Non-image forming effects of illuminance level

Non-image forming effects of illuminance level: Exploring parallel effects on physiological arousal and task performance

L.M. Huiberts, K.C.H.J. Smolders, Y.A.W. de Kort

PII: S0031-9384(16)30289-X
DOI: doi: 10.1016/j.physbeh.2016.05.035
Reference: PHB 11366

To appear in: *Physiology & Behavior*

Received date: 26 February 2016
Revised date: 15 May 2016
Accepted date: 19 May 2016

Please cite this article as: Huiberts LM, Smolders KCHJ, de Kort YAW, Non-image forming effects of illuminance level: Exploring parallel effects on physiological arousal and task performance, *Physiology & Behavior* (2016), doi: 10.1016/j.physbeh.2016.05.035

Non-image forming effects of illuminance level:

Exploring parallel effects on physiological arousal and task performance

L. M. Huiberts[a], K. C. H. J. Smolders[a], & Y. A. W. de Kort[a]

[a] *Human-Technology Interaction, School of Innovation Sciences, & Intelligent Lighting Institute, Eindhoven University of Technology, Eindhoven, the Netherlands*

Corresponding author:

Laura Huiberts, Human-Technology Interaction Group, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, tel: +31-(0)402474470, email: L.M.Huiberts@tue.nl

Abstract

This study investigated diurnal non-image forming (NIF) effects of illuminance level on physiological arousal in parallel to NIF effects on vigilance and working memory performance. We employed a counterbalanced within-subjects design in which thirty-nine participants (mean age = 21.2; *SD* = 2.1; 11 male) completed three 90-minute sessions (165 vs. 600 lux vs. 1700 lux at eye level) either in the morning (N=18) or afternoon (N=21). During each session, participants completed four measurement blocks (incl. one baseline block) each consisting of a 10-minute Psychomotor Vigilance Task (PVT) and a Backwards Digit-Span Task (BDST) including easy trials (4-6 digits) and difficult trials (7-8 digits). Heart rate (HR), skin conductance level (SCL) and systolic blood pressure (SBP) were measured continuously.

The results revealed a significant improvement on the BDST difficult trials under 1700 lux vs. 165 lux ($p = 0.01$), while illuminance level did not affect performance on the PVT and BDST easy trials. Illuminance level impacted HR and SCL, but not SBP. In the afternoon sessions, HR was significantly higher under 1700 lux vs. 165 lux during PVT performance ($p = 0.05$), while during BDST performance, HR was only slightly higher under 600 vs. 165 lux ($p = 0.06$). SCL was significantly higher under 1700 lux vs. 165 lux during performance on BDST easy trials ($p = 0.02$) and showed similar, but nonsignificant trends during the PVT and BDST difficult trials. Although both physiology and performance were affected by illuminance level, no consistent pattern emerged with respect to parallel changes in physiology and performance. Rather, physiology and performance seem to be affected independently, via unique pathways.

Keywords: Lighting; Physiological arousal; Vigilance; Working memory; Alertness; Time of day

Introduction

Since the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) [1-3] in our eye, a large number of studies have been conducted on the acute non-image forming (NIF) effects of illuminance level on alertness, mood, cognitive performance and physiology [e.g., 4, 5, 6]. IpRGCs signal to the suprachiasmatic nucleus (biological clock) in our brain and from there, numerous projections go to brain areas involved in alertness, mood and cognitive functioning [6]. It is known that ipRGCs are especially sensitive to the blue part of the light spectrum (~480 nm [1-3]) and may therefore increase signaling to these brain areas when they are exposed to a high vs. a low dose of light [7, 8]. Although it remains to be established whether these brain activating pathways may explain NIF effects of illuminance level, the reviews mentioned above [4, 5] suggest that bright (vs. dim) light exposure has the potential to increase alertness, cognitive performance, positive mood as well as physiological arousal levels.

Findings reported on NIF effects of illuminance level on *cognitive performance* have not always been consistent. Studies on nocturnal light exposure have revealed positive, but also null effects of bright light exposure compared to dim light exposure [9-13]. Results of diurnal studies are even more inconsistent, showing either null, positive, or negative findings of bright as opposed to dim light exposure [7, 11, 14-18]. In order to develop more healthy light applications that positively affect our vitality and performance during daytime, it is essential to learn more about underlying mechanisms, including potential moderating and mediating variables, which may explain these inconsistencies. The main goal of the current study was to further investigate diurnal NIF light-induced changes in cognitive performance by exploring light-induced changes in autonomous nervous system activity during performance on a relatively easy and difficult cognitive task. By investigating physiology and performance simultaneously, it is possible to explore whether previous inconsistent NIF

effects of illuminance level on cognitive performance may be explained by changes in autonomic nervous system activity.

Previous studies investigating NIF effects of light on physiology have already demonstrated that high compared to low illuminance levels increase autonomic nervous activity as measured by heart rate, heart rate variability, skin conductance levels and muscle sympathetic nerve activity [17, 19-22]. Moreover, studies also revealed changes in brain-related indicators of arousal and alertness under bright versus dim light exposure, for example increases in hemodynamic activity in the Locus Coeruleus [6] and changes in electroencephalographic (EEG) theta and alpha power density [23-25]. In these studies, physiological arousal levels were either measured during cognitive task performance [6, 17, 21, 22] or in rest (sitting or lying down) with eyes open or closed [19, 20, 23-25].

In the study by Rüger et al. [19], increases in heart rate (while sitting still with eyes open and closed) were found during nighttime, but not during daytime bright (5000 lux at eye level) vs. dim light exposure (< 10 lux at eye level). The diurnal study of Smolders et al. [17] revealed increases in skin conductance but not heart rate under bright (1000 lux at eye level) vs. dim light exposure (200 lux at eye level) during performance on an auditory Psychomotor Vigilance Task (PVT). In contrast, Smolders et al. [21] did report increases in heart rate under daytime bright (1000 lux at eye level) vs. dim light exposure (200 lux at eye level) while participants performed a PVT. All in all, similar to NIF effects of illuminance level on performance, NIF effects on physiology also seem to be inconsistent, showing either increased arousal or no significant changes. A previous study in our lab revealed partial evidence for a possible moderating role of task difficulty in the NIF effects of illuminance level on task performance [15]. The current study further investigated the inconsistent NIF effects of illuminance level on task performance by exploring whether illuminance-induced changes in physiological arousal may explain changes in task performance.

The relationship between physiological arousal and task performance was first investigated and described by Yerkes and Dodson [26]. The findings of their lab studies with mice revealed a different optimum level of physiological arousal for easy compared to difficult tasks. More specifically, they found that physiological arousal levels have an inverted U-shape relationship with performance levels in case of relatively difficult tasks (tasks requiring multi-tasking and/or higher executive functions), while the relationship between arousal and performance follows an increasing logistic curve in case of relatively simple tasks (tasks requiring attention for only one stimulus). This so called Yerkes-Dodson Law (YDL) suggests a different optimal physiological arousal level for performance on easy vs. difficult tasks. Later studies also (partly) confirmed the YDL for human subjects [27-30].

Alternatively, physiological arousal levels are known to vary as a function of the difficulty level of a task or, in other words, the amount of cognitive effort that is needed to perform a task [31]. Previous research has demonstrated that physiological indicators such as heart rate [32, 33], skin conductance [34, 35] and systolic blood pressure [35-37] can be used as indicators of the amount of effort one mobilizes to perform a task. These studies conclude that cardiovascular reactivity and electrodermal activity are higher when participants engage in more difficult as opposed to easy tasks, as long as successful performance is possible. In other words, if a task is too difficult or impossible to perform, effort falls and remains low (see Wright [38] for an overview). It is not yet clear which physiological indicator of arousal is the most valid predictor of mobilized effort during cognitive task performance (see Gendolla et al. [31]), but most evidence has been found for systolic blood pressure [31, 37, 39, 40]. This is hypothesized to be the case because systolic blood pressure is largely determined by sympathetic beta-adrenergic activity, which has been found to increase during effortful task performance [38]. Heart rate, on the other hand, is a function of both the sympathetic and the parasympathetic system and can therefore only be a valid predictor of

beta-adrenergic activity as long as parasympathetic activity remains stable [31]. Finally, skin conductance may also be an indicator of effort during cognitive task performance, but likely in a different way than cardiovascular responses. Skin conductance reflects activation of the sympathetic nervous system and is not influenced by the parasympathetic nervous system [41]. Moreover, skin conductance is mainly linked to behavioural inhibition during task performance, while cardiovascular responses are mainly linked to behavioural activation [42]. Therefore, skin conductance activity may show different activity patterns during task performance than cardiovascular activity.

By measuring multiple physiological indicators (heart rate, skin conductance and systolic blood pressure) during task performance under three illuminance levels (165 lux, 600 lux and 1700 lux at eye level), the current study tried to gain more insight in how illuminance level acutely affects physiological arousal levels and performance abilities. More specifically, the aim of the current study was to explore whether previously found increases in physiological arousal levels under bright vs. dim light exposure [19-21] vary with task difficulty and could explain light-induced changes in task performance. Therefore, physiology was continuously measured during performance on a relatively easy sustained-attention task and on a working-memory task consisting of easy and difficult trials.

Based on previous studies showing increased physiological arousal levels under high compared to low illuminance levels, it was expected that light-induced changes in physiology might explain differences in light-induced changes in performance on easy vs. difficult tasks. That is, optimal performance would be reached under different physiological arousal levels during performance on a relatively easy vs. a relatively difficult task because the relationship between physiological arousal and performance is task (difficulty level) dependent [26-28]. Thus, if higher illuminance levels increase physiological arousal levels, optimal performance may be reached on relatively easy tasks but not on relatively difficult tasks.

