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Effects of Spectrally Varied Lighting Conditions on Cognitive Performance, User Preference, and Cardiac Effort in Indoor Lighting Environments During Daytime

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Abstract

The time spent indoors under artificial (electric) lighting has continued to increase and currently amounts to up to 90% of the day. Light is the most important stimulus for the circadian rhythm and has, besides long-term effects, also a direct impact on emotional and physiological aspects such as sleepiness, alertness, or performance. This article presents the results of two studies investigating the acute effects of light during morning and early afternoon on people in a controlled office environment. Melanopically optimized lighting conditions, and a dose–response dependency are investigated, measuring cognitive performance, subjective sleepiness, and user preferences of the lighting scenarios as well as cardiac effort. The results show a dependency in subjective sleepiness ratings depending on light conditions and time of day. Further parameters did not show any statistical differences. The presented studies extend the findings of acute light effects during the day but are limited due to relatively small sample sizes.

Keywords: lighting conditions; non-image forming effects; acute effect of light; time-of-day-dependent effect; well-being; work performance; user preference; light spectra variation; MEDI

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1. Introduction

Light not only serves as the foundation of the visual process but also exerts numerous physiological effects on the human body and well-being. Since industrialization, the time spent indoors under artificial electric lighting has continued to increase and currently amounts to approximately 90% of the day [1]. Having a valid metric to specify and plan indoor working spaces is important for all people who work and live in buildings (e.g., offices, industrial halls, schools, hospitals, homes). Therefore, it is necessary to optimize indoor lighting conditions to prevent room users from experiencing poor lighting and to enable sustainable well-being that increases alertness, emotion, and performance. Modern LED-lighting enables lighting systems to generate designed individual lighting solutions that can create different spectral distributions and illuminance levels. Variable use of correlated color temperatures (CCTs) can enable different melanopic values and light colors for different contexts. Furthermore, metameric effects can be used to optimize well-defined chromaticities and CCTs with variable non-visual impacts. This is especially interesting for the optimization of lighting designs to improve the well-being of office workers and, at the same time, save energy and support the subjective preferences of CCTs.

Levels of lighting are often based on the visual requirements for visual processes (e.g., perception of movement, reading of documents, handling of mechanical tools) and do not consider the non-visual effects. In this context, the circadian rhythm is mainly regulated by the dark–light cycle while having long-term effects on health and well-being. Low indoor lighting levels can lead to desynchronizations of the internal clock, social jetlag, and the resulting health problems [2,3]. Good lighting conditions can support the physiological and psychological needs of users with regard to the optimal activation of the human visual and non-visual systems, which can contribute to improved sleep quality, overall well-being, and health [3–7]. Brown et al. (2022) published a scientifically indicated consensus on minimum values for the day (250 lx MEDI) and maximum values for the evening (10 lx MEDI) and nighttime (1 lx MEDI) for melanopic-equivalent daylight illuminance (MEDI) [8]. In Germany, the DIN/TS 5031-100 recommended a lighting design in indoor spaces to have a minimum melanopic-equivalent daylight illuminance (MEDI) of $E_{mel,D65}$ = 240 lx [9].

Besides long-term effects of light on the human body and well-being, there are also acute effects, like melatonin suppression at night or circadian phase shifts. These effects are well researched, as well as the physiological sensitivity of the included photoreceptors in the eye [10–16]. In addition to its effects at night, light also has acute effects during the day on alertness, attention, and cognitive performance [5,12,17–21]. The effect of light depends on the light intensity (melanopic-effective illuminance and luminance), light spectrum, time of day, exposure time, and the spatial distribution of light within the field of view [22].

To investigate the short-term effects of light, subjective measures lack significance because of the short time and subjective nature of the data [19,23,24]. For this reason, the design of recent studies includes both subjective and objective parameters to investigate the acute effect of light. Higher illuminance levels lead to an increase in subjective attention as well as higher physiological stimulation in heart rate and heart rate variability [18,25]. Light can also influence current physiological state, measured with EEG, during the day [26–29].

In the context of physiological analysis, the pre-ejection period (PEP) parameter offers the potential of a sensitive parameter that can be used to derive the mobilized cardiac effort of a task by measuring ECG and ICG [30,31]. Lasauskaite et al. [29] showed that mental effort is influenced by light stimuli at a constant illuminance level of 500 lx (at 2800 K (245 lx MEDI), 4000 K (339 lx MEDI), 5000 K (373 lx MEDI), and 6500 K (462 lx MEDI)), with an exposure duration of 15 min. With a higher CCT, less mental effort needs to be mobilized to work on a similar task, which means that the body must expend less energy for the same task [30]. They also showed that a light stimulus of under 4 min does not show any effect [32].

Zauner et al. investigated the acute effects of daily light settings in a test environment with a horizontal illuminance level of 500 lx and varying light MEDI levels at the eye (54 lx MEDI (2700 K), 128 lx MEDI (4000 K), and 241 lx MEDI (7000 K)). The results indicate that reaction time and task load are independent of the lighting condition, but that afternoon light has a stronger activating influence on cardiac effort, where lighting conditions of 4000 K had the strongest effect [33].

Melatonin suppression at night and the phase shift have also been well researched with a well-recognized establishment of a data-based dose–response function [34]. There is still a need for research during the day due to the complexity of physiological and psychological functions and the many influencing factors [19,20,35].

This paper examines the direct, acute effect of light on subjects in an office environment with the motivation of providing additional data and knowledge for an optimal light condition that has a positive effect on people. Two hypotheses are formulated and investigated:

(1) The melanopically effective illuminance influences cognitive performance at the office workplace during the morning and afternoon.
(2) The time of day influences the acute light effect.

The main parameters used are subjective sleepiness, performance tests, and the pre-ejection period (PEP) as a physiological marker. Two studies are being conducted: Study 1 considers lighting conditions optimized for the same melanopic-equivalent illuminance. Furthermore, this study is extended by a single-person experiment with eight trials in each condition. To the best of our knowledge, this is the first documented attempt in the field of ipRGC-related effects on cardiac effort in such a controlled, repeated-measures format within a single subject. Study 2 considers the lighting conditions for a dose–response approach in the morning and early afternoon.

