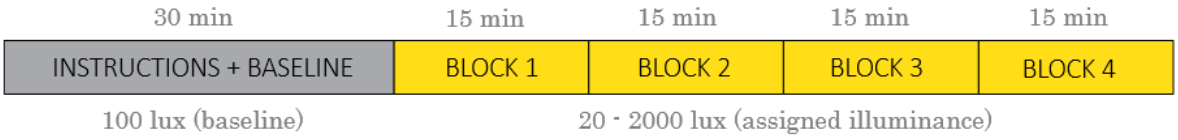


Figure 2.7. The complete overview

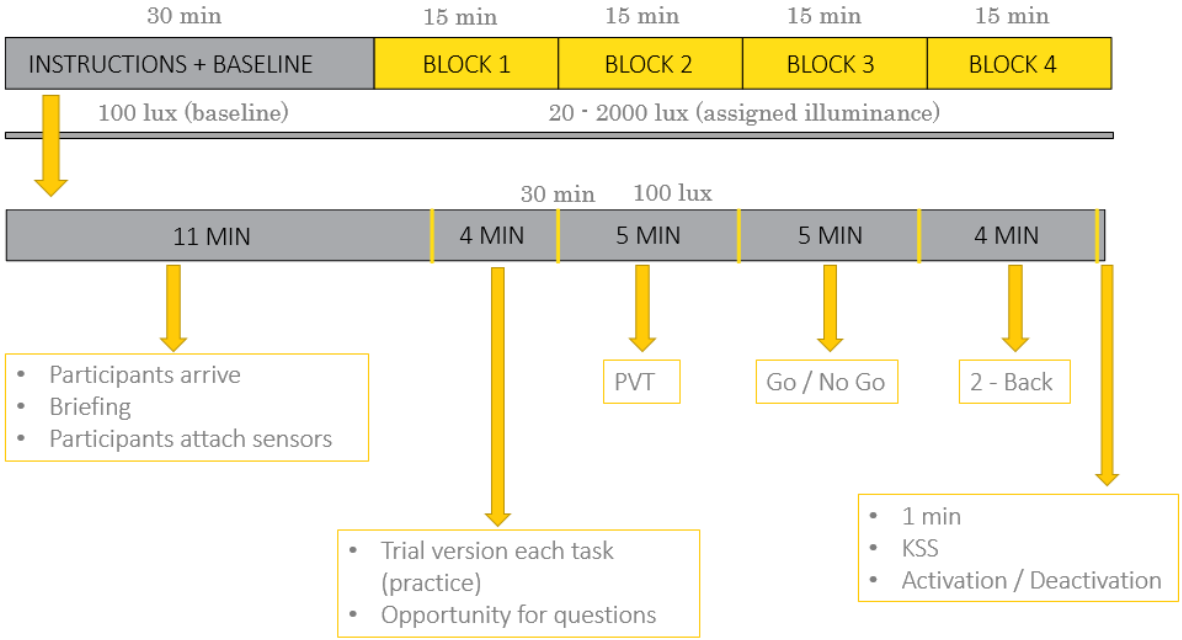


Figure 2.8. The baseline block

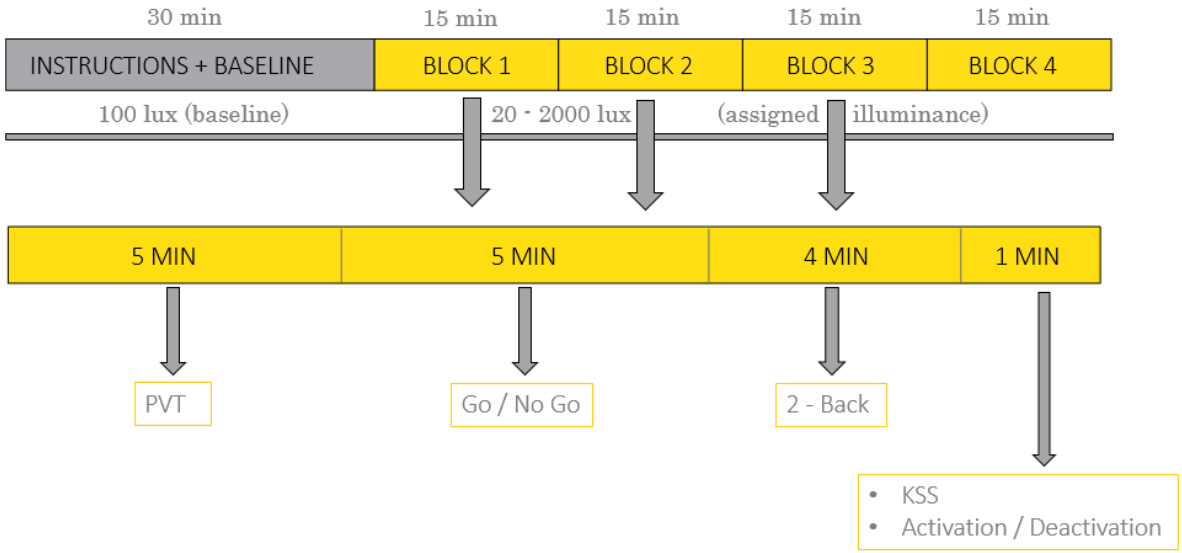


Figure 2.9. Block 1 + 2 + 3

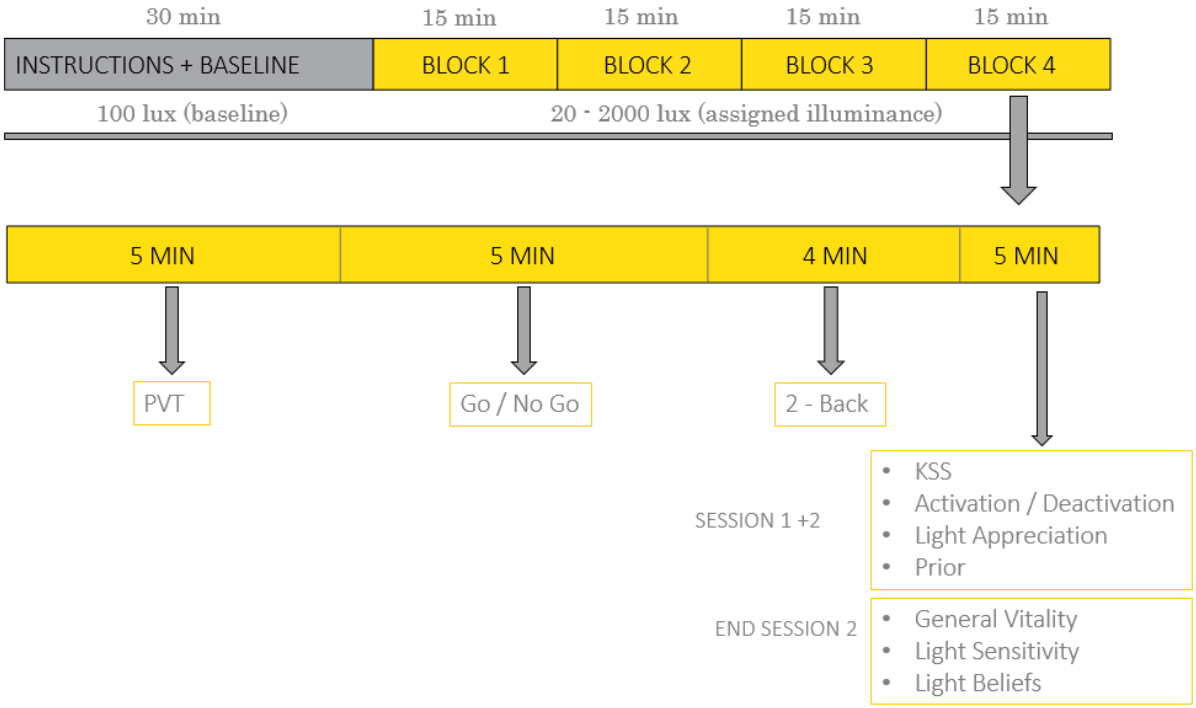


Figure 10. Block 4, the final measurement block

2.7 Statistical Analysis

For the analysis of the data, Linear Mixed Models (LMM) were used in SPSS. For the analysis itself, the focus will be on three variables: the psychomotor vigilance task (PVT), the Karolinska Sleepiness Scale (KSS) and heartrate (HR).