A tentative alternative hypothesis may be that physiological arousal levels are not directly influenced by illuminance level but via facilitation of task performance. That is, if bright compared to dim light exposure facilitates cognitive performance, one would expect that high as opposed to low illuminance levels would lead to *lower* autonomous nervous system activity (reflecting less cognitive effort mobilization), especially during challenging (but not impossible) cognitive tasks [31].

In addition to exploring the effect of illuminance level on physiology in parallel to performance, two additional aims of this study were to investigate and replicate NIF effects of illuminance level on subjective alertness, vitality and tension, and to assess subjective light appraisals regarding the pleasantness, brightness, colour and level of activation. In line with previous studies, subjective alerting and vitalizing effects were expected under high compared to low illuminance levels, and brighter compared to dimmer light conditions were expected to be rated as brighter, more stimulating, and less pleasant [11, 16, 21].

2. Methods

2.1. Design

This study employed a 3-within (lighting level: 165 vs. 600 vs. 1700 lux at eye level) x 2-between (morning vs. afternoon) mixed-model design. Participants came to the lab on three separate occasions (with at least two days in between sessions) at the same time of the day. They were randomly assigned to register either for morning (9:00-10:30) or afternoon (15:45-17:15) sessions. Moderation of NIF effects of illuminance level by time-of-day was taken into account as this was repeatedly found in previous studies [15, 17, 21].

During each session, participants completed four repeated measurement blocks of cognitive performance tasks (including the Psychomotor Vigilance Task (PVT) and Backwards Digit-Span Task (BDST)). Participants received different versions of the BDST (different number sequences) during each of the three sessions. Task versions as well as order of the light manipulation sessions were counterbalanced across participants. During the first (baseline) measurement block, light levels were the same for every participant (120 lux at eye level). After the baseline block and the final measurement block, participants completed questionnaires on sleepiness, vitality, tension, and mood.

2.2. Participants

Thirty-nine participants (mean age = 21.2; *SD* = 2.1; 28 female, 11 male) completed all three light manipulation sessions. Eighteen participants participated in the morning (7 male) sessions while 21 participated in the afternoon (4 male) sessions.

Participants were recruited at the Eindhoven University of Technology in the Netherlands via the university's participant database. Participants had no visual impairments other than myopia or hyperopia, which were corrected by wearing contact lenses or glasses.

Participants had no hearing impairments, motoric impairments and were not taking any medication other than birth control. They had not travelled across time zones and did not work any night shifts during the month preceding the study. Furthermore, they had no cardiovascular diseases.

Before participation, participants were screened using the Munich Chronotype Questionnaire (MCTQ) in order to exclude extreme chronotypes [43]. Based on the midpoint of sleep on free days corrected for accumulated sleep pressure during working days, participants falling outside the 25%-75% range for the 18-30 years age category (values ranging between 3.74 and 5.75) were excluded from participation [44]. The final sample had a mean chronotype value of 4.71 (SE = 0.09; Min. = 3.77; Max. = 5.75).

2.3. Setting

The laboratory setting was a simulated office environment at the Eindhoven University of Technology with a total size of 3.9 m by 7.4 m, which was separated by a curtain in the middle of the room so that two similar rooms were created.

The laboratory room was equipped with recessed Philips Savio luminaires in the ceiling. Each ceiling luminaire (Philips Savio TBS770 3x54W/827/865 HDF AC-MLO CVC) contained three fluorescent tubes of 54 W, of which two were 6500 K and one was 2700 K. All luminaires have an acrylate micro-lens optic cover, which blends the two lamp types to create a virtually homogeneous luminous surface. Colour temperature was kept constant at approximately 4700K. Using a calibrated spectroradiometer (JETI Specbos 1201), the illuminance level, spectral power distribution (SPD) and colour rendering index (CRI) were measured at eye level aimed in the gaze direction of the participants (while seated, 1.30m). The CRI at 4700K was R_a = 87. Figure 1 shows the SPD at 4700 K of the 165, 600 and 1700 lux conditions.

During the task practice phase and the baseline phase (25 minutes), the ceiling mounted luminaires provided illumination of approximately 120 lux at eye level (photon density: 9.93 x 10^{13} photons*s^{-1}*cm^{-2}; irradiance: 38 μW/cm^2) and 260 lux horizontally on the table surface. After the baseline phase, lighting was set to either 165 lux at 4700 K at eye level (photon density: 1.34 x 10^{14} photons*s^{-1}*cm^{-2}; irradiance: 51 μW/cm^2; 378 lux on the table surface), to 600 lux at 4700 K at eye level (photon density: 4.96 x 10^{14} photons*s^{-1}*cm^{-2}; irradiance: 188 μW/cm^2; 1170 lux on the table surface), or to 1700 lux at 4700 K at eye level (photon density: 1.39 x 10^{15} photons*s^{-1}*cm^{-2}; irradiance: 530 μW/cm2; 3400 lux on the table surface). Illuminance values at eye level for each of the photoreceptors can be reviewed in Table 1. These computations were determined using the calculation toolbox of α-opic illuminance values for corneal spectral irradiance developed by Lucas et al. [45]. These values are based on healthy human eyes (32 years old, dilated pupils, 7 mm).

The furnishing in each workstation consisted of a desk (1.4 m by 0.8 m) and a red chair. A 15.6-inch laptop was placed on each of the desks with a keyboard, in-ear headphones and mouse plugged in. Participants faced the wall opposite to the curtain. The tasks and questionnaires were displayed against a grey background, using a low brightness level that did not hinder reading abilities in all lighting conditions. The lighting measurements were performed with this background on the screen. The laboratory room was set up in such a way that the illuminance levels at eye level on both sides of the room were as similar as possible. Divergences of the illuminance level between the two workstations were minimal: ± 6 lux at eye level in the baseline condition, ± 5 lux at eye level in the 165 lux condition, ± 10 lux at eye level in the 600 lux condition and ± 25 lux at eye level in the 1700 lux condition.

The walls and ceiling of the laboratory room were off-white and had a reflectance of 87%, the floor was grey-blue with a reflectance of 19%, and the desk was light-grey and had a reflectance of 39%. There was no daylight contribution during the experiment.

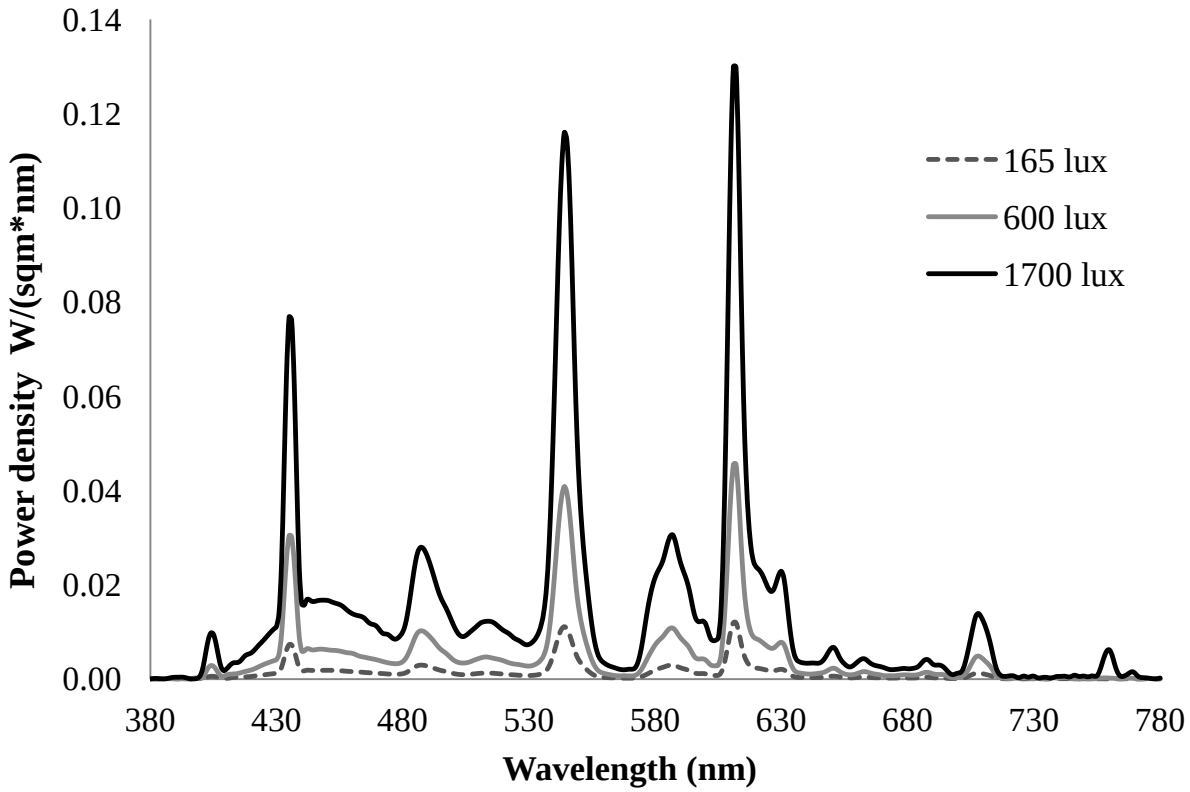

Figure 1. Spectral power distribution measured at eye level in the three lighting conditions (165 lux, 600 lux and 1700 lux, at 4700 K)

Table 1: Spectrally-weighted α-opic lux levels at eye level for each lighting condition based on calculations of Lucas et al. [45]

	λ max	α-opic lux value (165 lux)	α-opic lux value (600 lux)	α-opic lux value (1700 lux)
Melanopsin	480.0	130	465	1267
S-cone	419.0	135	495	1303
M-cone	530.8	153	559	1575
L-cone	558.4	158	585	1662
Rods	496.3	142	511	1413

2.4. Procedure

Before participating in the study, participants completed an online set of questionnaires consisting of several possible confounding variables (global sleep quality, light sensitivity, general fatigue and trait vitality). Participants were asked to keep their sleep-wake timing two days before each experiment session similar to their habitual sleep schedule on workdays (+/- 30 minutes) as reported in the MCTQ.