2. Materials and Methods

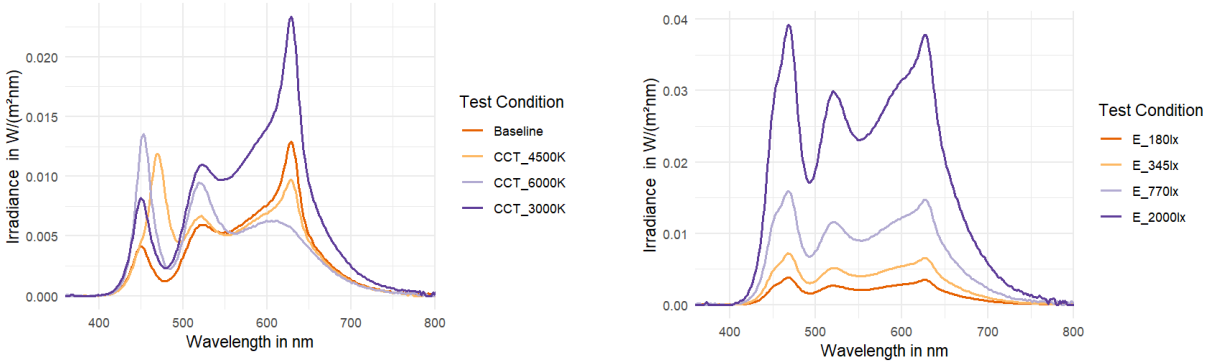
Participants: Two separate studies were conducted: Study 1 and Study 2. The first study was conducted from March 2019 to January 2020, coinciding with the onset of the pandemic. It is a randomized-controlled trial test design with 33 participants (10 female and 23 male, with an average age $MEAN_{age}$ = 26.3 years, SD_{age} = 5.3). These participants are randomly assigned to one of the four test conditions. All participants have normal view characteristics, and they had no color vision deficits, which were tested with Ishihara and Ishikawa test sheets. The participants are filtered by their chrono-type; only those with moderate scores (MSFSC-Score > 2.5 and <5, calculated by the MCTQ-Questionnaire [36]) could participate in the study. These thresholds were applied to exclude extreme morning or evening types to control for personal performance rhythms and to ensure that participants were likely to be naturally active and alert during the morning testing sessions and not during their biological night. The distribution of all participants was $MEAN_{MSFSC}$ = 4.2 and SD_{MSFSC} = 1.7. Very early and late types were excluded from the study [2]. Also, participants with signs of poor sleep quality, evaluated by the PSQI questionnaire (PSQI-Score > 10), were excluded from the experiment ($MEAN_{PSQI}$ = 4.5, SD_{PSQI} = 1.8). A score higher than ten can indicate poor sleep quality or sleep disorders.

Evaluating the age distribution of the participants regarding age and BMI shows no significant difference in BMI distribution ($p > 0.05$), but a difference in age between the four test groups ($p < 0.05$). The group with CCT = 6000 K and baseline had a greater variance in the age distribution, also with older participants. Because of the small sample size, the experiment was extended with a further series of 32 trials with one male participant with the following features: age = 32 years; $MCTQ_{MSFSC}$ = 4.04; PSQI = 5, and BMI = 26. This participant is the main author of this paper, and by a secret randomized order of the light settings, the potential bias was minimized in this experiment. This is, to the best knowledge of the authors, the first one-person experiment on this topic.

The second study was conducted during the COVID-19 pandemic between October 2020 and February 2021, as a within-subject design with 20 participants (6 female and 14 male) with an average age of 25.5 years (SD_{age} = 4). These participants were randomly assigned to one of the two time slots in the morning. No participants had a color vision deficit, again tested with Ishihara and Ishikawa test sheets. As described for Study 1, the participants were filtered by their chrono-type; only moderate scores (MSFSC Score > 2.5 and <5), calculated by the MCTQ-Questionnaire [36], could participate in the study. The distribution of all participants was $MEAN_{MCTQ}$ = 3.5 with SD_{MCTQ} = 0.75. The sleep quality test with the PSQI questionnaire (PSQI-Score > 10) was evaluated, with $MEAN_{PSQI}$ = 8.17 and SD_{PSQI} = 2.4 (not normal distributed). BMI values had a normal distribution with an average BMI = 23 (SD = 2.8).

Spectral Optimization of the Tested Lighting Conditions

In Study 1, the metameric effects of perception are used to optimize lighting situations depending on ipRGC-influenced effects of light, described by the actual metric of the melanopic-equivalent daylight illuminance (MEDI, [8]). A specially developed light engine based on two luminaires ARRI Skypannel S60-C [37], extended with a self-made 5th LED-channel containing 475 nm cyan LEDs, allows for optimizing spectral distributions. The baseline condition is set to 3000 K with a vertical photopic illuminance at the eye level of 450 lx, resulting in $E_{mel,D65}$ = 217 lx. The second and third light settings have a higher melanopic EDI $E_{mel,D65}$ = 405 lx, with a CCT of 4500 K and 6000 K. These are spectrally optimized with the aim of getting the same daylight equivalent illuminance. The final and fourth lighting condition uses the baseline spectral power distribution, but the daylight equivalent illuminance is set equal to that of the 4500 K and 6000 K conditions by increasing the illuminance level. The test conditions are characterized by taking luminance pictures (maps) with a calibrated luminance camera by the company Technoteam LMK 5_1 color (TechnoTeam Bildverarbeitung GmbH, Illmenau, Germany) with a 192° Fisheye camera lens at eye level of the participants. This corresponds to DIN EN 12464 [38] at 120 cm high at the edge of the desk: The spectral irradiance at the same observer's eye position is measured by the spectroradiometer Gigahertz CSS-45 and displayed in Figure 1. The luminance maps are shown in Figure 2 to visualize the light distribution in the room from a participant's field of view.



(**a**) (**b**)

Figure 1. The spectral irradiance of Study 1 (**a**) and Study 2 (**b**). The measurements were carried out vertically at a height of 120 cm at the average eye position of the participants during the study using the spectroradiometer CSS-45 (Gigahertz Optik GmbH, Türkenfeld, Germany).

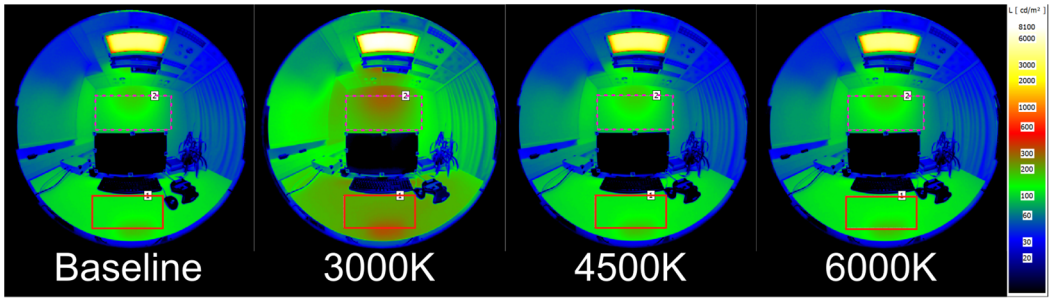


Figure 2. Luminance maps of Study 1, measured with a fisheye camera lens vertically at 120 cm high at the edge of a desk (this is the average eye position of the participants during the study). The solid red boxes mark the area on the desk, while the dotted ones mark the area on the wall above the monitor.

The pixel-resolved luminance distributions inside different geometries of fields of view (FOV) [39] are calculated by masking the measurement results and converted to the melanopic illuminances on the eye, which are summarized in Table 1. Data is provided by the luox framework [40] and can be downloaded from the databases luox-Study-1-Baseline-3000K and luox-Study-1-4500K-6000K (accessed on 14 August 2025).

Table 1. Characteristics of lighting conditions of Study 1, evaluated from spectrally measured illuminances at the average eye position of the participants during the study, at a vertical height of 120 cm.