For the analysis, it was decided to divide the 20 light intensities over four groups. When we would add all of the 20 light intensities to the model as a factor, the model will treat each light intensity as a separate condition, since there are two participants per lighting condition, the scores of one participant may heavily influence the results.

The first step in the analysis was to perform a null-mode. The dependent variables was added without any fixed factors. Participant and session were added as the random intercepts. Next a condition model will be performed. To this conditional model the dependent variable and the following fixed factors were added: light group, time of day and measurement block. Two interactions were added; light group * time of day, to investigate the effect of different light groups in the morning/afternoon on the dependent variable and light group * measurement block, to investigate the effect of different light groups in the different measurement blocks on the dependent variable. We expect to see a difference between the morning and afternoon sessions as well as differences between the measurement blocks.

After performing the null-model and conditional model, the raw data is plotted to see how a possible dose-response relationship could be fitted. Data is plotted both for the morning and afternoon as well as for Block 1- 4 and Block 3 -4. The reason for Block 3-4 is that the alerting effects often start 30 minutes after the lighting condition has started. Scatterplots have been constructed as well to gain insight into individual data.

To analyze the PVT data, the average reaction time was calculated per block for each participant. To improve the normality and readability of the data, we transformed the reaction times into speed by applying the following formula: 1000/reaction time. In this case, a lower score means slower reaction times and a higher score means faster reaction times.

3. RESULTS

In this section, we will focus on the effect of illuminance level on three variables: the psychomotor vigilance task (PVT), the Karolinska Sleepiness Scale (KSS) and heartrate (HR). The PVT provides an objective indicator of alertness, the KSS a subjective indicator of alertness and HR provides a physiological indicator of arousal.

3.1 Psychomotor Vigilance Task (PVT)

The PVT results are analyzed using linear mixed models (LMM). To determine the hierarchical model that best fits the data, a null model is run to assess how much variance can be explained on the different levels of the model, without adding the fixed factors and to see if the random intercepts are significant.

Table 3.1. Variance to be explained at different levels based on null model for the PVT

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	53.9%	**0.14**	**0.04**	**<0.01**
Session	19.2%	**0.05**	**0.02**	**<0.01**
Measurement block	26.9%	**0.07**	**0.01**	**<0.01**

Note: Significant results are indicated in bold

The results of the null model for speed on the PVT showed that a large amount of the variance can be explained on the participant level (53.9%). On the session level (nested within a participant) 19.2% of the variance can be explained. The remaining 26.9% of the variance occurred at the measurement block level (i.e., measurement nested within a session, which in turn was nested within a participant). Since the variance at all three levels was significant, Participant and Session were kept in the model as random intercepts.

To test the effect of lighting condition, timing of exposure and measurement block, Light Group, Time of Day and Measurement Block were added as fixed factors to these models, with the PVT Baseline as a covariate. Table 3.2 shows that the variance to be explained on the different levels was still significant after adding the fixed part to the model. When comparing the estimates of variance from Table 3.2 to the variance of the null model displayed in Table 3.1, it can be seen that the estimates become smaller in the model, indicating that a portion of the variance is explained by the fixed factors. After including the fixed factors in the LMM, most of the variance still occurs at the block level and the participant level. Table 3.3 shows that there were no significant main effects of Light Group or Time of Day, nor a significant interaction effect between Light Group and Time of Day or Light Group and Measurement

Block. Table 3.4 shows the estimated marginal means for the four light groups. Bonferroni post hoc comparisons confirmed that there were no significant differences between the four lighting conditions ($p>0.05$).

Table 3.2: Variance to be explained at different levels based on the model including fixed factors for PVT scores

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	38.9%	**0.07**	**0.03**	**0.02**
Session	27.8%	**0.05**	**0.02**	**<0.01**
Measurement Block	33.3%	**0.06**	**0.01**	**<0.01**

Note: Significant results are indicated in bold

Table 3.3: Fixed factor results from the model for the PVT

Fixed predictors	***F***	***dF***	***p***
Light Group	0.61	(3,33)	0.62
Time of Day	1.28	(1,35)	0.27
Light Group * Time of Day	0.64	(3,34)	0.60
Measurement Block	**14.06**	**(3,220)**	**<0.01**
Light Group * Measurement Block	0.80	(9,220)	0.62
PVT Baseline	**20.61**	**(1,74)**	**<0.01**

Note: Significant results are indicated in bold

Table 3.4: Estimated Marginal Means of PVT for the different light groups

Light Groups	***EMM***	***SE***
20-65 lux	2.46	0.10
82-189 lux	2.60	0.10
239-614 lux	2.45	0.10
778-2000 lux	2.41	0.11

Table 3.3 shows that Measurement Block had a significant main effect on PVT speed. A post hoc analysis with Bonferroni correction was performed to investigate potential differences between the various blocks. Results of these analyses showed that Block 1 (*EMM* = 2.63, *SE* = 0.06) was significantly different from Block 2 (*EMM* = 2.43, *SE* = 0.06), 3 (*EMM* = 2.42, *SE* = 0.06) and 4 (*EMM* = 2.43, *SE* = 0.06) ($p<0.01$). There were no significant differences between Block 2, 3 and 4 ($p>0.05$).

The original goal of the study was to create a dose-response curve. However, looking at the results of the model, no significant main effects or interaction effects of the lighting conditions were found for speed on the PVT. Therefore, some graphs will be presented, providing insights into the data and to demonstrate that fitting a dose-response curve might not be the right step to

take. Graphs have been constructed for Block 1-4 and Block 3-4, both for the morning and afternoon.