During their first visit to the laboratory, participants first signed an informed consent form and were guided to their workstation. They were then asked to apply the physiological sensors measuring heart rate (HR), blood volume pulse (BVP) and skin conductance level (SCL) according to instructions given by the experiment leader. After that, the physiological signals were checked, and sensors were re-applied if necessary. Subsequently, participants were informed about the general procedure of the experiment and completed a practice phase in which they rated subjective indicators of state sleepiness, vitality, tension and mood and practiced the PVT and the BDST for a short time. After the practice phase, physiological signals were again checked, and systolic blood pressure (SBP) was measured twice. The

average value of the two SBP measurements was used as a calibration value to continuously calculate SBP during each session (see *2.5.1. Physiological indicators*).

The first measurement block consisted of the baseline phase during which participants completed one measurement block of 18 minutes. This measurement block consisted of a 10-minute PVT and an eight-minute BDST. Subsequently, participants again reported on their subjective sleepiness, vitality, tension and mood. After completing the questionnaires, illuminance levels were set from 120 lux to either 165, 600 or 1700 lux at eye level depending on the experimental condition.

After the final measurement block, participants again completed questions probing state sleepiness, vitality, tension and mood as well as a short questionnaire on time of sleep onset and sleep offset, time spent outside, travelling time outside and caffeine and food consumption before the start of the experiment. In addition, participants evaluated the lighting in the room (i.e., whether it was warm or cold, relaxing or stimulating, dim or bright etc.). A full overview of the experimental procedure is depicted in Figure 2. Participants received a 45-euro compensation after completing all three sessions. The study was conducted from March 16th to June 5th 2015.

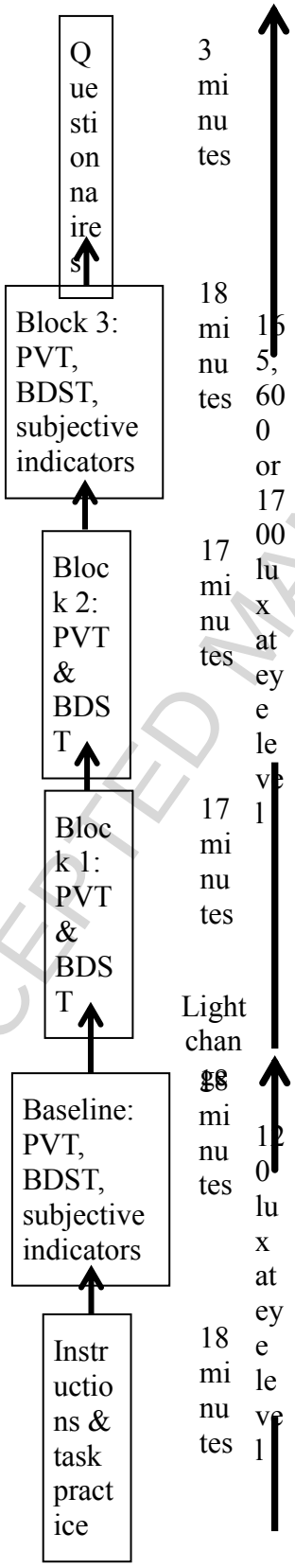

Figure 2. Overview of one experimental session

2.5. Measurements

2.5.1. Task performance

In each measurement block, two auditory tasks were employed to test the effects of illuminance level on vigilance and cognitive performance. The first task of each measurement block consisted of a 10-minute auditory variant of the PVT (referred to as PVT in this paper) as developed by Dinges and Powell [46]. The PVT has been found to measure vigilance levels reliably because of the monotonous, repetitive, and unpredictable nature of target presentation [47]. In contrast to the PVT developed by Dinges and Powell [46], the PVT in the current study did not provide performance feedback. During the task, participants were required to keep their dominant hand rested on the space bar and respond as fast as possible by pushing the space bar after hearing a short 400 Hz beep. Beeps were presented using random inter-stimuli intervals (ISI) between 6 and 25 seconds. The reason for using relatively long ISI was to induce task-fatiguing effects [48] in order to investigate whether illuminance level could impact these fatiguing effects. Sustained attention was measured by average reaction speed on targets (1/reaction times (RT)) during the 10-minute PVT. Average reaction speed (1/RT) of the 10% fastest and slowest trials were also investigated.

The second task of each measurement block was the BDST. The BDST is a relatively difficult task since stored information has to be mentally reversed in working memory, which requires executive functions [49]. The original BDST listen to a sequence of numbers and vocally report the numbers in backward direction afterwards. In the current study, however, participants did not respond vocally but by typing in the sequence in backward direction on a QWERTY keayboard after hearing. Digits were presented similar as in the original BDST (auditory) at a rate of 800 ms. per number. The task started with a sequence of four digits and ended with a sequence of eight digits. The length of the sequences increased with one digit

after each set of four trials with the same length. Participants had a limited time for each sequence, based on the amount of numbers in the sequence (2 seconds plus 2.3 seconds for every digit in the sequence). This was done because the timing of the light change and the duration of the light exposure had to be the same for every session. Total number of correct responses (i.e., correctly reported full digit-spans) per measurement block on easy trials (length four to six) and difficult trials (length seven and eight) were used as dependent variables to measure performance on this task.

2.5.2. Physiological indicators

Physiological arousal was assessed by continuously measuring HR, SCL and BVP using TMSi software with a sampling frequency of 1024 Hz.

To measure HR, three Kendall H124SG ECG electrodes were applied using the lead-II placement: the ground on top of the collar bone near the left shoulder, one electrode under the collar bone near the right shoulder and one electrode underneath the ribs on the left side of the torso. RR intervals were extracted from the raw electrocardiography (ECG) data, and average HR values (beats per minute (bpm)) were subsequently calculated for the duration of each separate task phase using Matlab R2013a. Average HR values during the 10-minute PVT, and during the easy and difficult trials of the BDST were used as dependent variables. Five experimental sessions were excluded from analyses as HR recordings failed during the light exposure period.

In order to measure SCL, two electrodes were used on the left middle and ring finger for all participants. Two participants who were left-handed indicated that they controlled the computer mouse with their right hand, thus SCL was measured on their left hand as well. Using Matlab R2013a, average SCL values in μSiemens during the 10-minute PVT, and during the easy and difficult trials of the BDST were calculated and subsequently used as

dependent variables. SCL data of two participants were not included in the analyses due to extreme values.

BVP (in bpm) was measured using a photoplethysmograph attached to the earlobe. This physiological indicator was not analyzed as a dependent variable, but it was necessary to calculate SBP values. Continuous SBP measurement was realized by using custom software which calculated pulse wave transit time (PWTT) values based on R-peak time in the ECG measurements [50] and the location of the maximum slope of the BVP measurements [51]. PWTT values were transformed into SBP values using the formula developed by Gesche et al. [52]. This formula included the participants' body height and calibrated values of the SBP measured by an automatic blood pressure device developed by Beurer [53]. Using Matlab R2013a, average SBP values in millimeters of mercury (mmHg) during the 10-minute PVT, and during the easy and difficult trials of the BDST were calculated and subsequently used as dependent variables.

Although the photoplethysmograph was taped to the earlobe, participants' head movements during the experiment led to loss of BVP signals in 24 of the 117 experimental sessions (including the five participants with failed HR recordings). These sessions were not included in the analyses of SBP.

2.5.3. Subjective sleepiness, vitality, tension and mood

Subjective sleepiness was examined with the Karolinska Sleepiness Scale (KSS, [54]). This measurement employs a 9-point scale using response options from 1 (extremely alert) to 9 (extremely sleepy - fighting sleep). Subjective vitality and tension were assessed using six items adopted from the activation-deactivation checklist [55]. Participants rated the six items on a scale from 1 (definitely not) to 5 (definitely). Four of these items belong to the vitality subscale (energetic, alert, sleepy (reversed), and lacking energy (reversed)), and two of these

items belong to the tension scale (tense and calm (reversed)). The internal reliabilities of the vitality and tension subscales were $\alpha = 0.88$ and $\alpha = 0.64$, respectively. Mood was assessed using single items for positive affect ('happy') and negative affect ('sad') on a similar 5-point Likert scale.

2.5.4. Evaluation of the lighting condition

At the end of each session, participants were asked to evaluate the lighting in the room using six 5-point Likert-scale items adopted from Flynn et al. [56]. Three items focused on the experienced pleasantness of the lighting ('unpleasant – pleasant', 'uncomfortable – comfortable' and 'disturbing – not disturbing'; $\alpha = 0.85$). Mean scores for pleasantness were calculated based on these three items. Furthermore, three single items were used to measure experiences concerning the lighting colour ('warm – cold'), brightness ('dim – bright') and whether the lighting was activating ('relaxing – stimulating').