	Baseline	3000 K	4500 K	6000 K
Illuminance (lx)	445.4	819.4	445.8	452.0
Illuminance (lx) FOV CIE	222.6	409.4	226.9	228.6
CCT (K)	2998	3020	4502	6013
CIE 1931 xy chromaticity [x]	0.438	0.436	0.358	0.321
CIE 1931 xy chromaticity [y]	0.407	0.404	0.351	0.344
Ra	95.6	95.5	83.9	94.6
R9	77.5	77.2	79.2	73.5
S-cone-opic EDI (lx)	149.9	289.7	316.5	399.4
M-cone-opic EDI (lx)	362.5	668.4	417.7	440.4
L-cone-opic EDI (lx)	450.4	828.8	453.6	446.5
Rhodopic EDI (lx)	258.0	479.1	401.9	418.3
Melanopic EDI (lx)	217.5	406.2	404.2	399.4
Melanopic EDI (lx) (FOV CIE)	110.8	206.1	208.8	203.1
CLA_{2018}	436.7	819.4	509.3	541.1
CS_{2018}	0.39	0.50	0.42	0.43
CLA_{2021}	348.8	659.7	552.9	545.1
CS_{2021} (t = 1; f = 1)	0.35	0.46	0.43	0.43

To investigate a dose–response relationship in Study 2, the four lighting conditions are generated for different melanopic EDI. During the dark period, an illuminance of 0.8 lx is measured at the position of the eyes of the participants. During preparation for the experiments, the light condition was 2700 K with 100 lx (MEDI is 43 lx) vertical at eye position. For all four main test conditions, the relative spectral distribution corresponds to a CCT of 4000 K, while the intensity level changes according to Table 2 with the following lighting conditions:

- 180 lx (MEDI: 151 lx).
- 345 lx (MEDI: 288 lx).
- 770 lx (MEDI: 651 lx).
- 2000 lx (MEDI: 1637 lx).

Table 2. Characteristics of lighting conditions in Study 2, evaluated from spectrally measured illuminances at the average eye position of the participants during the study, at a vertical height of 120 cm.

	180 lx	350 lx	770 lx	2000 lx
Illuminance (lx)	177.1	339.0	763.3	1962.3
Illuminance (lx) FOV CIE	91.1	175.7	386.9	1005.9
CCT (K)	4480	4492	4536	4441
CIE 1931 xy chromaticity [x]	0.359	0.359	0.357	0.361
CIE 1931 xy chromaticity [y]	0.352	0.353	0.350	0.355
Ra	89.1	89.6	89.9	90.5
R9	93.5	94.4	94.1	94.3

Table 2. *Cont.*

	180 lx	350 lx	770 lx	2000 lx
S-cone-opic EDI (lx)	127.0	241.0	560.5	1371.9
M-cone-opic EDI (lx)	164.2	314.4	708.3	1813.0
L-cone-opic EDI (lx)	179.4	343.0	772.6	1984.1
Rhodopic EDI (lx)	153.2	292.6	660.5	1670.6
Melanopic EDI (lx)	151.3	288.4	651.6	1637.4
Melanopic EDI (lx) (FOV CIE)	82.8	160.3	353.5	891.7
CLA_{2018}	186.7	357.3	882.7	2324.8
CS_{2018}	0.23	0.35	0.51	0.62
CLA_{2021}	207.0	395.7	942.6	2468.5
CS_{2021} (t = 1; f = 1)	0.25	0.37	0.52	0.63

This intensity selection is based on knowledge of research on dose–response relationships [23,24,34,35]. Absolute vertical spectral irradiance at the eye position (see Figure 1, right diagram) can be downloaded at luox-Study-2-180lx-350lx and luox-Study-2-770lx-2000lx (accessed on 14 August 2025). The horizontal illuminances which were measured in the middle of the table of the test subject are $E_{v,180lx}$ = 207.5 lx; $E_{v,345lx}$ = 398.2 lx; $E_{v,770lx}$ = 894.5 lx; and $E_{v,2000lx}$ =2314 lx. Luminance maps are shown in Figure 3 to visualize the light distribution in the room from the participants' field of view.

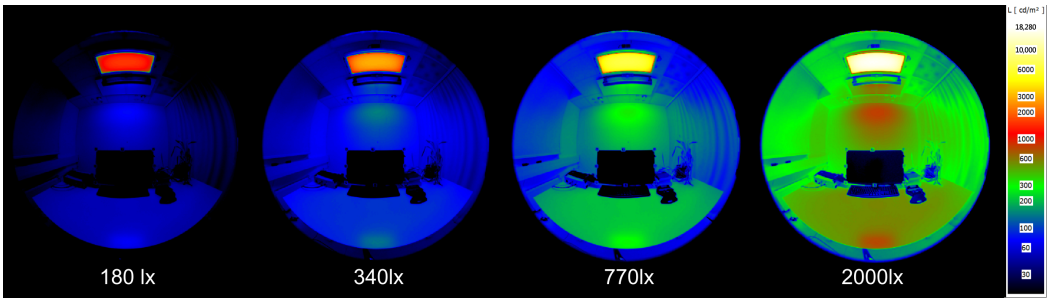
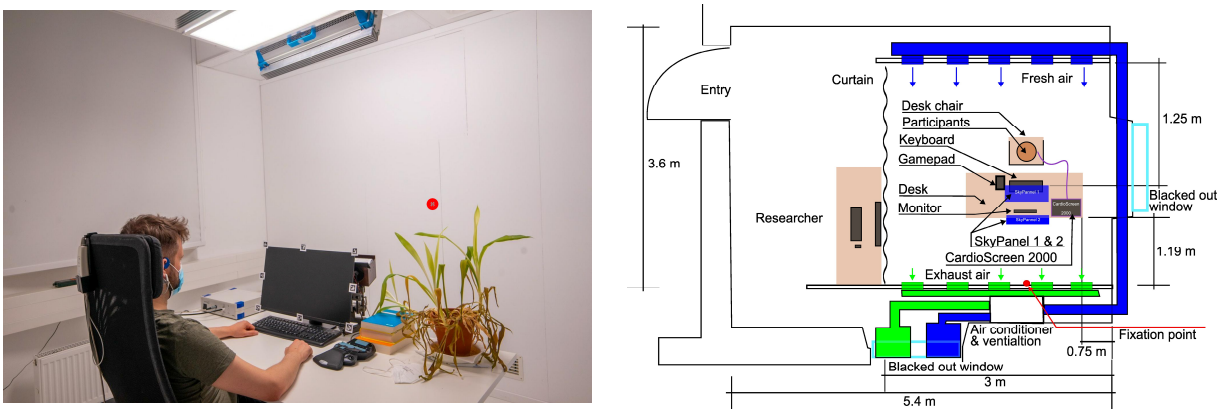


Figure 3. Luminance maps of Study 2, measured with a fisheye camera lens vertically at 120 cm high at the edge of the desk (this is the average eye position of the participants during the study).

Study Setup: The experiment takes place in the test room at the Laboratory of Adaptive Lighting Systems and Visual Processing at the Technical University of Darmstadt (Germany) in a controlled environment. The room is painted completely white and diffuse, air-conditioned, and ventilated for stable and comfortable test conditions. Additionally, the air quality is logged by Extech SD800 (Extech Instruments Corporation (FLIR Systems GmbH), Frankfurt am Main, Germany) to evaluate carbon-dioxide concentration, temperature, and humidity during the experiment. During all the runs, the air quality in the test room is good [41].

The room simulates a realistic office environment. It has a desk with a monitor, keyboard, mouse pad, several books, a plant, and the CardioScreen2000 (medis Medizinische Messtechnik GmbH, Illmenau, Germany) measuring device on the left side of the table. Additionally, to the mouse pad, a game pad with two indicated keys is used for the reaction tests (Sternberg and PVT). The participant takes a seat on the office chair with a head-high backrest and a holder for the measuring device. This secures a mostly fixed position during the physiological measurements. Furthermore, the room is equipped with the two described five-channel LED luminaires, one placed above the desk and one to illuminate the wall in the participants' field of view (see Figure 4). Natural light is blocked by

window curtains, and a red laser marker is projected on this wall as a fixation point. The whole setup, including all dimensions, is shown in Figure 4.