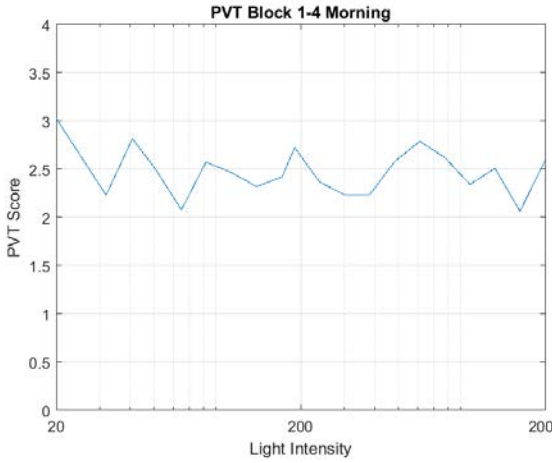


Figure 3.1. PVT Block 1-4 Morning

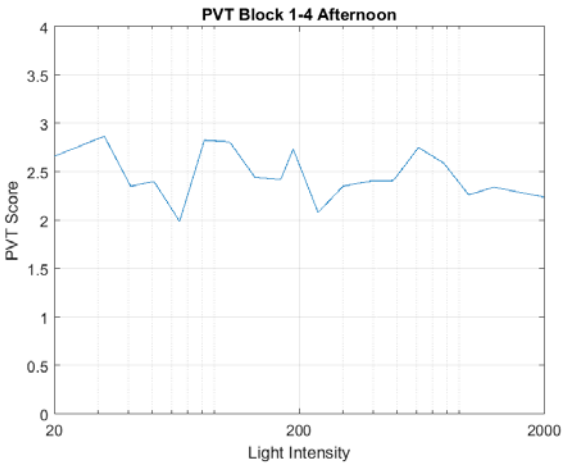


Figure 3.2.: PVT Block 1-4 Afternoon

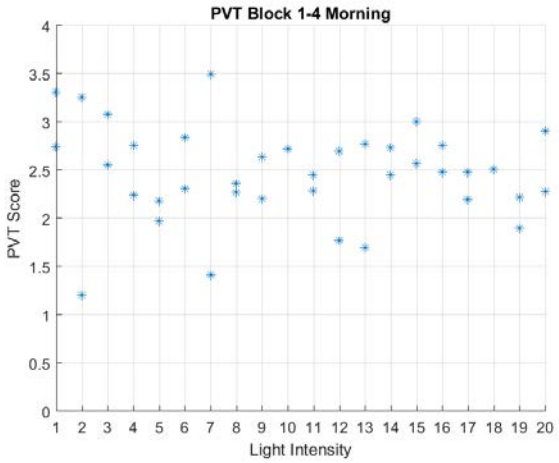


Figure 3.3. PVT Block 1-4 Morning Scatterplot

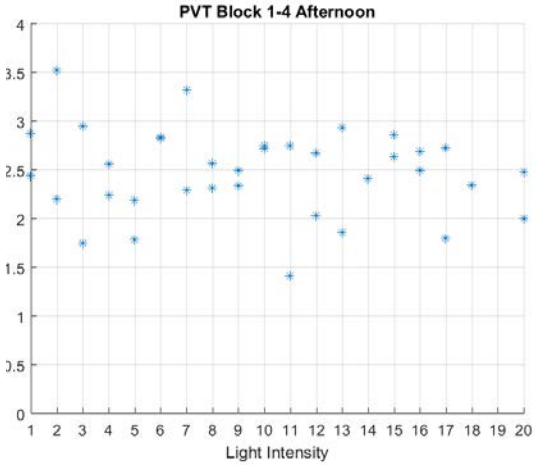


Figure 3.4. PVT Block 1-4 Afternoon Scatterplot

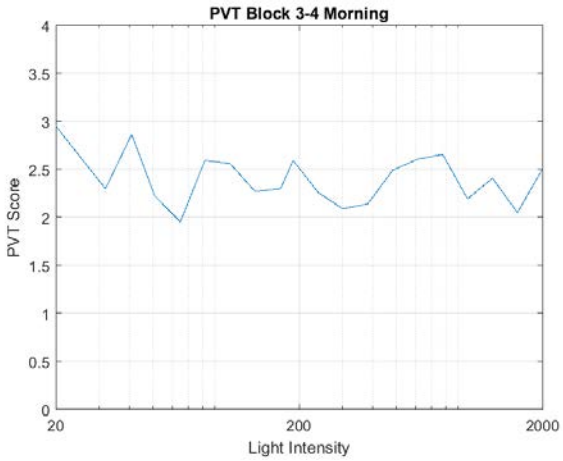


Figure 3.5. PVT Block 3-4 Morning

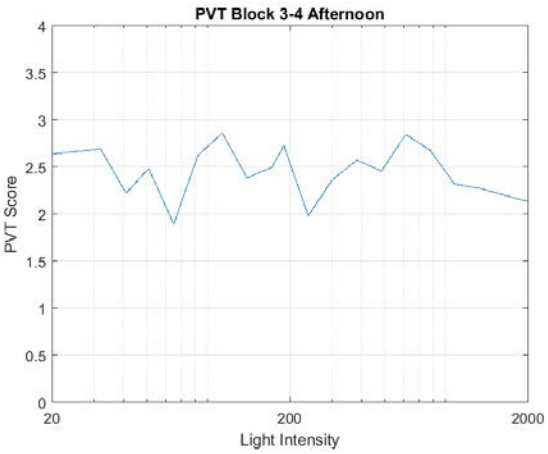
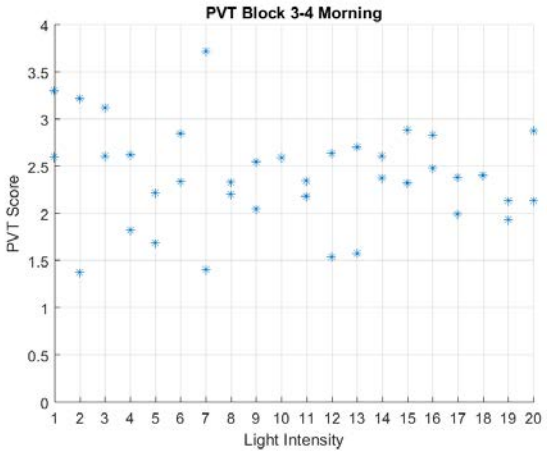


Figure 3.6. PVT Block 3-4 Afternoon



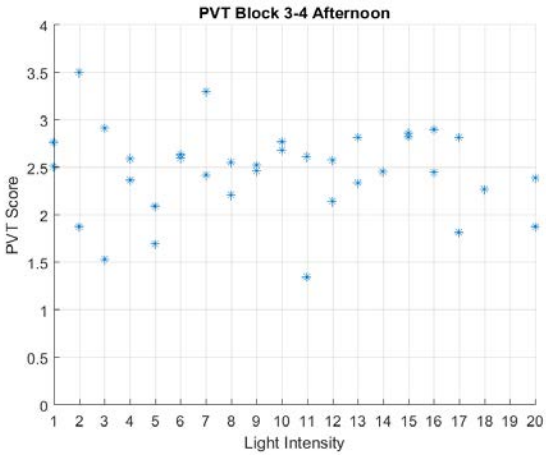


Figure 3.7. PVT Block 3-4 Morning Scatterplot

Figure3.8. PVT Block 3-4 Afternoon Scatterplot

When looking at Figure 3.1 – 3.8, we can see that the speed on the PVT varied quite a lot between participants under exposure to the same lighting condition. It also becomes apparent that there was no clear pattern in the results to which we could fit a dose-response curve. Because there is no clear curve in the data and no significant differences between the light conditions were found, it was decided to not model the data.

3.2 Sleepiness (KSS)

For the KSS results, the same steps were applied as for the PVT results. First a null model was run, to determine the hierarchical model that best fits the KSS data, and investigate the amount of variance that can be explained on the different levels of the model, without adding the fixed factors.

Table 3.5: Variance to be explained at different levels based on null model for the KSS

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	27.0%	**1.12**	**0.48**	**0.02**
Session	27.2%	**1.13**	**0.38**	**<0.01**
Measurement Block	45.8%	**1.90**	**0.18**	**<0.01**

Note: Significant results are indicated in bold

Table 3.5 shows that for sleepiness on the KSS, the largest amount of the variance can be explained on the measurement block level (45.8%). On the participant level 27% of the variance can be explained. The session level explains the remaining 27.2% of the variance.

Since the variance all three levels was significant, Participant and Session were kept in the model as random intercepts. After investigating the amount of variance to be explained at the different levels, Light Group, Time of Day and Block were added as fixed factors, with the KSS Baseline as a covariate. Table 3.6 shows that, after adding the fixed factors to the model, the variance explained on the different levels remains significant. When comparing the estimates of the variance from the null model to the hierarchical model, it can be seen that the estimates became smaller in the hierarchical model, indicating that a portion of the variance is explained by the fixed factors. A large portion of the variance (64.1%) occurs at the measurement block level, even after including Measurement Block as a fixed factor in the LMM. Table 3.7 shows that there were no significant main effects of Light Group or Time of Day, nor a significant interaction effect between Light Group and Time of Day or Light Group and Measurement Block. Table 3.8 shows the estimated marginal means for the four light groups. Post hoc comparisons with Bonferroni correction also revealed no significant differences between the four lighting groups ($p>0.05$).

Table 3.6. Variance to be explained at different levels based on the model including fixed factors for KSS sleepiness scores

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	20.8%	**0.58**	**0.26**	**0.03**
Session	15.1%	**0.42**	**0.21**	**0.04**
Measurement Block	64.1%	**1.79**	**0.17**	**<0.01**

Note: Significant results are indicated in bold

Table 3.7. Fixed factor results from the model for KSS sleepiness scores

Fixed predictors	***F***	***dF***	***p***
Light Group	1.13	(3,37)	0.35
Time of Day	0.01	(1,38)	0.95
Light Group * Time of Day	1.95	(3,38)	0.14
Measurement Block	2.28	(3,225)	0.08
Light Group * Measurement Block	0.81	(9,225)	0.61
KSS Baseline	**61.55**	**(1,64)**	**<0.01**

Note: Significant results are indicated in bold

Table 3.8. Estimated Marginal Means of KSS sleepiness scores for the different light groups

Light Groups	***EMM***	***SE***
20-65 lux	6.78	0.32
82-189 lux	6.67	0.33
239-614 lux	6.07	0.32
778-2000 lux	6.20	0.36

Table 3.7 shows that Measurement Block had a non-significant trend for a main effect. A Bonferroni post hoc analysis was run to investigate whether there were significant differences between the different Blocks. Results of these analyses showed no significant differences between the Blocks. ($p>0.05$).