2.5.5. Possible confounding variables

Potential confounding variables were assessed before the start of the experiment. These consisted of chronotype (MCTQ, [43]); Global sleep quality (Pittsburg Sleep Quality Index, [57]); General fatigue (Checklist Individual Strength, [58]), with $\alpha = 0.89$; Trait subjective vitality (subjective trait level vitality scale, [59]) with $\alpha = 0.91$; and Light sensitivity using three items regarding light exposure sensitivity [21]. Furthermore, sleep onset and sleep offset, sleep quality, time spent outside, travelling time outside, and food and caffeine consumption one hour before the start of the experiment were examined at the end of each session by single items.

2.6. Statistical analyses

Due to the nested structure of the data, Linear Mixed Model (LMM) analyses were conducted to investigate the effects of illuminance level (Light) on repeated measurements (Block one to three) of performance and physiological indicators. The hierarchical model consisted of the levels 'Participant', 'Experimental session' and 'Block'. The participant identifier variable was included as random intercept in the analyses. All analyses were corrected for baseline values and the individual characteristics described in section *3.1.1. Potential confounding variables* by adding these as covariates in the analyses. Because subjective indicators were only measured at baseline and at the end of the light exposure, LMM analyses without a repeated measurement structure for Block were carried out to test the effect of light on sleepiness, vitality, tension, mood. In addition, light appraisals were analyzed in a similar way as these were only measured after the final measurement block. Due to technical problems during one session (600 lux at eye level), switching the lights from 120 to 600 lux failed. Data of this session were therefore not included in the analyses.

First, preparatory LMM analyses were conducted to investigate whether the tasks indeed differed in difficulty level. These analyses included baseline differences in performance on BDST easy vs. difficult trials, and baseline differences in physiological arousal between tasks (PVT vs. BDST easy vs. BDST difficult). Furthermore, preparatory LMM analyses were carried out to investigate the occurrence of significant relationships between physiological arousal and task performance (speed and percentage correct) during the light manipulation.

Subsequent LMM analyses were conducted to examine the effect of Light on task performance, physiological arousal levels during each task, subjective indicators of sleepiness, vitality, mood and tension and light appraisals. First, for each of these outcome variables an LMM analysis was conducted to investigate main effects of Light and possible moderating effects of time in session. In addition to baseline values and other covariates,

these models included Light (165 vs. 600 vs. 1700), Block (measurement block two to four), Time of day (morning vs. late afternoon), and Light*Block as fixed factors. In cases where the effect of illuminance level was not moderated by time in session, the interaction term was excluded from the model. A second LMM was carried out including baseline values and covariates, Light, Block, Light*Block (if significant) Time of day, and Light*Time of day as fixed factors to examine possible moderation of time of day. If a significant main effect of Light or interaction effect of Light*Block or Light*Time of day was found, post-hoc tests using Bonferroni correction were used to investigate differences between lighting conditions during respectively one full session, each measurement block, or each time of day (morning vs. afternoon). To ensure a concise results section, only statistics on main and interaction effects of Light are reported. Statistics on main effects of Block, Time of day and other covariates are not reported as they were not the main focus of this study.

Effect sizes (pseudo R^2-values ($R^{2pseudo}$)) were calculated for models containing statistically significant or near-significant ($p < 0.10$) main or interaction effects of Light that were further investigated in post hoc analyses. $R^{2pseudo}$ indicates the proportion (percentage) of reduction in variance of residuals from the null-model to the final (full) model at level 2 [60]. Note that the full models also contain baseline measurements, Block, Time of day and covariates (see *3.1.1.*) as predictors for the outcome measures. Therefore, the total reduction in residual variance is attributed to including all of these variables to the null-model.

3. Results

3.1. Preparatory analyses

3.1.1. Potential confounding variables

Based on correlations between all potentially confounding variables (see section 2.5.5.) as well as correlations between confounding variables and outcome measures, it was decided to control for chronotype, light sensitivity and general fatigue in all analyses as these variables were not significantly inter-correlated and showed the strongest correlations with most of the outcome variables.

3.1.2. Baseline differences in performance on BDST easy vs. difficult trials

LMM analyses revealed a significant effect of Task type on BDST easy vs. difficult trial performance ($F(1,192) = 294.08$, $p < 0.001$). Post-hoc comparisons showed that participants performed significantly better (in terms of percentage correct) on the easy trials (*EMM* = 84.60%; *SE* = 2.57%) compared to the difficult trials (*EMM* = 43.00%; *SE* = 2.58%; $p < 0.001$). This result indicates that long BDST trials were indeed significantly more difficult than shorter trials.

3.1.3. Effects of task type on physiological arousal

To investigate whether task type influenced physiological arousal levels (because of variations in difficulty level) , separate LMMs were conducted with each of the physiological indicators as outcome measures and Task Type (PVT vs. BDST easy trials vs. BDST difficult trials) as predictor. These analyses were conducted during the baseline measurement block, i.e., prior to illuminance manipulation.

Results revealed that HR differed significantly between the different tasks ($F(2,110) = 12.94$, $p < 0.001$). Post-hoc tests revealed that HR was significantly higher during the BDST easy (*EMM* = 76.45; *SE* = 1.11; $p < 0.001$) and BDST difficult trials (*EMM* = 76.09; *SE* = 1.11; $p < 0.001$) than during the PVT (*EMM* = 74.85; *SE* = 1.13). There was no difference in HR between BDST easy and difficult trials ($p = 0.21$). With respect to SCL, results revealed a significant main effect of Task Type ($F(2,109) = 56.83$, $p < 0.001$). Post-hoc comparisons revealed a similar pattern as HR, showing significantly higher SCL during the BDST easy (*EMM* = 3.92; *SE* = 0.22; $p < 0.001$) and BDST difficult trials (*EMM* = 3.97; *SE* = 0.22; $p < 0.001$) than during the PVT (*EMM* = 3.17; *SE* = 0.18). There was no difference in SCL between BDST easy and difficult trials ($p = 0.98$). Finally, for SBP values, results revealed a significant main effect of Task Type ($F(2,90) = 14.78$, $p < 0.001$). Post-hoc comparisons revealed significantly higher SBP values during the BDST easy (*EMM* = 115.26; *SE* = 1.36; $p < 0.001$) and BDST difficult trials (*EMM* = 115.47; *SE* = 1.39; $p < 0.001$) than during the PVT (*EMM* = 113.20; *SE* = 1.29). Again, no difference in SBP emerged between BDST easy and difficult trials ($p = 0.51$).

Based on the analyses in this section, it can be concluded that there is a significant difference in physiological arousal levels between the PVT and the BDST, likely because of increased effort necessary for the more difficult BDST. No significant differences in arousal level were found between easier and more difficult trials of the BDST.

3.1.4. Association between physiological arousal and performance

In order to investigate whether variations in physiological arousal were significantly related to variations in task performance on each task, separate LMMs were conducted using each arousal measure (HR, SCL and SBP) as predictor variable and the relevant performance indicator of each task (PVT, BDST easy trials and BDST difficult trials) as outcome measure.

For these analyses, data of all measurement blocks during the light manipulation were used, taking into account the repeated measurement structure and variations in time of day by respectively including Block and Time of day as a main factors in the model. In order to maximize the informative value of the Beta Estimates of the physiological measures, all variables (predictor and outcome) were standardized.

Analyses on PVT performance only showed a nonsignificant trend for a correlation between HR and reaction speed performance (β = 0.09; F(1,244) = 3.22, p = 0.07), indicating that somewhat better PVT performance (increased speed) was related to a higher HR. SBP and SCL were not significantly related to PVT performance (both p's ≥ 0.56).

With respect to BDST performance, HR was not significantly related to accuracy on the easy trials (percentage correct) (F(1,140) < 1, *ns.*) nor difficult trials (F(1,185) < 1, *ns.*). However, results revealed a negative significant relationship between SCL and performance on the BDST easy trials (β = -0.20; F(1,143) = 8.72, p = 0.004), indicating a significant co-occurrence of increased arousal and decreased performance. No significant relationship between SCL and difficult trials was found (F(1,139) = 2.09, *ns.*). Last, SBP was not significantly related to performance on BDST easy trials (F(1,125) = 1.36, *ns.*) and near-significantly negatively related to BDST difficult trials (β = -0.13; F(1,112) = 3.66, p = 0.06), indicating a nonsignificant trend for co-occurring increased arousal and decreased performance.

3.2. Effects of Light on performance

3.2.1. PVT performance

LMM analyses investigating the effect of illuminance level on PVT performance (speed) did not reveal any significant differences between the light conditions for average speed on all trials, average speed on the 10% fastest trials and average speed on the 10% slowest trials (all p's ≥ 0.25). In addition, no significant interaction effects of Light*Block and Light*Time of day were found for each of these outcome variables (all p's ≥ 0.11)

3.2.2. BDST performance

LMM analyses on BDST performance showed a significant main effect of Light ($F(2,96) = 4.44$, $p = 0.01$; $R^{2pseudo} = 13.47\%$) on performance on difficult trials, but not on easy trials ($F(2,86) < 1$, *ns.*). Post-hoc comparisons revealed that participants completed significantly more difficult trials successfully under 1700 lux (*EMM* = 50.11%; *SE* = 2.22%) compared to 165 lux (*EMM* = 42.97%; *SE* = 2.19%; $p = 0.01$). Performance on difficult trials under 600 lux was also better than under 165 lux, but not significantly so (*EMM* = 47.21%; *SE* = 2.21%; $p = 0.25$). LMM analyses investigating possible moderation of Light by Time of day and Block for performance on easy and difficult trials revealed no significant interactions with Light for both easy and difficult trials (all p's > 0.21). Figure 3 shows the percentage of correct trials for both easy and difficult trials during each light condition.