(**a**) (**b**)

Figure 4. Experiment setup in the air-conditioned and ventilated laboratory. (**a**) The participants are seated at a desk in the middle of the room. Two five-channel LED luminaires provide different spectral light distributions. The red point indicates a marker (realized as a printed and red laser dot) used as a fixation point during the experiment. (**b**) Floor plan of the test location.

The study procedure of both studies is very similar, and Study 2 is minimally adapted from the learning effects from Study 1. The participants come to the Laboratory of Adaptive Lighting Systems and Visual Processing of the Technical University of Darmstadt (Germany) some days before the experiment in order to sign the information sheet and declaration of consent. In Study 2, they also receive sunglasses and an introduction to the Messenger-Bot (the messenger app Telegram was used) that is used for the notifications for a sleep diary. Both studies were advertised by brochures in the cafeteria at TU Darmstadt, on the institute's website, and via newsletter to interested people. Both studies were confirmed by the Ethics Commission of the Technical University of Darmstadt.

The experiments of Study 1 are conducted between 8:00 am to 1:00 pm, and each session needed 1:30 h. Study 2 is conducted at three time slots: 08:15 am, 10:30 am, and 2:00 pm, each lasting 1:45 h. The participants arrive at the laboratory with the instructions to come relaxed without great physical exertion, to have had no heavy meal intake, caffeine, or alcohol 2 h before the experiment. Then they are prepared with the electrodes and an ear-clip for the ECG and ICG measurements. The participants are seated on a chair with a fixed backrest position and are asked not to move during specific periods of the experiment. The whole study is automated by a self-developed MATLAB (R2020a) script, and all instructions are read aloud by the system's text-to-speech function, so every procedure is the same for all test subjects. Only the Sternberg and PVT-Task has to be started on the monitor by the researcher, who is always behind a curtain in the room to control the experiment, as shown in Figure 4.

Study 1: All participants were selected as naive participants. To avoid bias, the study was advertised as "Laboratory study to examine the gaze and pupil behavior at office workplaces, to derive statements about sleepiness and concentration". Figure 5 schematically shows the procedure of Study 1, which is described in detail in the following. In the beginning, the participants rate their subjective sleepiness with the Karolinska Sleepiness Scale [42] (so-called KSS1) questionnaire. The Karolinska Sleepiness Scale is rated on an ordinal scale from 1 ("Extremely alert") to 9 ("Extremely sleepy, can't keep awake"). After a dark period of 12 min, light is switched on to the baseline condition. Participants are asked to evaluate subjective sleepiness (KSS2) again. Then the participants are free to read texts in a provided newspaper without glossy pages or illustrations. After

seven minutes, they must stop any movements and focus on the fixation marker to record the PEP-baseline, followed by a KSS rating. During the following ten minutes, the newspaper can be read again, and the light fades linear to the test lighting condition without prior announcement, to leave the participant as naive as possible. Once the test person is in the test spectrum, the fixation point must be focused on. No newspaper reading is allowed at this point. The experiment ends after two cognitive tasks: First, a five-minute Sternberg task [43], which shows a sequence of numbers, and the participant has to answer as quickly as possible whether the following shown number is part of the displayed sequence or not. The parameter of the task was chosen to mirror the experiment of Lasauskaite et al., with a sequence size between three and six numbers [30]. After finishing and rating their subjective sleepiness, the second task—a five-minute PVT reaction task—begins [44]. The experiment is finished with several questionnaires: The German version of the Pittsburgh Sleep Quality Questionnaire (PSQI) [45,46] to evaluate the subjective sleep quality during the last four weeks, the NASA Task Load Index (TLX) [47], and a questionnaire from the Indoor Lighting Experts of LiTG Germany (LiTG: German Society for Lighting, the so-called EFI-Questionnaire) to evaluate the emotional and perceived lighting quality of the whole room [48]. The participants were paid EUR 25.

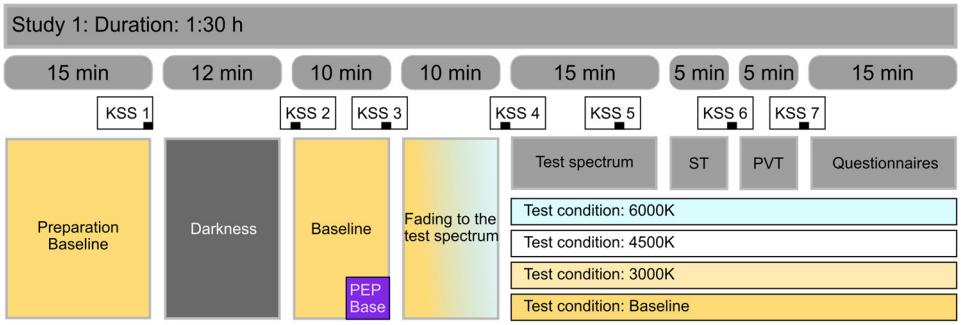


Figure 5. Procedures of Study 1. After preparing the participants for physiological measurements and the first subjective sleepiness rating (KSS1), the study starts with a dark period. Further tests and measurements are conducted as marked in the diagram: KSS: Subjective Sleepiness with Karolinska Sleepiness Scale, PEP: measurement period of pre-ejection period, ST: Sternberg task, PVT: PVT Test, questionnaires: MCTQ (Chronotype), PSQI (sleep quality), EFI (subjective evaluation of lighting), TLX (task load).

For Study 1b, the second intrapersonal experiment, the procedure is the same, without the subjective ratings of the EFI-questionnaire, because of a potentially high bias. The procedure is randomized and automated, so that the test subject participates blindly in the 32 runs.

Study 2 was advertised with the title "Laboratory study to investigate physiological parameters at the office workplace to evaluate the ability to concentrate". This is a within-subject test design. Three days before each study date, each test subject must complete the consensus sleep diary (CSD) [49]. The link to the online questionnaire is always sent via the Messenger-Bot (BotFather Telegram Bot) at 6:00 a.m. and completed after the test subjects wake up. They arrive at the test location wearing the welding goggles provided to limit the influence of daylight on the test subjects. Measurements show that in a worst-case scenario at the height of summer at Ev = 100,000 lx with standard light D65, only 861 lx MEDI would be measured vertically at eye-level. As the study took place in the winter months, a maximum MEDI of 172 lx can be assumed for a maximum 20,000 lx condition during the test period (between 8th October and 20th February). The procedure for Study 2 is shown in Figure 6 and described in more detail in the following. After arriving at the test room, the subjects are prepared, and the experiment starts with the first evaluation of

subjective sleepiness rating with the KSS1-questionaire (see Figure 6). In this experiment, there is no fading from base to test-light condition—it is randomized to one of the four conditions after the dark period. After the light is switched on, the test subjects carry out the second assessment of subjective sleepiness (KSS2). After 20 min, the first PEP baseline is measured without movements and task load, followed by the first Sternberg task for 5 min. The questionnaires and tasks are similar to Study 1. The participants were paid EUR 30 per session, which results in EUR 120 for completing Study 2.