The results of the hierarchical model analysis for subjective sleepiness demonstrated that there were no significant differences between the lighting conditions. Figures 3.9 – 3.16 show the raw data for the KSS in Block 1-4 and Block 3-4, both for the morning and afternoon.

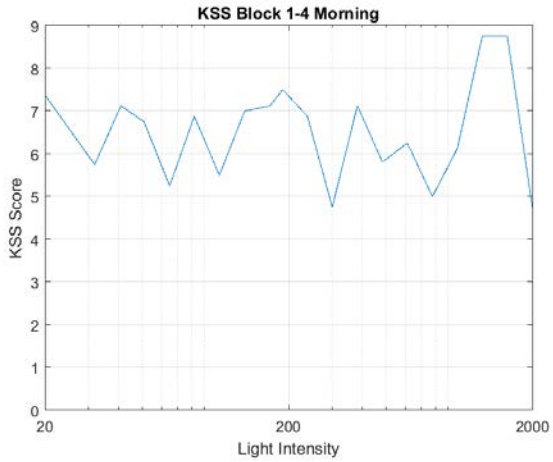


Figure 3.9. KSS Block 1-4 Morning

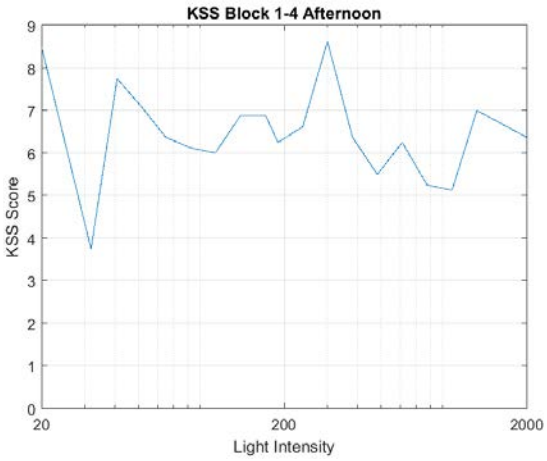


Figure 3.10. KSS Block 1-4 Morning

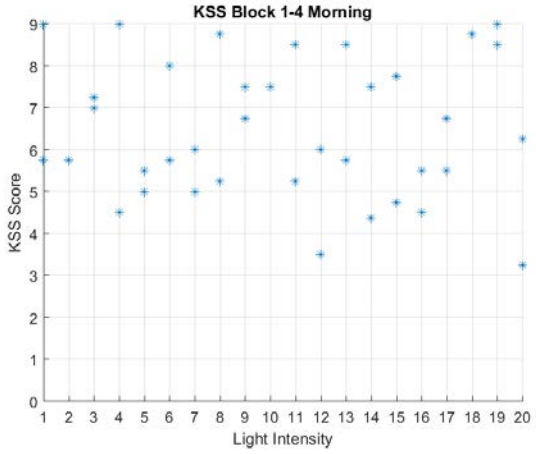


Figure 3.11 KSS Block 1-4 Morning Scatterplot

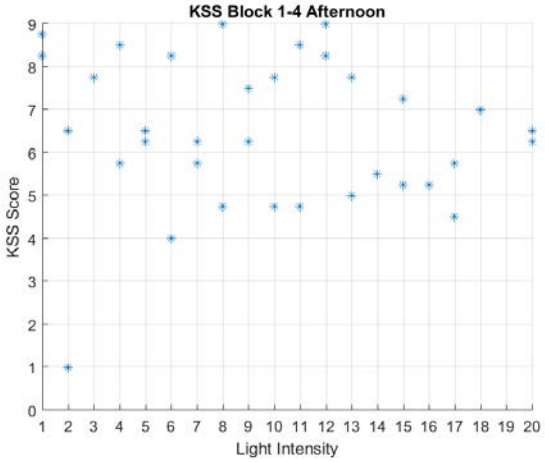


Figure 3.12. KSS Block 1-4 Afternoon Scatterplot

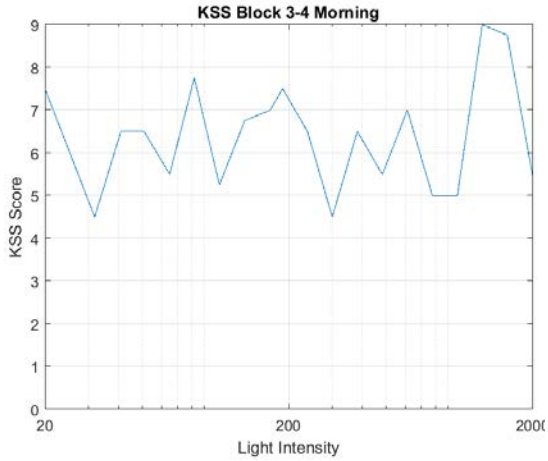


Figure 3.13. KSS Block 3-4 Morning

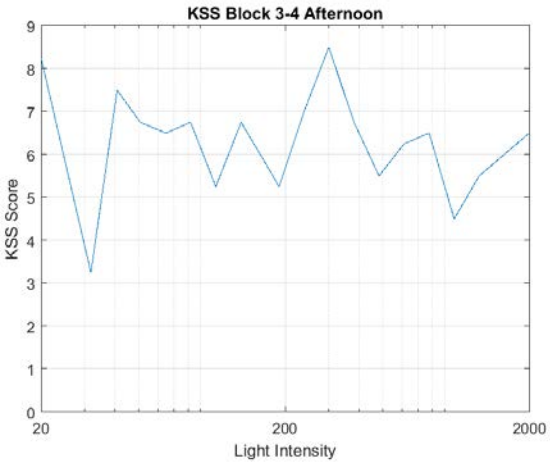


Figure 3.14. KSS Block 3-4 Afternoon

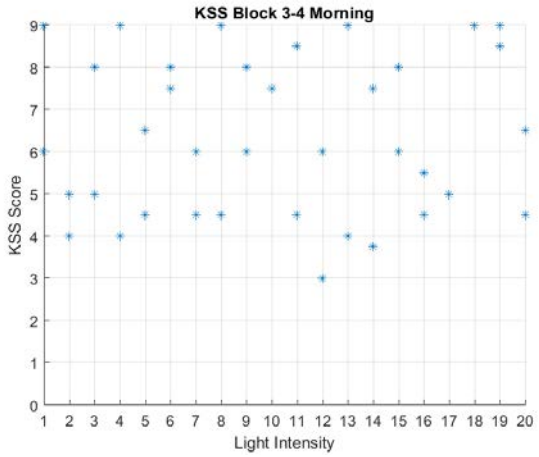


Figure 3.15 KSS Block 3-4 Morning Scatterplot

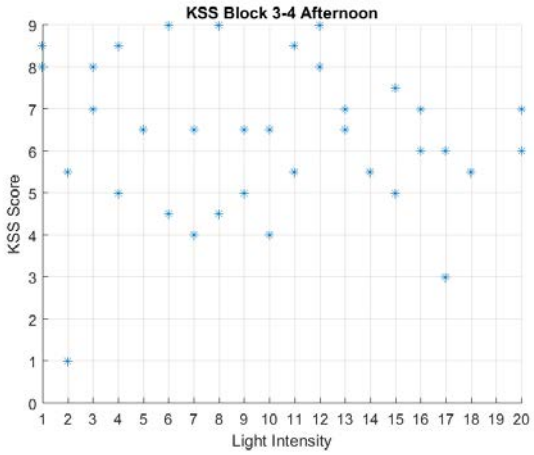


Figure 3.16. KSS Block 3-4 Afternoon Scatterplot

The KSS results as can be seen in Figure 3.9 - 3.16, showed (similar to the PVT results) no clear pattern. The graphs confirm there was quite some variance in the data, even within lighting levels. Additionally there does not seem to be a clear and systematic difference between morning and afternoon. Which was confirmed by the model, as no significant effect for time of day was found. Due to the high amount of variance, the absence of a clear pattern and no significant main effect of lighting condition in the LMM, it was decided to not fit a dose-response curve.