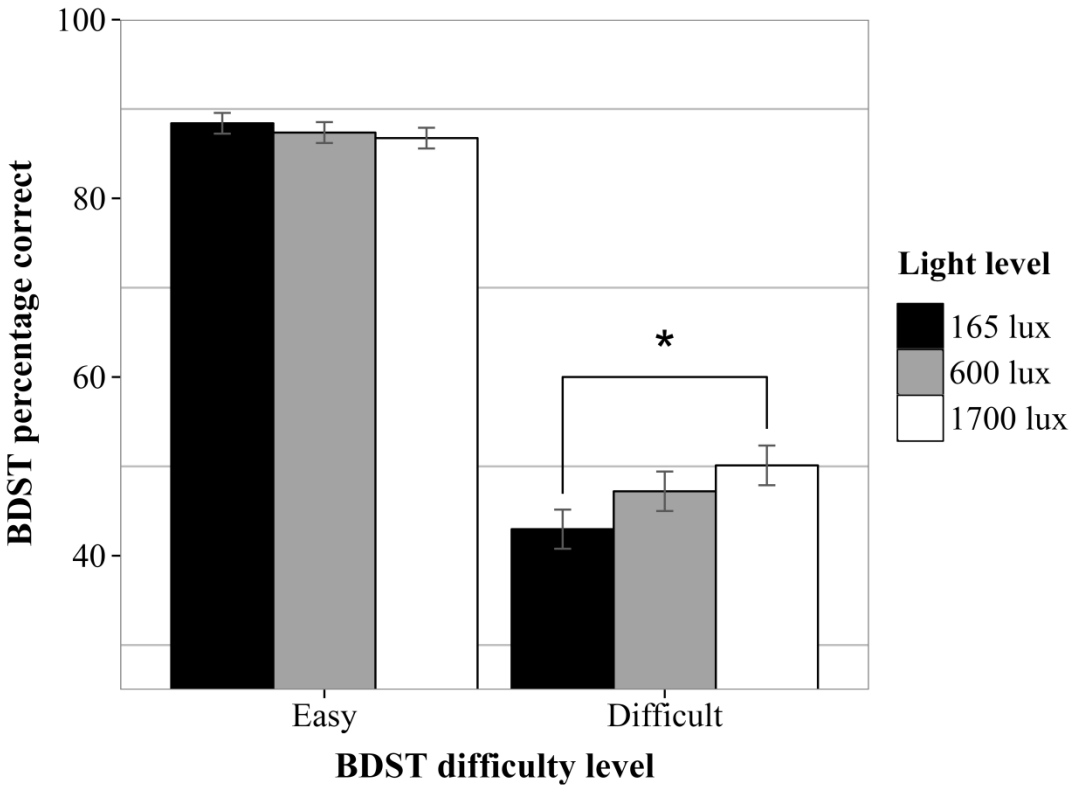

Figure 3. BDST percentage of correct trials (easy vs. difficult) for each light level. Whiskers represent standard errors. *$p < 0.05$.

3.3. Effects of Light on physiological arousal

This section describes the LMM analyses investigating the effect of illuminance level on HR, SBP and SCL measures for during the PVT, BDST easy and BDST difficult trials.

3.3.1. Effects of Light on HR

LMM analyses on HR during the PVT revealed no significant main effect of Light ($F(2,80) = 2.10$, *ns.*) and no significant Light*Block interaction ($F(4,216) = 1.13$, *ns.*). However, a non-significant trend was found when investigating the interaction effect of Light*Time of day ($F(2,77) = 2.46$, $p = 0.09$; $R^{2pseudo} = 71.55\%$). Post-hoc tests revealed that, in the afternoon,

HR was significantly higher under 1700 lux (*EMM* = 73.00; *SE* = 0.66) compared to HR under 165 lux (*EMM* = 71.20; *SE* = 0.68; *p* = 0.05). In addition, HR was near-significantly higher under 600 lux (*EMM* = 72.98; *SE* = 0.67) compared to 165 lux in the afternoon (*p* = 0.06). Differences in HR between the three illuminance levels in the morning sessions were not significant (EMM_{165}= 71.19; *SE* = 0.71; EMM_{600} = 70.55; *SE* = 0.75; EMM_{1700} = 71.61; *SE* = 0.73; all *p*'s > 0.60).

LMM analyses on HR during the easy and difficult trials of the BDST revealed no significant main effects of illuminance level on HR during performance on the easy (F(2,80) = 1.43, *ns.*) or difficult trials (F(2,73) < 1, *ns.*). In addition, no moderations of time in session (Block) were found (both *p*'s ≥ 0.18). Although there was no significant main effect of Light on HR during the easy trials of the BDST, LMM analyses revealed a significant Light*Time of day interaction for HR during the easy trials (F(2,81) = 3.35, *p* = 0.04; $R^{2pseudo}$ = 64.52%). Post-hoc analyses showed that, in the afternoon, HR was higher under 600 lux (*EMM* = 74.36; *SE* = 0.75) than under 165 lux (*EMM* = 72.34; *SE* = 0.78; *p* = 0.06). HR was also higher under 1700 lux (*EMM* = 73.50; *SE* = 0.75) than under 165 lux, but this difference was not significant (*p* = 0.51). In the morning, there were no significant differences in HR between the three lighting conditions during performance on the easy trials (all *p*'s > 0.15).

LMM analysis revealed no Light*Time of day interaction on HR during the difficult trials of the BDST (F(2,74) = 1.85, *ns.*). Post-hoc comparisons for HR values during difficult trials in the afternoon sessions showed similar nonsignificant trends as those during the easy trials with higher HR under 600 lux (*EMM* = 74.38; *SE* = 0.67) compared to 165 lux (*EMM* = 72.63; *SE* = 0.70; *p* = 0.10). Figure 4 depicts an overview of HR values in the afternoon during PVT and BDST performance.

3.3.2. Effects of Light on SCL

LMM analyses of SCL during the PVT revealed neither a significant main effect of Light nor any significant interaction effects of Light*Block and Light*Time of day (all *p*'s > 0.10).

LMM analyses on SCL during the easy and difficult trials of the BDST revealed a significant main effect of Light during the easy trials (F(2,76) = 4.06, *p* = 0.02; $R^{2pseudo}$ = 84.90%) but not during the difficult trials (F(2,71) = 1.52, *ns.*). Post-hoc investigations for SCL during easy trials revealed that SCL was significantly higher under 1700 lux (*EMM* = 4.56; *SE* = 0.10) compared to 165 lux (*EMM* = 4.19; *SE* = 0.10; *p* = 0.02). No interactions with Block or Time of day were found for the easy or difficult BDST trials (all *p*'s > 0.19). SCL was also higher under 600 lux (*EMM* = 4.39; *SE* = 0.11) than under 165 lux, but not significantly so (*p* = 0.43). Figure 5 shows average SCL values during the PVT and the easy and difficult BDST trials for each illuminance level.

3.3.3. Effects of Light on SBP

LMM analyses on SBP during the PVT revealed neither a significant main effect of Light nor any significant interaction effects of Light*Block and Light*Time of day (all *p*'s > 0.58). Similarly, LMM analyses on SBP during the easy and difficult trials of the BDST revealed no significant main effects of Light or interaction effects of Light*Block and Light*Time of day (all *p*'s > 0.35).