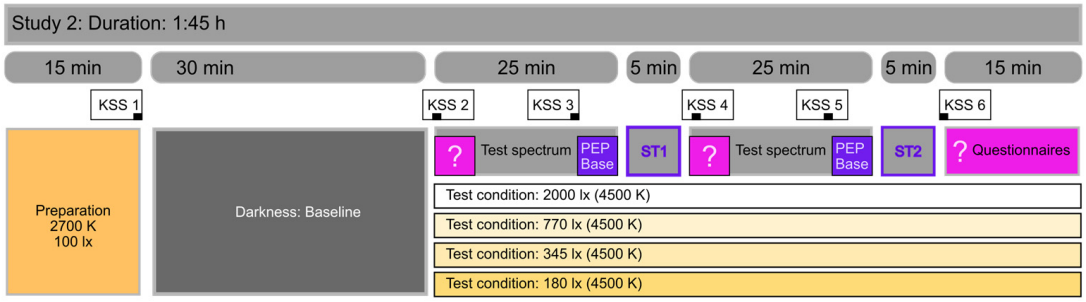


Figure 6. Procedures of Study 2: After preparing the participants for physiological measurements, the test starts with a dark period. Further tests and measurements are conducted as marked in the diagram: KSS: Subjective Sleepiness with Karolinska Sleepiness Scale, PEP: Measurement period of Pre-ejection period, ST: Sternberg Task, Questionnaires: MCTQ (Chronotype), PSQI (sleep quality), EFI (subjective evaluation of lighting), TLX (task load).

Data Analysis: Electrocardiogram (ECG) and impedance cardiogram (ICG) are measured with Cardioscreen2000 (Medis Medizintechnik GmbH Illmenau, Germany) and recorded with CardioVascularLab (version 3.8) software from the company Medis Medizintechnik GmbH Illmenau [50]. Features from the measurements are calculated and derived by the software provided by CardioVascularLab (version 3.8). The cardiac data is exported and further analyzed with all other recorded data with RStudio running R version 4.3.2.

The baseline values are recorded during a three-minute period at the end of the baseline section. The participants are asked not to move and to fix their gaze on a marker on the wall. The instruction takes one minute before the values are recorded. A second period during the light condition is also recorded during the last three minutes of the test spectrum period. To calculate the delta values, the recorded baseline values in a relaxed state without any movements and any task load are subtracted from the PEPmean values during each test episode (defined load by Sternberg and PVT test):

$$\mathrm{DPEP} = \mathrm{PEPtest} - \mathrm{PEPbaseline}$$

All parameters are statistically tested by corresponding statistical methods for the data dependencies in Study 1 and Study 2 described in the next section.

3. Results

3.1. Study 1

Study 1 is divided into part 1a (test subjects) and 1b (a one-person-experiment series). Beginning with the results of the subjective ratings, the subjective sleepiness ratings (see Figure 7, left and right diagrams) evaluated by KSS-questionnaire showed no significant differences between the participants at the start of the experiment; all have a similar sleepiness rating, "awake" (Study 1a: $KSS1_{mean,1a}$ = 3.39 ($\pm$0.27); Study 1b: $KSS1_{mean,1b}$ = 2.84 ($\pm$0.09). After the dark period, there is a significant difference between the groups, H(3) = 11.412; p = 0.0097, with the Kruskal–Wallis test. The post hoc analysis (pairwise comparison with Bonferroni correction) shows a difference between baseline and

3000 K: p_{adj} = 0.0751 (r = −0.645), as well as between baseline and 4500 K: p_{adj} = 0.0549 (r = −0.632). These differences may result from differences in age between the test groups. A Pearson correlation coefficient of r = 0.414; p = 0.016 tends to show a correlation between age and KSS2 rating in Study 1a. During the rest periods of the experiment, there are no statistical differences between light conditions and KSS ratings. Evaluating the sleepiness in study 1b reveals a recognizable difference. Additionally, the data shows a significantly lower variance. This is also recognizable in all other parameters.

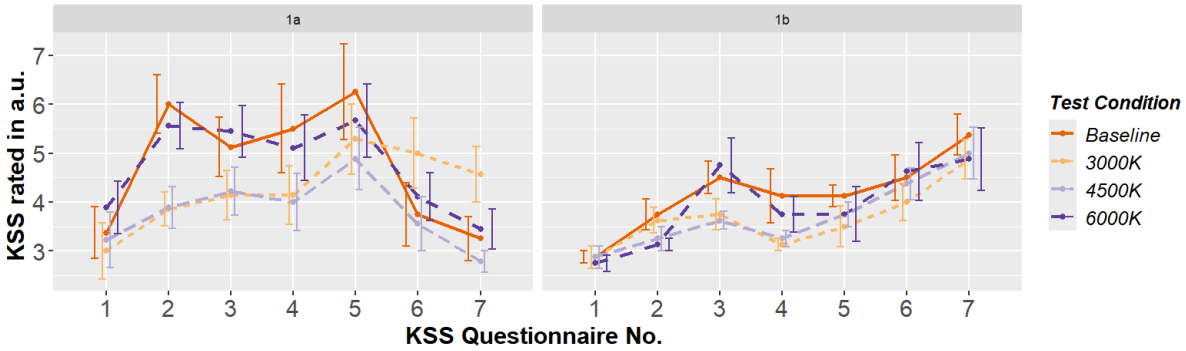


Figure 7. The graphs show the subjective sleepiness ratings of Study 1a on the left and Study 1b on the right. Each point represents the mean values of the test subjects in each test condition with the standard error (SE).

The subjective rated task load (TLX) during the Sternberg task and PVT-test shows no significant differences between the lighting conditions in both studies (1a: H(3) = 2.0152; p = 0.5693; 1b: H(3) = 0.93028; p = 0.8181). It can therefore be assumed that the task load during the tests was similar for all test subjects. The reaction times of both tests did not show any significant differences: Sternberg task (1a: ANOVA F(3, 29) = 0.698; p > 0.561; 1b: pairwise t-test with Bonferroni correction p_{adj} > 0.92) and PVT (1a: ANOVA F(3, 28) = 0.187; p > 0.904; 1b: pairwise t-test with Bonferroni correction p_{adj} > 0.16).

Evaluating the subjective ratings of emotional aspects of the light conditions from Study 1a shows that the subjects tended to rate the artificial light positively, with the 6000 K group rating it best: Kruskal–Wallis test (H(3) = 7.8326; p = 0.0496). Dunn's test (Bonferroni correction) shows differences between 3000 K and 6000 K p_{adj} = 0.0653 (effect size r = 0.637). The baseline is rated darkest, the test subjects prefer the workplace to be brighter at "baseline" (Mean = 0.63) and "3000 K" (Mean = 0.57), and no change is desired at "4500 K" and "6000 K".

The CCT is rated (−3 "very cold "−3 "very warm") and whether the subject prefers it colder or warmer (−3 "significantly colder"−3 "significantly warmer"). There are no statistical differences here; "4500 K" and "6000 K", however, tend to be rated somewhat colder. Individual preferences for the CCT can be identified, but there is no common trend. The questionnaire concludes with an assessment of the general lighting situation: "6000 K" is rated best with $Mean_{6000K}$ = 2; SD_{6000K} = 1, and "3000 K" is rated worst with $Mean_{3000K}$ = 0; SD_{3000K} = 1.15. This pair also differs statistically: the Kruskal–Wallis test (H(3) = 8.2196; p = 0.04168). Dunn's test (Bonferroni correction) shows differences between 3000 K and 6000 K p_{adj} = 0.0659 (effect size r = 0.636). The tendency is that all people are satisfied with the lighting situation. In the assessments of reflection, glare, and flicker, no negative ratings tend to be given.

The mobilized effort, evaluated by DPEP during the Sternberg task, shows no statistical differences in Study 1a and 1b (p = 0.495, baseline—4500 K); Study 1b (p = 0.419, 4500 K–6000 K). As shown in Figure 8, it can be qualitatively shown that in both Study 1a

and Study 1b, the 4500 K lighting conditions tended to require less energy to solve the tasks than the baseline or 6000 K condition, as these have a greater DPEP value.