3.3 Heartrate

For the analysis of the heartrate (HR) data, a null model was run to determine how much variance can be explained on the different levels of the model. Moreover, the model was run to determine the hierarchical model that best fits the heartrate data.

Table 3.9. Variance to be explained at different levels base on null model for heartrate

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	46.3%	**51.56**	**18.99**	**<0.01**
Session	44.2%	**49.19**	**12.27**	**<0.01**
Measurement Block	9.5%	**10.65**	**1.03**	**<0.01**

Note: Significant results are indicated in bold

The results of the null model for the heartrate data, showed that the largest amount of the variation can be explained on the participant level (46.3%). Next is the session level, where 44.2% of the variation can be explained. The remaining 9.5% of the variance occurs at the measurement block level.

The variance was significant at all three levels. Therefore, Participant and Session will be kept in the model as random intercepts. For the LMM, Light Group, Time of Day and Block were added as fixed factors to the model, with the HR Baseline as a covariate. Table 3.10 shows that after adding the fixed factors to the model, the variance explained on the different levels remained significant. When comparing the estimates of the variance from Table 3.10 to the ones from Table 3.11, the estimates become smaller in the fixed factor model. Indicating that a portion of the variance was explained by the fixed factors. Table 3.11 shows there were no significant main effects of Light Group or Time of Day, nor a significant interaction effect between Light Group and Time of Day or Light Group and Measurement Block.

Table 3.10. Variance to be explained at different levels based on the model including fixed factors for heartrate

Level	***% Variance***	***Estimate of Variance***	***SE***	***p***
Participant	35.9%	**8.99**	**3.35**	**<0.01**
Session	25.2%	**6.32**	**2.11**	**<0.01**
Measurement Block	38.9%	**9.74**	**0.94**	**<0.01**

Note: Significant results are indicated in bold

Table 3.11. Fixed factor results from the model for heartrate

Fixed predictors	***F***	***dF***	***p***
Light Group	1.72	(3,38)	0.18
Time of Day	0.90	(1,47)	0.35
Light Group * Time of Day	2.16	(3,39)	0.11
Measurement Block	**4.15**	**(3,216)**	**<0.01**
Light Group * Measurement Block	0.94	(9,216)	0.50
HR Baseline	**261.76**	**(1,71)**	**<0.01**

Note: Significant results are indicated in bold

Table 3.12. Heartrate means of the different light groups for morning and afternoon

Light Groups	***EMM Morning***	***SE***	***EMM Afternoon***	***SE***
20-65 lux	76.70	1.40	78.10	1.34
82-189 lux	78.99	1.41	80.25	1.39
239-614 lux	81.47	1.37	79.14	1.42
778-2000 lux	75.72	1.49	78.42	1.57

Table 3.11 does show a significant main effect of Measurement Block on the HR. A Bonferroni post hoc analysis was performed, to see if there were significant differences between the various measurement blocks. The Bonferroni post hoc showed there was a significant difference ($p<0.01$) between Block 1 (*EMM* = 79.39, *SE* = 0.68) and Block 4 (*EMM* = 77.60, *SE* = 0.68). The rest of the Block combinations did not differ significantly from each other ($p>0.05$).

Table 3.12 shows the estimated marginal means for the four light groups, both for the morning and the afternoon. The mean heart rate of each light group does not seem to differ a lot from one another and this is mostly confirmed by a Bonferroni post hoc analysis. The only significant difference ($p=0.03$) found was between the 239-614 lux group and the 778-2000 lux group, but only in the morning. However there was no significant main effect of light groups.

The results of the hierarchical model has shown that no significant main or interaction effects of the lighting conditions on HR were found. Graphs are presented of the HR data, to gain insight into the raw data. Graphs have been constructed for the Block 1-4 and Block 3-4, both for the morning and afternoon.