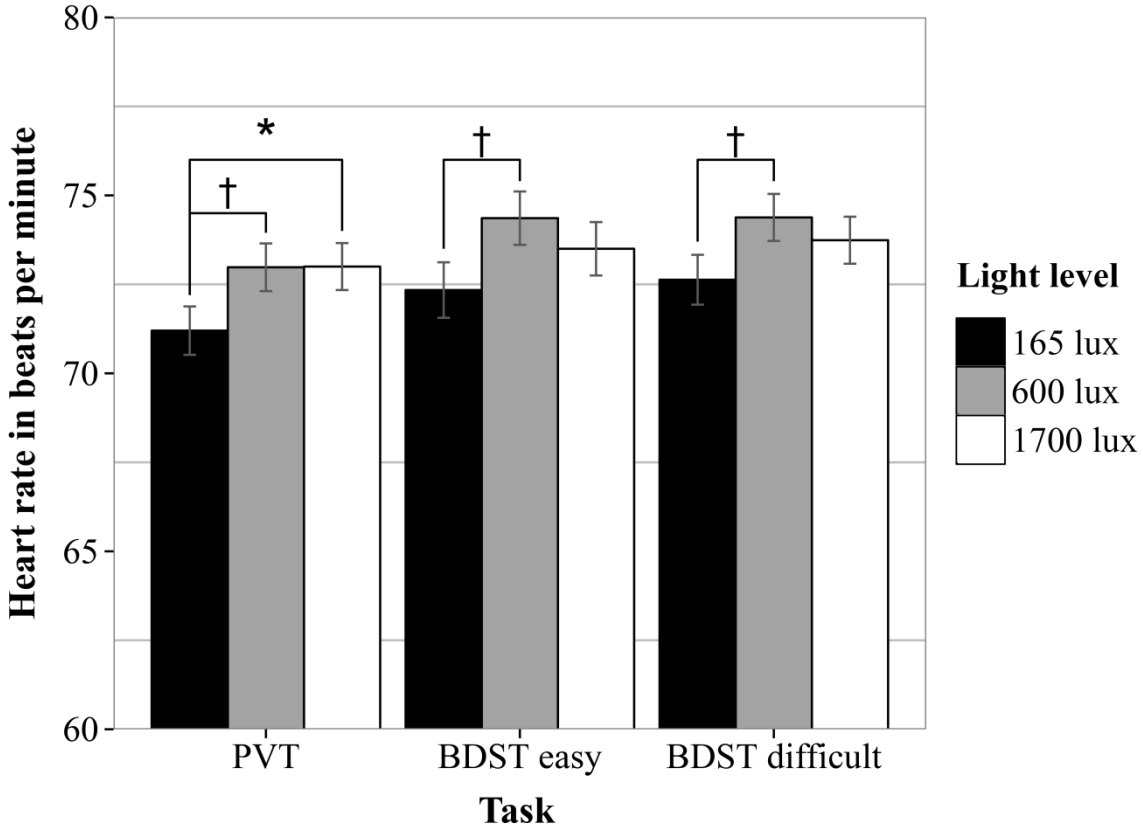

Figure 4. HR values during the PVT and the easy and difficult trials of the BDST for each light level. Note that all average HR values are given for the afternoon sessions only. Whiskers represent standard errors. *$p < 0.05$; † < 0.10.

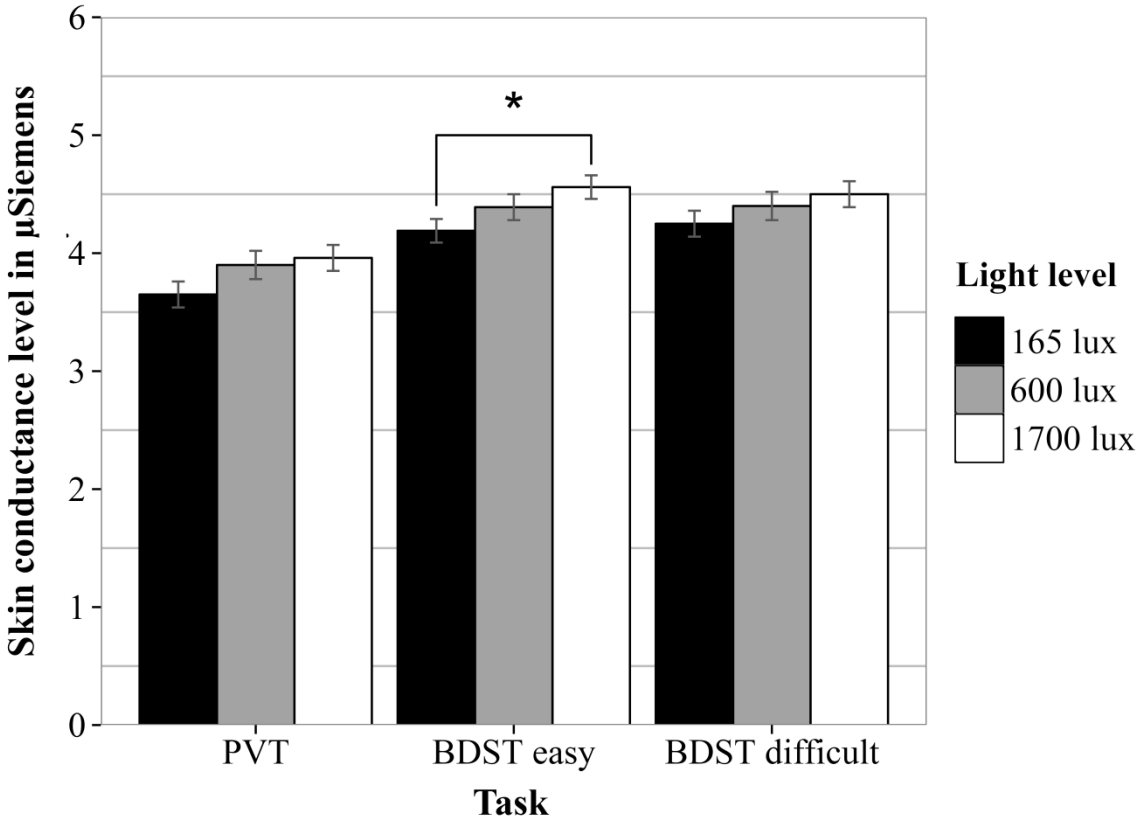

Figure 5. SCL values during the PVT and the easy and difficult trials of the BDST for each light level. Note that SCL values are averaged over morning and afternoon sessions. Whiskers represent standard errors. *$p < 0.05$.

3.4. Effects of Light on subjective indicators

This section describes the LMM analyses effects of light on subjective indicators of sleepiness, vitality, tension, mood and light appraisals.

3.4.1. Sleepiness, vitality, tension and mood

Self-reported sleepiness was only measured once during the light manipulation. LMM analysis for sleepiness ratings therefore only focused on differences in illuminance level at the end of each session, and a possible moderation by Time of day. The results showed no main effect of illuminance level on sleepiness ratings after approximately 54 minutes of light exposure ($F(2,78) = 1.06$, *ns.*). In addition, there was no significant interaction effect between Light and Time of day on subjective sleepiness ($F(2,78) = 1.60$, *ns.*).

Similar to sleepiness ratings, LMM analyses for vitality, tension and mood ratings focused on the effect of illuminance level on participants' momentary state after the final measurement block, and a possible moderation of Time of day in this effect. With respect to vitality, LMM analyses neither found a significant main effect of Light ($F(2,77) < 1$, *ns.*) nor a significant interaction between Light and Time of day ($F(3,58) = 1.50$, *ns.*). Similarly, for tension, LMM analyses did not reveal a significant main effect of Light ($F(2,77) = 1.11$, *ns.*), or a significant Light*Time of day interaction ($F(3,58) < 1$, *ns.*). Furthermore, no significant main effect of Light or interaction effect of Light*Time was found for subjective happiness or sadness (all p's > 0.28).

3.4.2. Light appraisals

LMM analyses focusing on differences in light appraisals between the three lighting conditions revealed a significant main effect of Light on pleasantness of the lighting ($F(2,78) = 9.31$, $p < 0.001$; $R^{2pseudo} = 20.48\%$). Participants rated the highest illuminance level (1700

lux) as significantly less pleasant (*EMM* = 3.04; *SE* = 0.13) compared to the two lower illuminance levels (165 lux: *EMM* = 3.51; *SE* = 0.0.13; $p = 0.001$; 600 lux: *EMM* = 3.62; *SE* = 0.13; $p < 0.001$). There was no significant difference in pleasantness between 165 lux and 600 lux ($p = 0.45$). Furthermore, as expected, a significant main effect of Light on brightness was found ($F(2,77) = 41.25$, $p < 0.001$; $R^{2pseudo} = 50.57\%$). The two highest illuminance levels were rated as significantly brighter (600 lux: *EMM* = 3.94; *SE* = 0.13; $p < 0.001$; 1700 lux: *EMM* = 4.49; *SE* = 0.13; $p < 0.001$) compared to the lowest illuminance level (165 lux: *EMM* = 3.08; *SE* = 0.13). In addition, participants evaluated 1700 lux as significantly brighter than 600 lux ($p = 0.001$). Last, a significant main effect of Light on stimulation ratings was found ($F(2,78) = 12.12$, $p < 0.001$; $R^{2pseudo} = 23.99\%$). Participants rated the two highest illuminance levels as significantly more stimulating (600 lux: *EMM* = 3.66; *SE* = 0.13; $p < 0.001$; 1700 lux: *EMM* = 3.78; *SE* = 0.13; $p < 0.001$) than the lowest illuminance level (*EMM* = 3.02; *SE* = 0.13), while no difference was observed between the 600 and 1700 lux conditions ($p = 0.49$). None of these light appraisal effects were significantly moderated by Time of day (all p's > 0.36). There was no significant effect of illuminance level on participants' light colour ratings (warm vs. cold: $F(2,78) = 1.40$, *ns*.).

4. Discussion

The current study investigated the NIF effects of three different illuminance levels on sustained attention and working memory task performance, autonomic nervous activity, and subjective sleepiness, alertness, vitality, tension and light appraisals. More specifically, the study was set up to explore whether previous inconsistencies with respect to NIF effects of light intensity on performance could be explained by differences in light-induced changes in physiological arousal level during task performance. This was examined by exposing each participant to three different light levels (165 lux, 600 lux and 1700 lux at eye level) for approximately one hour on separate workdays at the same time of day. During the light exposure, participants completed three blocks of repeated measures for performance on a sustained attention (PVT) and working memory task (BDST). In addition, heart rate, skin conductance (level) and (systolic) blood pressure were continuously measured. Before the start and towards the end of the light exposure, participants also completed questionnaires on state alertness, sleepiness, vitality and tension. The questionnaire at the end of each session also included light appraisals.