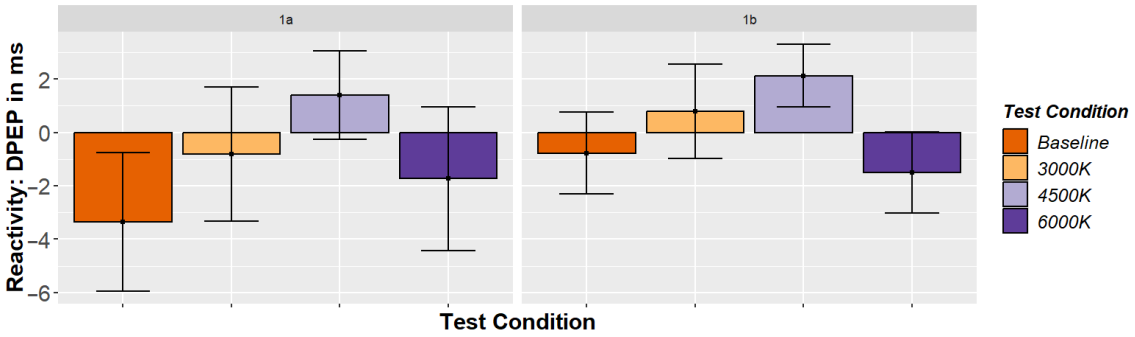


Figure 8. The DPEP measurements of Study 1a and Study 1b are presented, divided by the test condition. Each point represents the mean values of the test subjects with the standard error (SE). The DPEP values in ms represent the difference between exercise and resting states. The more positive the difference is, the less effort is required to solve the task. It is calculated as the difference between the Sternberg task and the baseline condition without any load.

3.2. Study 2

Starting with the results of the subjective ratings, the subjective sleepiness, which is evaluated depending on lighting conditions at different time points of the day, is displayed in Figure 9. The points in time at the start of the study (KSS1) and after the dark period (KSS2) are of particular interest. Subjective sleepiness is rated lowest at the start of the study. Separated into the three starting times (shown in Figure 9), the ratings fall as the day progresses, so the participants are less sleepy in the beginning of the study: KSS1mean, 1 =3.89 (SE = 0.21), KSS1mean,2 = 3.49 (SE = 0.21), and KSS1mean,3 = 3.47 (SE = 0.25). This can only be seen as a tendency, not a statistical difference. A subjective rating of three equals the state "awake".

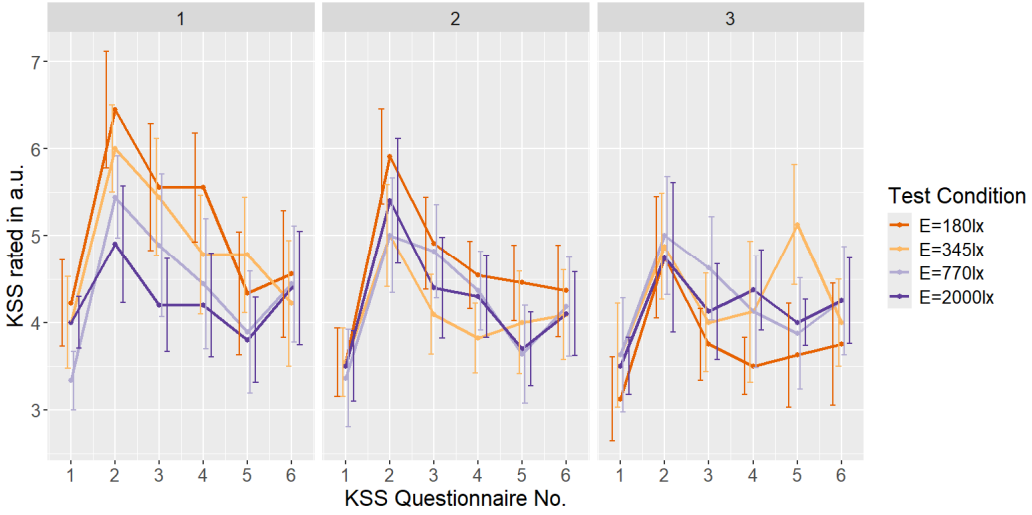


Figure 9. The subjective sleepiness ratings (KSS) of the test subjects from Study 2 at the three start times: 1: 08:15 (n = 37), 2: 10:30 (n = 43), and 3: 14:00 (n = 32) (from left to right). The x-axis represents the KSS questionnaires 1–6, and on the y-axis, the corresponding ratings with 1—"extremely awake" to 9—"extremely sleepy (fighting sleepiness)".

Evaluating the direct light effect after the dark period and the assessed sleepiness with KSS2, the earliest session at 8:00 am had the biggest rise in subjective sleepiness after the dark period in condition "180 lx" (mean rating 6.4: 7- "sleepy, but no difficulty

remaining awake") with the biggest difference to the "E = 2000 lx" lighting condition. This results in the sole tendency towards statistical differences (repeated measures ANOVA) F(3, 21) = 2.525; p = 0.085 (f = 0.43). All other sleepiness ratings do not show any statistical differences during any time period, but in general, a two-way ANOVA shows that time of the day has an impact on the acute influence of light directly after the dark period, rated with KSS2: F(1104) = 3.182; p = 0.07; f = 0.176.

The subjectively rated task load (TLX) during the Sternberg task and PVT test shows no significant differences between the lighting conditions during both the Sternberg tasks (Kruskal–Wallis test $p > 0.5536$). Evaluating the CSD (Consensus Sleep Diary), there is a correlation between the average sleep duration during the four days before the study date and the sleep duration on the study day. The sleep duration on the study day at start time 1 (08:15 a.m.) is on average (±SE) $t_{SleepDuration,1}$ = 6.87 h (±0.13), at start time 2 (10:30 a.m.) $t_{SleepDuration,2}$ = 7.84 h (±0.12), and start time 3 (02:00 p.m.) $t_{SleepDuration,3}$ = 7.88 h (±0.17). Statistically, there is a significant difference between start time 1 and the other two points of time, with H(2) = 28.845; $p < 0.01$ (due to the non-normal data distribution, the Kruskal–Wallis test is used).

Since the test subjects were randomly assigned to the start times, the shortened sleep duration appears to be attributable to the start time of the study at 08:15 am and may explain the differences in the KSS ratings (see Figure 9, left diagrams). Sleep quality rated with CSD also correlates between the four days before and the day of the study, which was rated as follows with a tendency to good sleep quality: $t_{SleepQuality,1}$ = 3.68 (±0.13), $t_{SleepQuality,2}$ = 3.57 (±0.15), and $t_{SleepQuality,3}$ = 3.44 (±0.13). Statistically, there are no differences; also, the shorter sleep duration of start time 1 seems to have no negative effect on the sleep quality.