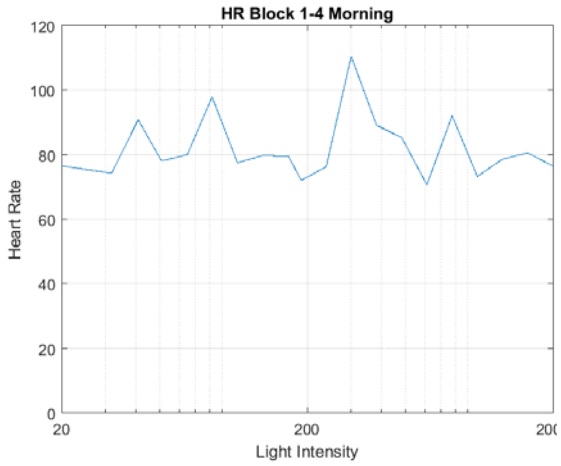


Figure 3.17.: HR Block 1-4 Morning

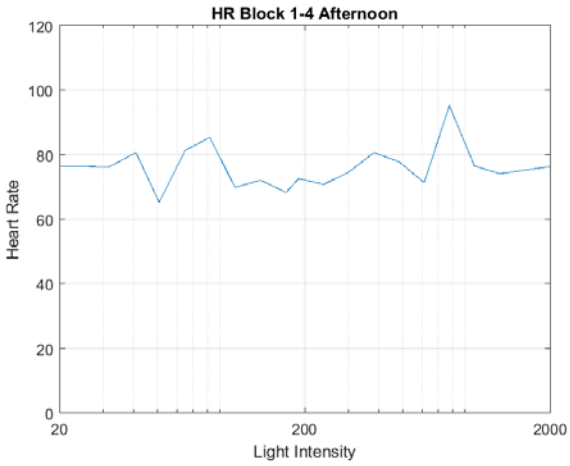


Figure 3.18 HR Block 1-4 Afternoon

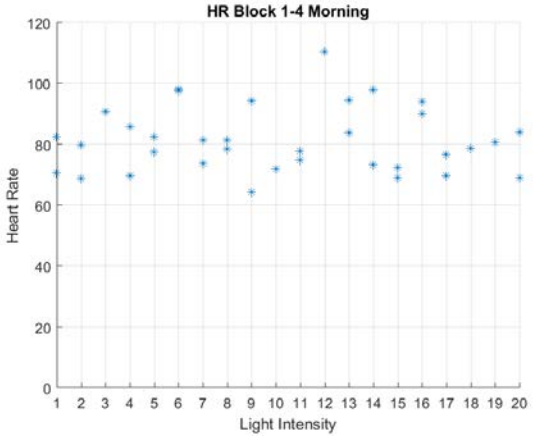


Figure 3.19 HR Block 1-4 Morning Scatterplot

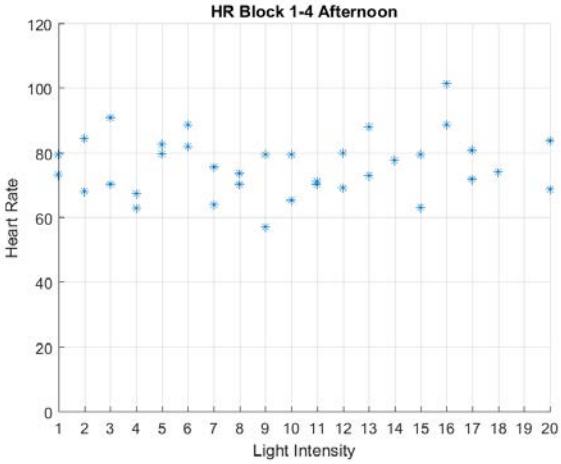


Figure 3.20 HR Block 1-4 Afternoon Scatterplot

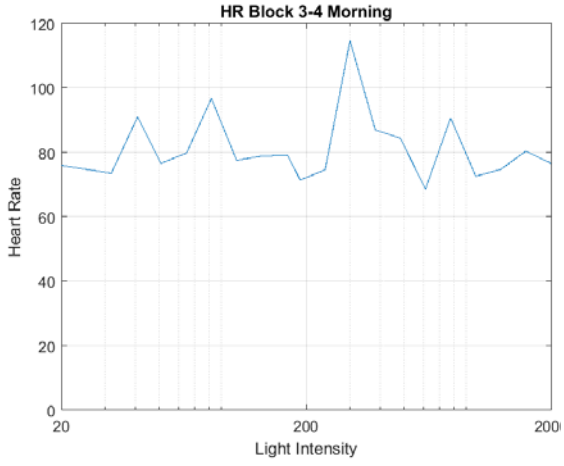


Figure 3.21 HR Block 3-4 Morning

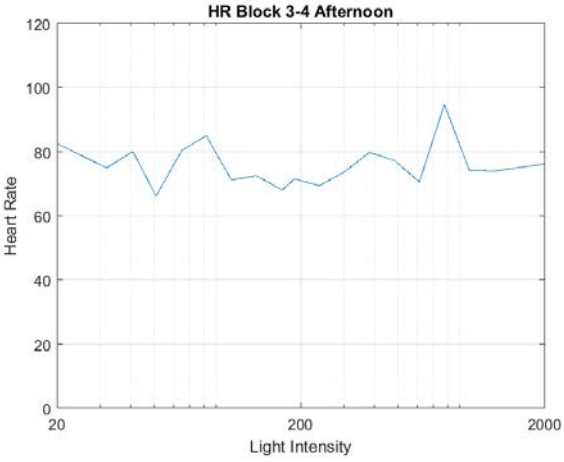


Figure 3.22 HR Block 3-4 Afternoon

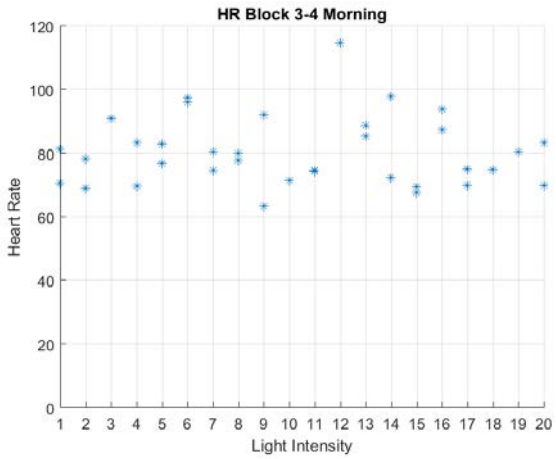


Figure 3.23 HR Block 3-4 Morning Scatterplot

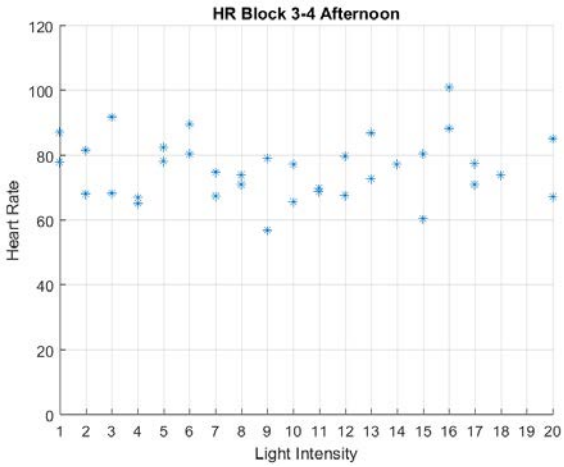


Figure 3.24 HR Block 3-4 Afternoon Scatterplot

There was again no clear pattern, as can be seen in figures 3.17 – 3.24. The graphs show that HR sometimes varied quite a lot between the two participants exposed to the same light intensity, and that there was no clear systematic difference between morning and afternoon.

4. DISCUSSION

In the current study, we tested acute effects of light intensity on alertness and arousal during daytime, employing a large range of illuminance levels. The research question of this thesis is: What is the optimal light intensity to induce non-image forming acute effects of white light during the day in terms of subjective and objective indicators of alertness and vitality? One of the main objectives was to investigate if it would be possible to create a dose-response curve for daytime light exposure, similar to the dose-response curve for nighttime by Cajochen et al. (2000).

In the present study, participants came to the lab twice, once in the morning and once in the afternoon (at least three days apart). In the lab, participants were exposed to a 100 lux baseline, after which they were exposed to one of the light intensities for 60 minutes. In total there were 20 lighting conditions within a 20 – 2000 lux range, and two participants were assigned to each lighting condition. During the lab sessions, we used a multi-measure approach. This thesis will focus on three of the measurements: performance on a sustained attention task, subjective sleepiness and heartrate, a physiological indicator of arousal.

The results revealed no significant effects of light intensity on the different indicators for alertness and arousal, and showed that there was no clear indication for a dose-response curve.

These findings contrast the results of the study by Cajochen et al. (2000) which did find a logistic dose-response curve for subjective sleepiness (also assessed with the KSS). The main difference between the current study and the study by Cajochen was the timing and duration of the light exposure. They performed the study in the early biological night and exposed participants to one of the illuminance levels for 6.5 hours. Furthermore, participants underwent a constant routine before the light exposure (range 3 – 9100 lux at eye level), during which they were exposed to about 3 lux for 4.75 hours. In contrast, the current study was performed during daytime and the light exposure lasted 1 hour, which was preceded by a 100 lux baseline for 30 minutes. The most significant difference between the two studies is perhaps the daytime and nighttime difference. Furthermore there is a large difference in the light range, the duration of the exposure and, pre-treatment

Numerous studies have been performed during nighttime, (Badia et al, 1991; Cajochen, 2000; Campbell and Dawson, 1990; Foret et al., 1996; Lockley et al, 2006; Phipps-Nelson, 2003) as well studies during daytime (Phipps-Nelson, 2003; Smolders & de Kort, 2014; Rüger et al., 2005; Huiberts, Smolders & de Kort, 2015; Smolders & de Kort, 2012; Vandewalle et al, 2006).

These studies have shown that the alerting effects of light occur both during the night and day. However, the alerting effects seem to be stronger and more robust during the night compared to during the day. An important difference here is melatonin, which is present during the night, but is minimal during daytime. In the Cajochen et al. (2000) study they assigned participants either to a low level, middle level or high light level group for the analysis. In the results it became clear that these light groups differed from each other. Alerting effects were found for the middle and high light level group, while almost no effects were found in the low light level group. In this study, our participants were assigned to four different light groups, however no significant differences were found between these groups. Perhaps, the suppression of melatonin during nighttime is the largest contributor to the alerting effect, which explains why more robust and stronger effects are found in the Cajochen study. Furthermore, in the Cajochen study they used more extreme manipulations. Our light range was 20- 2000 lux at the eye, while theirs was 3- 9100 lux at the eye. This might explain why no significant differences were found between our light groups. However, in other daytime studies they still found alerting effects during daytime, without extreme light levels (Smolders & de Kort, 2014; Rüger et al., 2005).

Another difference between the study by Cajochen et al. (2000) and this work, is the duration of the light exposure: 6.5 hours versus 1 hour in the current study. This would suggest that it is necessary to have a longer exposure period to induce activating effects. However, there are other studies in which acute alerting effects of light were found within an hour of exposure. (Vandewalle et al., 2006; Smolders & de Kort, 2014; Smolders et al. 2012).

As mentioned, an additional difference between the two studies is the pre-treatment. In the study by Cajochen et al. (2000), participants were exposed to about 3 lux for 4.75 hours before the experiment, while in this study participants entered the lab after traveling from their homes, classes, work etc. This may have induced substantial variations in participants' light history. Especially in the afternoon they are more likely to have been exposed to a relatively high light dose, as it is likely that they spent the day in well-lit rooms or outside in the sun. In the current study we wanted to study the effects under a more realistic, everyday-life setting to ensure a relatively high ecological validity. When designing an intelligent lighting system for example for an office, it is very unlikely that the workers enter the building after exposure to very dim light (e.g., 3 lux) for multiple hours. In contrast they will likely be exposed to a variety of light conditions.

Which is why in the current study a 100 lux baseline was used. The purpose was to create a realistic situation, so without constant routines, a 100 lux baseline is a relatively low but also

commonly experienced light intensity during daytime (Smolders et al., 2013), which is why we use it as the baseline. The baseline period lasted for 30 minutes, however it is unknown what the adaptation period is for non-image forming effects. In the Cajochen study 50% of maximal alerting effect was found at 100 lux, in which case the baseline might seem high, however it is representative for daytime situations. The Cajochen study was performed during the night, i.e. at times when you would expect effects at lower light intensities compared to daytime, due to melatonin levels, relatively high sleep pressure, and low levels of light exposure before the experiment. It was difficult to determine at what light intensity the alerting effects would occur during daytime, since little is known about specific illuminance levels for alerting effects of light during daytime. We did expect the illuminance threshold for the occurrence of acute alerting effects would be higher than in the Cajochen study, since in our study melatonin is minimal, sleep pressure is low and participants are exposed to higher light doses beforehand.