4.1. Lighting effects on performance

Based on previous research, it was expected that performance on the (relatively easy) sustained attention task would be better under high compared to low light intensities [16, 21]. These studies revealed significant improvements in reaction times on a PVT under bright (1000 lux) compared to dim light exposure (resp. < 5 lux and 200 lux). In contrast to these previous results, the current study revealed no significant effects of the light manipulation on sustained attention speed on all trials, the 10% fastest or the 10% slowest trials. Two previous studies also found no or only very subtle effects of illuminance level on vigilance performance during the daytime [11, 17]. Although differences in study characteristics make

it impossible to directly compare findings between these studies and the current one, it can be concluded that improvements in sustained attention under bright vs. dim light do occur occasionally, but not consistently. Perhaps differences in lighting characteristics (e.g. direction of the lighting, colour temperature, exposure duration etc.) can explain these differences. In addition, although the current study controlled for several individual characteristics (such as chronotype and light sensitivity), future studies investigating NIF effects of illuminance level on sustained attention in specific groups of individuals (e.g., early vs. late chronotypes, and high vs. low light-sensitive people) would be highly informative, and may reveal different NIF effects of illuminance level in participants with different individual characteristics.

With respect to performance on the more difficult working memory task (BDST), it was expected that no improvements or even decrements in performance under higher light intensities would appear, especially in the afternoon [15]. In contrast to this expectation, the current study revealed that participants completed significantly more difficult backward spans (length 7 and 8) successfully in the morning and afternoon under the 1700 lux compared to 165 lux at eye level. However, important differences between the Huiberts et al. [15] study and the present one are the number and types of tasks that were performed before the BDST. In our previous study, participants first completed an *n*-back task and a Forward Digit-Span Task (FDST) in each measurement block, which both rely on working memory, before performing the BDST. In the current study, participants performed a 10-minute PVT prior to the BDST. Potentially, NIF effects of illuminance level on cognitive performance depend on previous cognitive effort as both the type and amount of cognitive effort exerted in that study [15] were different from the current one. In case of relatively easy spans (length 4 to 6), illuminance level did not significantly influence working memory performance. However, as baseline accuracy scores on easy trials were already quite high (on average 85% correct)

there was less room for illuminance-induced performance improvements on easy compared to difficult trials.

Overall, based on the results of the current study regarding working memory performance, it can be concluded that bright light exposure may be beneficial in case relatively difficult working memory tasks are performed. However, since previous research also showed mixed effects of bright light vs. dim light exposure on working memory performance [11, 14, 15, 17], further investigation with respect to moderating and mediating factors that may play a role in these NIF effects of illuminance level is needed.

4.2. Co-occurrence of lighting effects on performance and arousal

Regarding NIF effects of light on physiological indicators, two possible hypotheses were formulated. Our main hypothesis was that high (compared to low) illuminance levels would consistently increase physiological arousal levels, independent of task difficulty. This hypothesis had been partly confirmed by previous studies investigating physiological arousal levels during task performance under different illuminance levels [19-21]. According to this line of reasoning, light-induced increases in physiology could subsequently affect task performance [26-28]. Alternatively, it is was conjectured that physiological arousal levels might be indirectly affected by illuminance level via changes in effort necessary for task performance [31]. In that case, if a certain illuminance level facilitates performance on a specific task, cognitive effort may be reduced leading to decreased physiological arousal, especially while performing challenging tasks.

The first hypothesis with respect to physiological arousal levels was partly confirmed in the current study. Heart rates were significantly higher under 1700 lux and slightly higher under 600 lux compared to 165 lux during PVT performance in the afternoon. However, PVT performance was not affected (positively nor negatively) by this change in physiological

arousal. The increase in heart rate in the current study is consistent with the study of Smolders et al. [21] who also found increased heart rate during PVT performance under 1000 lux vs. 200 lux at eye level, although they found this both during the morning and afternoon. In contrast, a more recent study reported no increase in heart rate during PVT performance under 1000 lux vs. 200 lux [17]. Also contrary to our findings, PVT performance was found to be better under bright compared to dim light exposure in these two previous studies – both the one with and the one without reported increases in heart rate – even though the designs of these studies were quite similar to that of the current one. Thus, NIF effects of illuminance level on both vigilance and co-occurring heart rate changes are quite inconsistent.

During BDST performance a different trend of effects of illuminance level on heart rate was found. The results showed that heart rate values were highest under 600 lux, intermediate under 1700 lux, and lowest under 165 lux while performing the BDST. Because this was only a modest trend, it would be premature to conclude that illuminance-induced changes in heart rate during BDST performance show a different pattern than during PVT performance. Future research should establish whether light-induced changes in heart rate depend on the type of task that is performed during measurement. It does appear quite safe to conclude though, that changes in performance on the more difficult BDST tasks were not (negatively) impacted by light-induced heart rate increases. In fact, performance on difficult BDST trials was significantly better during 1700 lux vs. 165 lux exposure, and there was no significant difference in heart rate between these two conditions during performance on these trials. With regard to heart rate, both the over-arousal hypothesis and the alternative reduced effort mobilization hypothesis should therefore be rejected.

The current study revealed that skin conductance - a second indicator of arousal - was significantly higher under 1700 lux compared to 165 lux at eye level in the morning and afternoon sessions while participants performed easy BDST trials. A similar pattern of

increasing skin conductance with higher illuminance level was found during PVT and BDST difficult trial performance, but statistical significance was not reached. Previous research in our laboratory also revealed significant increases in skin conductance, but this was only investigated during PVT performance [17, 22]. Also in case of skin conductance, no consistent relationship between changes in physiological arousal and performance can be observed. That is, although skin conductance seems to increase with higher illuminance levels during each task, only performance on difficult BDST trials improved under the highest illuminance level vs. the lowest illuminance level, which is the exact opposite of what was predicted based on the Yerkes-Dodson Law. As for heart rate, we conclude that both hypotheses should be rejected for skin conductance.

In contrast to heart rate and skin conductance, blood pressure was unaffected by the light manipulation in the current study. Possibly, blood pressure as a physiological measure was too insensitive to capture changes between lighting conditions [38]. Consistent with previous findings [35-37], blood pressure measurement was sensitive to capture changes in effort mobilization during a relatively easy (PVT) compared to a more difficult task (BDST). However, the current results indicate no significant difference in effort mobilization as reflected by blood pressure during task performance while exposed to the three illuminance levels. So again, both hypotheses should likely be rejected.

Overall, the current results do not suggest a mediating role of physiological arousal in the relationship between illuminance level and performance, i.e. our main hypothesis. In case of significant NIF effects of illuminance level on physiological indicators (heart rate and skin conductance), no parallel changes in performance were found, and certainly not a pattern of beneficial effects of bright light for easy vs. detrimental effects bright light for more difficult tasks. Similarly, a mediating role of performance in the relationship between illuminance level and physiology as described in the alternative hypothesis also seems unlikely. Both

during PVT and BDST performance, results did not reveal decreases in physiology (decreased effort) in parallel with increased (or stable) performance under high vs. low illuminance levels. Moreover, if there would be a mediating role of performance or physiology, significant associations between physiology and performance would also be expected, which was only found for skin conductance and performance on the BDST easy trials. BDST easy trial performance was, however, not affected by the light manipulation. Thus, based on the results of the current study, it is more likely that illuminance level affects physiology and performance independently via unique pathways.

4.3. Lighting effects on subjective indicators and appraisals

In addition to performance and physiological indicators, we investigated NIF effects of illuminance levels on subjective indicators of sleepiness, vitality, tension and mood as well as effects of light on light appraisals. Previous studies often (but not always) showed positive effects of bright light compared to dim light exposure on subjective indicators of alertness, vitality and mood [11, 16, 17, 21]. The current study did not render positive effects on subjective indicators for individuals' momentary affective state, as none of them were affected by illuminance level. We should, however, acknowledge that the current study only employed one measurement point for subjective indicators during the light manipulation, resulting in less power to test for differences in subjective indicators as opposed to physiological and performance indicators as well as similar subjective indicators tested in previous studies [15, 17, 21].

With respect to subjective evaluations of the lighting conditions, in spite of the null effects on vitality, alertness and tension, results did reveal that participants rated the two highest illuminance levels as significantly more stimulating than the lowest illuminance level. These ratings are largely in line with the physiological data, as skin conductance and heart

rate rose (be it modestly and not always significantly) with illuminance during BDST and PVT performance. Furthermore, the highest illuminance level was rated as significantly less pleasant than the two lower illuminance levels. Thus, although participants preferred the more common, lower indoor illuminance levels (165 and 600 lux at eye level), they performed best on the difficult trials of the BDST when they were exposed to the highest illuminance level (1700 lux). Although this seems counterintuitive, the negative appraisals may be explained by the fact that participants are not used to such high indoor illuminance levels (psychologically), even though biologically these levels may be beneficial while performing relatively difficult tasks. For future studies, it would be interesting to investigate whether participants could get used to working under these higher illuminance levels over time, without losing the beneficial NIF effects on cognitive performance performance.

Some limitations of the current study should be mentioned when interpreting the results. First, although we controlled for chronotype in each analyses, it should be noted that about half of the participants did not keep their regular sleep-wake pattern based on their chronotype values during the night before and morning of their laboratory session. In most cases, however, this was not more than 45 minutes earlier or later than their sleep and wake time limits. Moreover, deviations from regular sleep-wake patterns should be reflected in baseline scores of the outcome measures (performance, physiology and subjective indicators), for which we controlled in each analysis. For future studies, it would be good to more strictly control for sleep-wake patterns by using actigraphy by means of for example actiwatches. With respect to generalization of the current findings, it should be noted that our sample is substantially female. It is not yet known whether diurnal NIF effects of illuminance level are influenced by gender, but it may play a role (see for example [61]). However, as it was not our goal to test gender effects, and because power of the current study would be too low to

add another categorical term to our models (resulting in three-way interactions) we decided not to test these.