Evaluating the subjective ratings on emotional aspects of the light conditions shows that during all starting times, "2000 lx" is rated brightest and "180 lx" darkest. CCT is rated as neutral. There are no differences in the frame of these experiments here, neither depending on the start time nor on the lighting condition. At start time 1 (08:15 a.m.), 180 lx tends to be rated slightly warmer than the other lighting conditions. The well-being shows no statistical differences; the test subjects feel rather comfortable. The room is rated as rather ugly and boring. The satisfaction with the artificial lighting is also rated rather well. The time of day does not appear to have any influence here, but the lighting condition does. At start time 3, the 770 lx condition tends to be the one with the highest satisfaction (Kruskal–Wallis: H(3) = 5.9683; p =0.1132); post hoc Dunn's test: p_{adj} = 0.0972; effect size r = 0.601). At start time 2, 345 lx and 770 lx tend to be rated with the highest satisfaction. Finally, general satisfaction with the lighting situation is assessed and tends to be rated positively overall, with the lighting conditions at 345 lx and 770 lx tending to be rated better. This is also the case if all data is considered independently of the time of day. No negative ratings tend to be given for the assessments of reflection, glare, and flicker. The 2000 lx lighting condition tends to cause more glare than the other lighting conditions, which is due to the significantly higher luminance of the luminaires used, SkyPanel. However, the ratings here are in the positive, not disturbing range. With a few outliers, all test subjects rated the flicker as imperceptible.

Evaluating the cognitive performance, the reaction times during both Sternberg tasks show nearly no differences depending on time of the day or lighting conditions. There is only a difference in the afternoon, between conditions "345 lx" and "770 lx" of Sternberg task 1, where the subjects in "345 lx" were faster: F(3, 21) = 3.069; p = 0.05; f = 0.662. Sternberg task 2 shows a tendency between the lighting conditions (ANOVA "repeated measure ": F(3, 27) = 2.524; p = 0.079; f = 0.529). "2000 lx" tends to have faster reaction times than "180 lx" (post hoc test: p_{adj} = 0.112; d = 0.906).

Evaluating the mobilized cardiac effort to solve the tasks tends to show that, regardless of the start time, the least energy is required under the light condition of 345 lx, while the highest energy expenditure is required at 180 lx. The lowest DPEP value is measured here during starting time 1 (p_{adj} = 0.027; d = 1.191) (see Figure 10). Due to the small group sizes and the high scattering, however, it is not possible to make a clear statement about the course of the day in relation to the start times. There are differences between Sternberg tasks 1 and 2: the values of Sternberg 2 (after 55 min test light condition) were smaller compared to Sternberg 1.

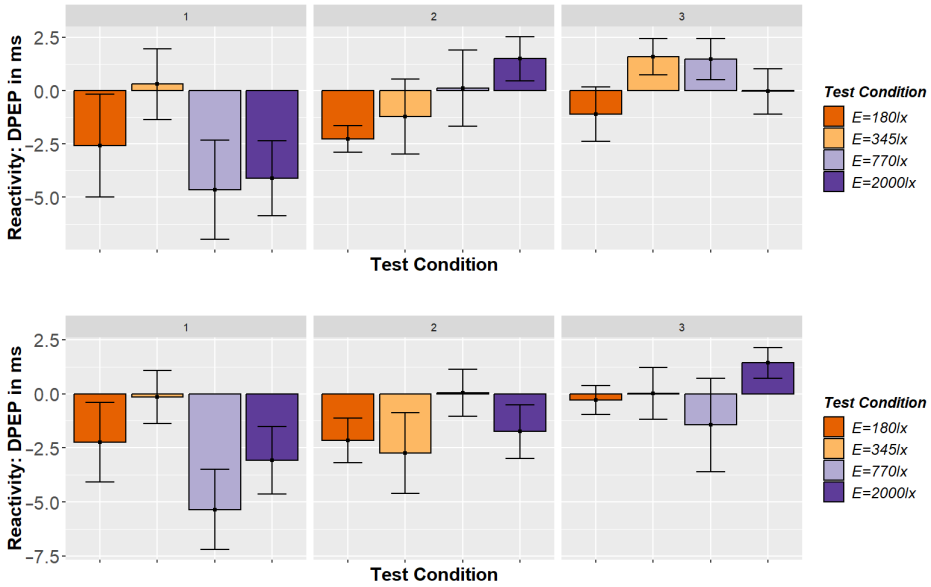
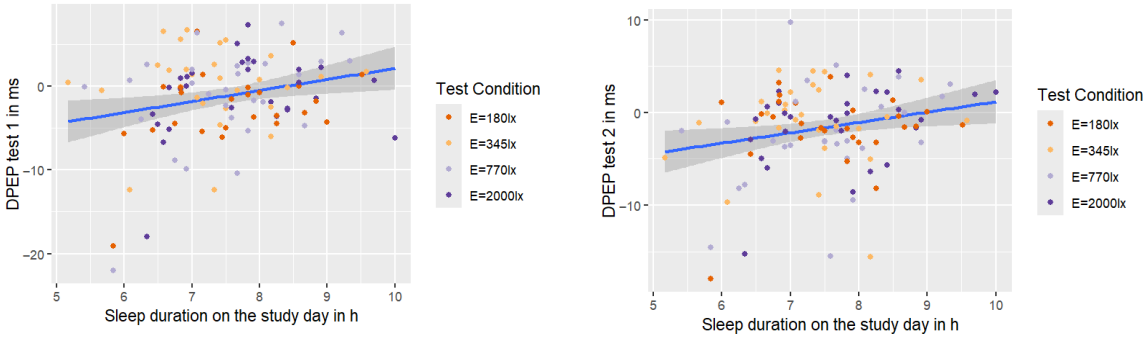


Figure 10. The top graph shows the reaction values of the DPEP during the 1st Sternberg task. The bottom graphs show the results during the 2nd Sternberg task. Shown are the mean values at start times 1: 08:15 a.m. (n = 40), 2: 10:30 a.m. (n = 40), and 3: 02:00 p.m. (n = 32) (from left to right). The DPEP values in ms represent the difference between exercise and resting states (same lighting condition without any load). The more positive the difference is, the less effort is required to solve the task. Each bar represents the mean values of the test subjects with the standard error (±SE).

When examining the influence on the necessary mobilized energy, both tests show a correlation with the duration of sleep the night before studying: a Pearson correlation coefficient of r = 0.248 (p = 0.009) result for Sternberg task 1, and a correlation coefficient of r = 0.231 (p = 0.014) for Sternberg test 2. Both datasets are shown in Figure 11.



(**a**) (**b**)

Figure 11. The correlation of DPEP during Sternberg tasks and sleep duration during the night before the study: (**a**) task 1 has a Pearson correlation coefficient of r = 0.248 (p = 0.009), and (**b**) task 2 has a correlation coefficient of r = 0.231 (p = 0.014).

4. Discussion

Study 1 investigates the acute effect of light in an office environment during the morning time in different melanopically optimized lighting conditions. The study was extended with a one-person experiment. As an experimental supplement to the main study, the data shows a smaller variance in the individual data (Study 1b) as well as an individual KSS course during the study compared to the other participants, showing that generalization is limited. Another limiting factor is the long period during which the study data was collected, resulting in possible seasonal influences, which were not focused on in Study 1 but may have an impact on the effects of light.

The rise of subjective sleepiness as an acute effect of light has also been described by Chellappa et al. [51]. Subjective sleepiness does not appear to be dependent on the subjective perception of CCT. With a melanopic EDI value of at least $E_{v,mel,D65,eye}$ = 217 lx and a vertical illuminance of $E_{v,eye}$ =450 lx at the eye position, all lighting conditions are at a relatively high level. The TLX questionnaire in both studies shows no difference in the subjectively perceived task load between the lighting conditions. There is also no statistical difference in reaction times. This confirms the findings of many research groups that the acute light effect has no influence on reaction times [20,23,30,33]. The evaluation of the DPEP values shows that the two light conditions, 3000 K and 4500 K, tend to be favored for task execution, as less effort must be mobilized. However, these are trends, as no statistical differences can be observed due to the small sample size, not least due to the COVID-19 conditions during the study period and the large variance.