Possibly, light history play an important role in the acute alerting effects of bright light. In the current study, light loggers were used to keep track of a participants' environment, this data has not been analyzed. If this data were analyzed, it would be possible to see if there is a lot of variance in light history between participants and between morning and afternoon. This might explain some of the results that have been found and could show how light history can influence sensitivity for light exposure. Another light exposure related factor of this study is the season when the study was done. The current study was carried out in May during the spring. This could lead to a higher exposure to light during the day, because there are more sun hours per day in spring compared to the winter. Perhaps acute alerting effects are stronger in winter, because there are less sun hours per day (i.e., shorter photoperiod) which would likely lead to a lower exposure to light during the day. In fact, Smolders et al. (2013) provide indications that sensitivity to acute alerting effects are most pronounced in the fall and winter period. However, previous studies did find acute alerting effects of bright light during daytime in the spring (Smolders & de Kort, 2014). As the influence of season on sensitivity to the acute alerting effects is relatively unknown, it would be interesting to look at the effect of the season in which the experiment is performed. Perhaps, when performing the current study in the winter, with less sun hours, the light groups might have a stronger alerting effect. Future studies are needed to investigate whether sensitivity to the non-image forming effect of light is moderated by season.

It is clear that more research is needed in the area of light history. In this study we kept track of the light exposure patterns of the participants since sleep offset until the start of the experiment.

However, due to time constraints, we haven't inspected the light history data and its potential moderating effect yet. Additional analyses will have to be performed to investigate inter- and intra-individual differences in prior light exposure, and test whether there were significant differences in the light exposure patterns prior to the various light groups.

What really struck in the results, were the relatively high scores on subjective sleepiness (KSS) (mean = 6.27, SD = 2.03). Already in the baseline phase, participants scored relative high (mean = 5.63, SD = 1.87), as can be observed in the graphs constructed for baseline in Appendix I. Such high levels on the sleepiness scale is not something that is expected during daytime. Throughout the experiment the KSS scores stayed high, or became even higher. The reaction times of the performance task seem to be a bit higher than you would normally expect during daytime as well (mean = 428 , SD = 129.24), in the baseline the reaction times were better, but still high (mean = 399, SD = 358). For example in the study by Smolders & de Kort (2014) average reaction time was around 350 milliseconds. Reaction times on the performance task do not seem to improve significantly compared to the baseline, which can be observed in Appendix I. These results indicate that participants might not have been sensitive enough towards the light exposure.

The results found for the KSS and performance task, possibly indicates large differences in sensitivity towards light manipulations during daytime, which can be observed in the scatter plots in the results section. The scatter plots show that there are a lot of inter-personal differences for each light condition. In the study by Cajochen et al. (2000) there do not seem to be a lot of inter-personal differences, even though in their study they used 23 participants. In this study 38 participants were used, of which each participant came to the lab twice (once the morning, once in the afternoon). If the inter-personal differences for light sensitivity would play an important role, we would expect to see this as well in the Cajochen study, but we don't. This could be because they were exposed to the light for a longer amount of time and all received the same pre-treatment. Another explanation could be the use of the performance task. In the Cajochen study they did not use performance tasks, which could have influenced the results. It is a possibility that participants became fatigued in the current study due to the performance tasks. Possibly more participants are required to see where such differences in light sensitivity come from and if they perhaps could be explained by certain personal characteristics.

Another limitation of the present study could be the fact that it is unknown what participants exactly were doing during the experiments with their gaze, as there was no camera present in the cabinets where the experiment was conducted. Because of the focus on the non-image

forming effects of light, all the tasks performed during the experiment were auditory. During these auditory tasks, the screen of the laptop was black, not showing anything, except during the questionnaires. It could have happened that participants sometimes closed their eyes during the tasks, since it was not necessary for them to look anywhere (they just had to listen and press the spacebar in order to perform the tasks). If this did happen, they would not receive the intended amount of light at eye level, which could have reduced the difference in light dosage between the various lighting conditions. For future studies, it can be considered to do eye tracking, to be able to see if participants close their eyes or look in different directions. One could even consider to place a focus point in front of the participant and instruct them to focus on that point during the experiment.

In this study our goal was to investigate the effects of a large rang of light intensities on alertness and vitality during daytime. Furthermore it was investigated if it would be possible to construct a dose-response curve for daytime light exposure. However, no significant effects of light on the different indicators for alertness and arousal were found. The data itself showed no clear pattern for a relationship between light intensity and the various indicators, making it unsuitable for fitting a dose-response curve.

These results suggest that we cannot translate the dose-response curve for nighttime by Cajochen et al. (2000) one-to-one to daytime situations. Yet, more research is needed in order to establish the optimal lighting settings for daytime situations. Additionally, the results indicated substantial inter-personal differences for various light intensities, suggesting that participants responded differently to the light exposure. This could imply that it is necessary to use personally tuned lighting systems. However, as indicated before, more research is necessary to gain insights in order to define the optimal, potentially personalized, lighting scenarios. We still need to learn a lot about the non-image forming effects of light, and how these could eventually contribute to intelligent lighting systems for example in offices and schools.

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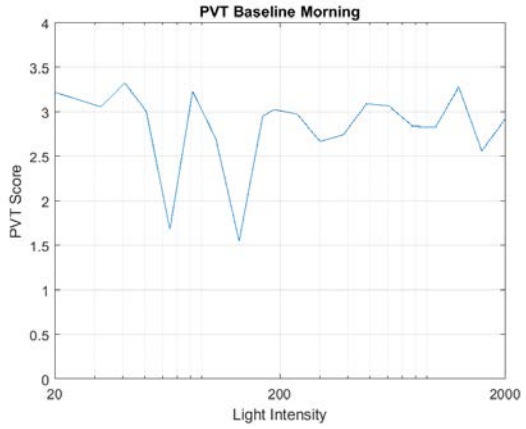
APPENDIX I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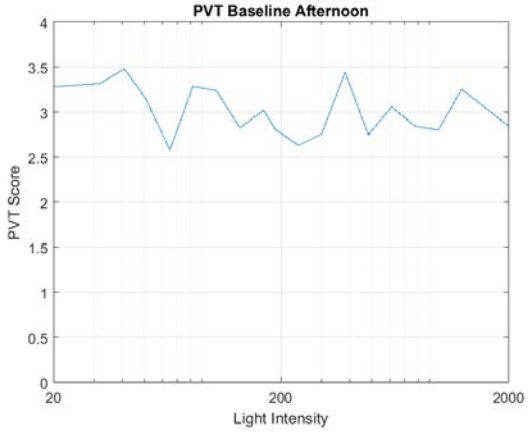
PVT Score
Light Intensity
20
200
2000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PVT Score
Light Intensity
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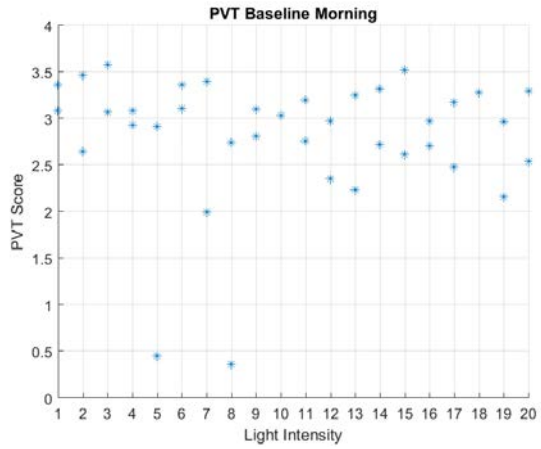
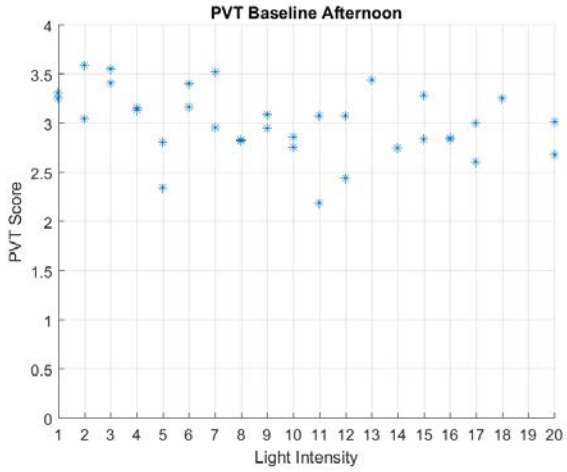
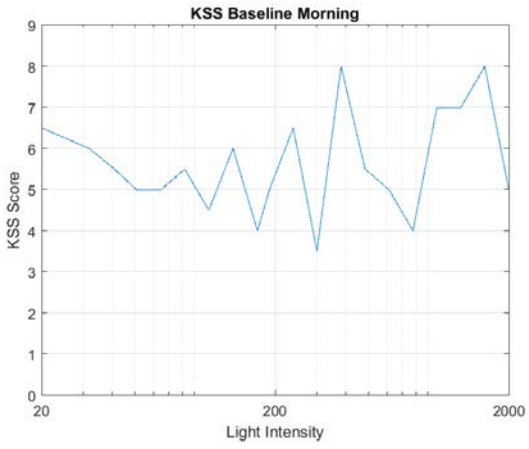
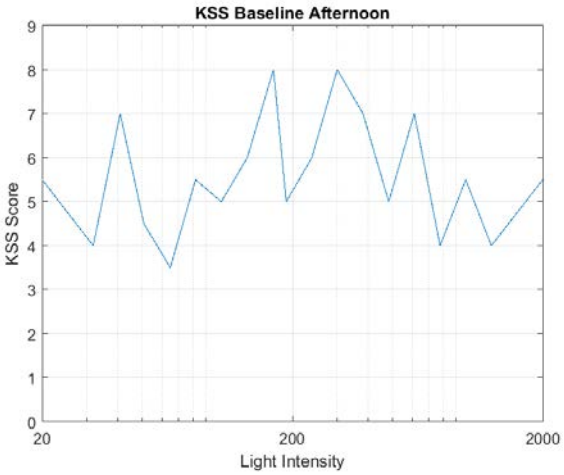
200
2000