Comparing the results of Lasauskaite et al. [29], DPEP values increase with rising melanopic EDI, meaning that less energy must be mobilized. The levels range from $E_{v,mel,D65,eye}$ = 245 lx at 2800 K to $E_{v,mel,D65,eye}$ = 462 lx at 6500 K, resulting in a significant difference in the DPEP values between the 6500 K and 4000 K pair [30]. In Study 1, the melanopic EDI values $E_{v,mel,D65,eye}$ = 405 lx are similar to the level of the 6500 K light condition of Lasauskaite et al. This supports that no differences in the response of PEP values were measured during the task. Zauner et al. [32] used in their experiments melanopic EDI levels that are significantly lower than those in this study, with a maximum at $E_{v,mel,D65,eye}$ = 241 lx.

Study 2 examines a dose–response relationship at an exemplary office workplace in a controlled environment during daytime. The illuminance is varied in four lighting conditions (180 lx, 345 lx, 770 lx, and 2000 lx) in addition to the time of day (three start times). Difficulties were encountered in recruiting test subjects in both studies due to the COVID-19 pandemic, which limited the sample size. As a result, Study 2 was converted to a "within-subject" test design. The small number of test subjects is also reflected in the scattering of the data collected. The timing of Study 2 was optimized to reduce the potential influence of daylight. It was conducted exclusively during the dark winter months from October 2020 to February 2021. From the second intensity level onwards, the visual requirements are met, and the non-visual minimum values according to Brown et al. are also met during the day [8]. The subjective sleepiness shows a dependence on the time of day and the lighting conditions; high intensities have a significant acute effect in the morning. The physiological parameters tend to show a U-shape with a maximum at 345 lx, independent of the time of day. Separated by start time, there are different curves depending on the melanopic effect.

The emotional aspects of the room on the subjective evaluation of the lighting situation show no statistical differences and no dependency on time of day, although 345 lx and 770 lx tend to be rated best in terms of general satisfaction. Subjective preferred light levels from other studies, like Boyce, Tops et al., and Klir et al., summarized in their work, indicate that a horizontal illuminance on the table of approximately 1500–1700 lx are most preferred

by the participants [52–54]. For an indoor environment with a moderate contribution of diffuse light, e.g., by the diffuse walls, ceiling, and other indoor objects, the resulting vertical illuminance at eye level can be approximately calculated on a rule of thumb, based on our experiences, as half (0.4–0.6 times) of the horizontal illuminance measured on the table. So, a horizontal illuminance of 1500–1700 lx would correspond in such a working room with a substantial amount of diffuse light components to the vertical illuminance of 770 lx condition from Study 2.

Cajochen et al. found a dose–response relationship for the nighttime (as an S-curve), which shows half of the effect in the parameters from 90 to 180 lx [34]. Smolders et al. [35] and Lok et al. [23] were unable to evaluate a dose–response curve (20–2000 lx) during the day. There were no dependencies on the reaction time, the KSS evaluations, and the physiological parameters depending on the lighting conditions [23,35]. The statement by Lok et al. [22], that the intensity has no influence on awake and active persons, cannot be confirmed with this study, as the light condition also has an influence on subjective sleepiness in addition to the time of day. Evaluating the CSD sleep diaries shows that at the earliest study start time, the average sleep duration is approximately one hour shorter than at other start times. Therefore, the target group should also be selected more specifically in the future when selecting test subjects, as many in this study were university students who do not always have regularly scheduled weeks.

The first hypothesis, "The melanopically effective illuminance influences cognitive performance at the office workplace during the morning and afternoon", is tending towards being denied, since the light situations within the studies do not show a statistically significant acute impact on cognitive performance (reaction time and error rate of the Sternberg task) or cardiac effort (DPEP). The second hypothesis, "The time of day influences the acute light effect", can be partially confirmed because of the differences and dependencies of the subjective sleepiness ratings (KSS) depending on lighting conditions and time of day.

5. Conclusions and Outlook

This paper presents the results of two studies conducted to investigate the acute effects of light in an office environment during morning and early afternoon. Lighting conditions are created by a five-channel lighting system providing optimized lighting conditions. Study 1 investigated light effects during the morning time under different melanopically optimized lighting conditions. These were spectrally optimized for the same melanopic-equivalent illuminance with different CCTs at the same time. This allows for research into acute light effects in dependence on the spectral distribution (light source spectra) or the CCT. The one-person extension of Study 1 shows a smaller variance in the individual data (Study 1b) as well as an individual KSS course during the study compared to the other participants, showing that generalization is limited. Another limiting factor was the seasonal context, which was not focused on during Study 1 but may have an impact on the effects of light. Study 2 examined a dose–response relationship at an exemplary office workplace. Based on the findings from Study 1, this study was carried out exclusively during the winter months to minimize seasonal effects, particularly those related to daylight exposure. Wearing welding goggles on the way to the test site created another way to limit the influence of daylight. Study 2 took place in a controlled environment during daytime at four anchor illuminance points (180 lx, 345 lx, 770 lx, and 2000 lx) that were varied in addition to the time of day: 08:15 am, 10:30 am, and 2:00 pm. In summary, a vertical illuminance at the eye level of the room user between 345 lx and 770 lx at a CCT of 4500 K seems to correspond to the physiological and subjective needs of the test subjects in the frame of the lighting conditions in these studies. Study 2 shows a clear correlation between subjective sleepiness and the time of day and lighting conditions. This effect

is particularly evident in the morning, during the earliest session at 8:15 am, when the light effect on subjective sleepiness after the dark period was rated with the biggest rise under the 2000 lx condition compared to 180 lx. Most other parameters did not show any statistical differences.

These studies extend the findings of the acute light effect during the day to the reaction of the pre-ejection period (PEP) and the quantified energy mobilized with it, but further investigations with more participants are necessary. Both studies are limited by the small sample size due to the COVID-19 pandemic. Furthermore, no daylight was available in the room, which is required by the workplace guidelines, but these were purely laboratory studies in which as many influencing factors as possible were to be eliminated. The studies focused only on healthy individuals, mainly students. It is important to investigate real office environments over a long period of time, including in all seasons, with more extensive age groups, and expand the investigations with non-healthy participants. Recent research provides important knowledge about tracking the real influence of light by wearable sensors. This could be a valuable tool for further design of field studies and to investigate the influence of light. So future studies should aim to include a broader range of participants, such as older adults or individuals with different health conditions. Long-term investigations in real office environments across different seasons are essential to better understand the dose-dependent impact of lighting on well-being and performance. It would offer important insights into further optimizing individualized indoor lighting to further improve the well-being, health, and comfort of indoor workers.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the Technical University of Darmstadt (protocol code EK 54/2019, 26 November 2019, and protocol code EK 46/2020, 21 September 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study is available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CCT	correlated color temperatures
MEDI	melanopic-equivalent daylight illuminance
PEP	pre-ejection period
MCTQ	Munich ChronoType Questionnaire
MSFSC	sleep-corrected mid-sleep on free days

PSQI	Pittsburgh Sleep Quality Questionnaire
BMI	body mass index
FOV	field of view
KSS	Karolinska Sleepiness Scale
PVT	psychomotor vigilance task
ECG	electrocardiogram
ICG	impedance cardiography
TLX	NASA Task Load Index
CSD	consensus sleep diary

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