PVT Baseline Morning
PVT Score
Light Intensity


PVT Baseline Afternoon
PVT Score
Light Intensity


KSS Baseline Morning
KSS Score
Light Intensity
20
200
2000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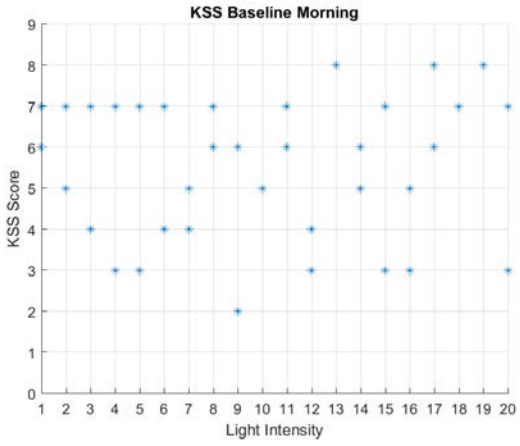
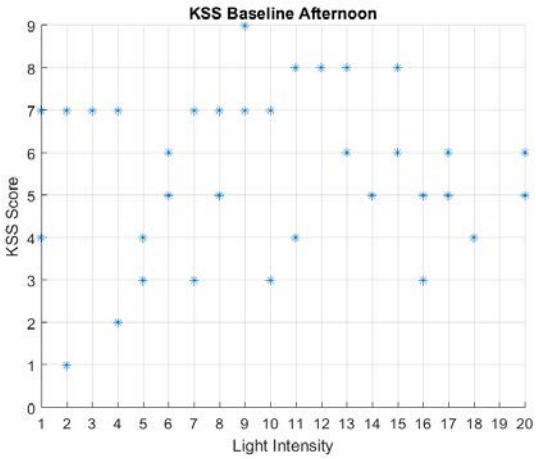
KSS Score
Light Intensity
20
200
2000


KSS Baseline Morning
KSS Score
Light Intensity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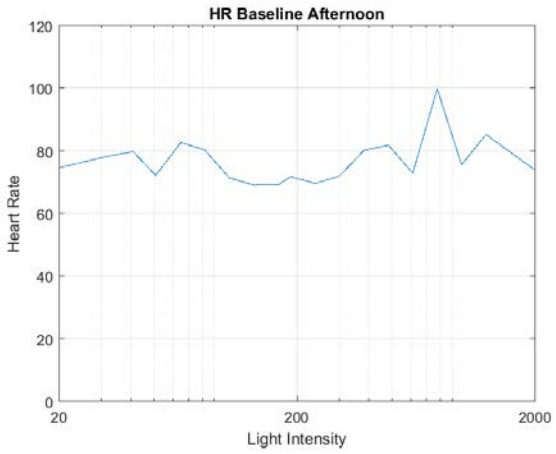
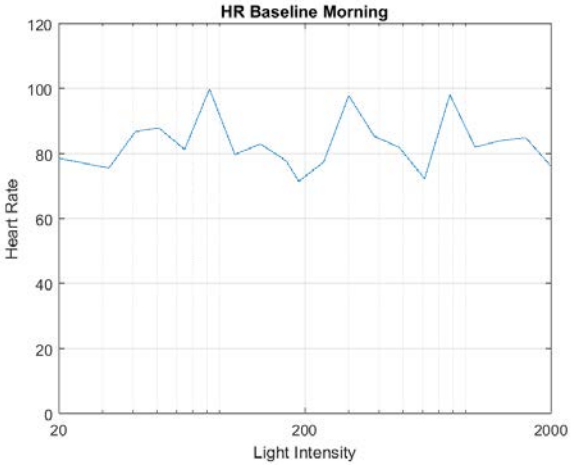
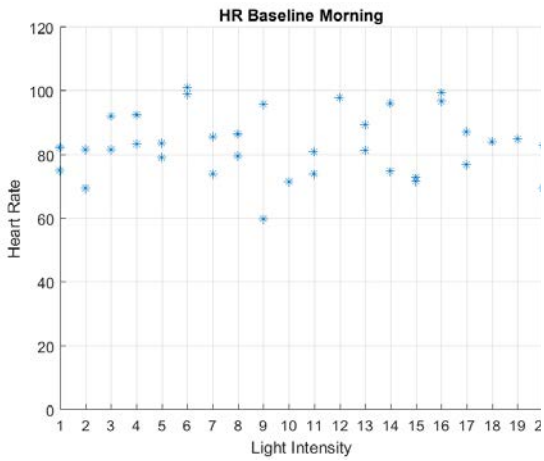
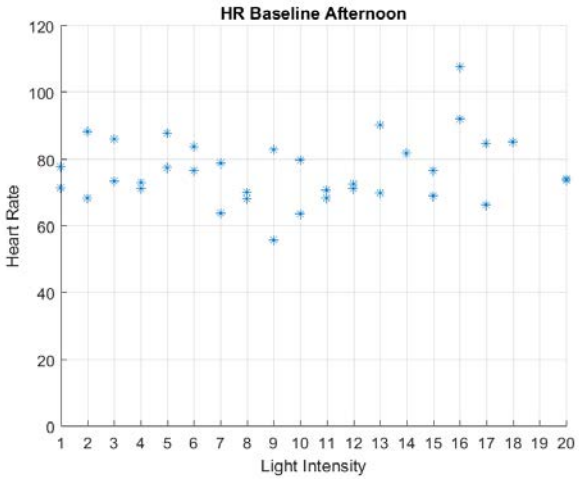
KSS Score
Light Intensity


HR Baseline Afternoon
Heart Rate
Light Intensity


HR Baseline Morning
Heart Rate
Light Intensity


HR Baseline Morning
Heart Rate
Light Intensity


HR Baseline Afternoon
Heart Rate
Light Intensity