5. Conclusion

Overall, the current findings suggest that, while sustained attention performance was unaffected by illuminance level, 1-hour of exposure to very bright light (1700 lux at eye level) can improve performance on a relatively difficult working memory task. In contrast, a somewhat lower, but still substantial illuminance level of 600 lux at eye level, did not improve working memory performance. With respect to physiological NIF effects of light, it can be concluded that very bright light levels (1700 lux) increase heart rate during sustained attention performance, while light exposure of 600 lux (but not 1700 lux) slightly increased heart rate during working memory performance. In case of skin conductance, an increase in physiological arousal level was observed with higher illuminance levels, which only showed to be significant during easy trials of a working memory task. Future studies should further investigate possible task dependency of NIF effects of illuminance level on heart rate and skin conductance.

Although both performance and physiology were affected by the light manipulation, no consistent pattern emerged with respect to parallel changes in physiology and performance. In other words, the current results do not suggest a mediating role of physiology in the NIF effects of illuminance level on performance, nor a mediating role of performance in the NIF effects of illuminance level on physiology.

Although reported in previous research, the current study did not show an effect of illuminance level on subjective indicators of alertness, vitality, tension, and mood. Participants did, however, evaluate the two highest illuminance levels as significantly more stimulating than the lowest illuminance level. Since NIF effects of illuminance level on both

performance and physiology show inconsistent results between and within study paradigms, future research is necessary to investigate the conditions that may determine the occurrence and direction of these effects.

Acknowledgements

We would like to thank Martin Boschman and Aart van der Spank for their technical assistance in the lighting lab.

References

[1] Berson, D. M., Dunn, F. A., Takao, M. Phototransduction by retinal ganglion cells that set the circadian clock. Science. 2002,295:1070-3.
[2] Freedman, M. S., Lucas, R. J., Soni, B., Von Schantz, M., Munoz, M., David-Gray, Z., et al. Regulation of mammalian circadian behavior by non-rod, non-cone, ocular photoreceptors. Science. 1999,284:502-4.
[3] Provencio, I., Rodriguez, I. R., Jiang, G., Hayes, W. P., Moreira, E. F., Rollag, M. D. A novel human opsin in the inner retina. Journal of Neuroscience. 2000,20:600-5.
[4] Cajochen, C. Alerting effects of light. Sleep Medicine Reviews. 2007,11:453-64.
[5] Chellappa, S. L., Gordijn, M. C. M., Cajochen, C. Can light make us bright? Effects of light on cognition and sleep. Progress in Brain Research. 2011,190:119-33.
[6] Vandewalle, G., Maquet, P., Dijk, D.-J. Light as a modulator of cognitive brain function. Trends in Cognitive Sciences. 2009,13:429-38.
[7] Vandewalle, G., Balteau, E., Philips, C., Degueldre, C., Moreau, V., Sterpenich, V., et al. Daytime light exposure dynamically enhances brain responses. Current Biology. 2006,16:1616-21.
[8] Perrin, F., Peigneuz, P., Fuchs, S., Verhaege, S., Laureys, S., Middleton, B., et al. Nonvisual responses to light exposure in the human brain during the circadian night. Current Biology. 2004,13:1842-6.
[9] Badia, P., Myers, B., Boecker, M., Culpepper, J. Bright light effects on body temperature, alertness, EEG and behavior. Physiology & Behavior. 1991,50:582-8.
[10] Campbell, S. S., Dawson, D. Enhancement of nighttime alertness and performance with bright ambient light. Physiology & Behavior. 1990,48:317-20.
[11] Rüger, M., Gordijn, M. C. M., de Vries, B., Beersma, D. G. M. Effects of diurnal and nocturnal bright light exposure on human performance and wake EEG. Doctoral dissertation. In: Rüger M, ed. Lighting up the clock: Effects of bright light on physiological and psychological states in humans. Groningen: Van Denderen; 2005. p. 61-85.
[12] Boyce, P. R., Beckstead, J. W., Eklund, N. H., Strobel, R. W., Rea, M. S. Lighting the graveyard shift: The influence of daylight-simulating skylight on the task performance and mood on night-shift workers. Lighting Research and Technology. 1997,29:105-34.
[13] Kretschmer, V., Schmidt, K.-H., Griefahn, B. Bright light effects on working memory, sustained attention and concentration of elderly night shift workers. Lighting Research and Technology. 2012,44:316-33.
[14] Gabel, V., Maire, M., Reichert, C. F., Chellappa, S. L., Schmidt, C., Hommes, V., et al. Dawn simulation light impacts on different cognitive domains under sleep restriction. Behavioural Brain Research. 2015,281:258-66.
[15] Huiberts, L. M., Smolders, K. C. H. J., de Kort, Y. A. W. Shining light on memory: Effects of bright light on working memory performance. Behavioural Brain Research. 2015.
[16] Phipps-Nelson, J., Redman, J. R., Dijk, D. J., Rajaratnam, S. M. Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. Sleep. 2003,26:695-700.
[17] Smolders, K. C. H. J., de Kort, Y. A. W. Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal. Journal of Environmental Psychology. 2014,39:77-91.
[18] Santhi, N., Groeger, J. A., Archer, S. N., Gimenez, M., Schlangen, L. J., Dijk, D. J. Morning sleep inertia in alertness and performance: Effect of cognitive domain and white light conditions. PLoS ONE. 2013,8.
[19] Rüger, M., Gordijn, M. C. M., Beersma, D. G. M., de Vries, B., Daan, S. Time-of-day-dependent effects of bright light exposure on human psychophysiology: comparison of

daytime and nighttime exposure. American Journal of Physiology–Regulatory, Integrative and Comparative Physiology. 2006,290:1413–20.
[20] Saito, Y., Shimizu, T., Takahashi, Y., Mishima, K., Takahashi, K.-., Ogawa, Y., et al. Effect of bright light exposure on muscle sympathetic nerve activity in human. Neuroscience Letters. 1996,219:135-7.
[21] Smolders, K. C. H. J., de Kort, Y. A. W., Cluitmans, P. J. M. A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures. Physiology & Behavior. 2012,107:7-16.
[22] Smolders, K. C. H. J., de Kort, Y. A. W., Cluitmans, P. J. M. A higher illuminance induces alertness even during office hours findings on subjective measures, task performance, EEG, heart rate and skin conductance. In: Smolders KCHJ, ed. Daytime light exposure: effects and preferences. Eindhoven: Eindhoven University of Technology; 2013.
[23] Kaida, K., Takahashi, M., Haratani, T., Otsuka, Y., Fukasawa, K., Nakata, A. Indoor exposure to natural bright light prevents afternoon sleepiness. Sleep. 2006,29:462-9.
[24] Sahin, L., Wood, B. M., Plitnick, B., Figueiro, M. G. Daytime light exposure: Effects on biomarkers, measures of alertness, and performance. Behavioural Brain Research. 2014,274:176-85.
[25] Smolders, K. C. H. J., de Kort, Y. A. W., Cluitmans, P. J. M. Higher light intensity induces modulations in brain activity even during regular daytime working hours. . Lighting Research and Technology. 2015.
[26] Yerkes, R. M., Dodson, J. D. The relation of strength of stimulus to rapidity of habit-formation. Journal of Comparative Neurology and Psychology. 1908,18:459-82.
[27] Anderson, K. J. Impulsivity, caffeine, and task-difficulty - A within-subjects test of the Yerkes-Dodson Law. Personality and Individual Differences. 1994,16:813-29.
[28] Coles, M. G. H. Physiological activity and detection: The effects of attentional requirements and the prediction of performance. Biological Psychology. 1974,2:113-25.
[29] Humphreys, M. S., Revelle, W. Personality, motivation, and performance: A theory of the relationship between individual differences and information processing. Psychological Review. 1984,91:153-84.
[30] Watters, P. A., Martin, F., Schreter, Z. Caffeine and cognitive performance: The nonlinear yerkes-dodson law. Human Psychopharmacology. 1997,12:249-57.
[31] Gendolla, G. H. E., Wright, R. A., Richter, M. Effort intensity: Some insights from the cardiovascular system. In: Ryan RA, ed. Oxford handbook of human motivation. New York: Oxford University Press; 2012.
[32] Eubanks, L., Wright, R. A., Williams, B. J. Reward influence on the heart: Cardiovascular response as a function of incentive value at five levels of task demand. Motivation and Emotion. 2002,26:139-52.
[33] Wright, R. A., Dill, J. C., Geen, R. G., Anderson, C. A. Social evaluation influence on cardiovascular response to a fixed behavioral challenge: Effects across a range of difficulty levels. Annals of Behavioral Medicine. 1998,20:277–85.
[34] Shi, Y., Ruiz, N., Taib, R., Choi, E., Chen, F. Galvanic skin response (GSR) as an index of cognitive load. Paper presented at the Conference on Human Factors in Computing Systems - Proceedings. 2007:2651-6.
[35] Gendolla, G. H. E., Krüsken, J. The joint impact of mood state and task difficulty on cardiovascular and electrodermal reactivity in active coping. Psychophysiology. 2001,38:548-56.
[36] Wright, R. A., Contrada, R. J., Patane, M. J. Task difficulty, cardiovascular response, and the magnitude of goal valence. Journal of Personality and Social Psychology. 1986,51:837-43.

[37] Richter, M., Friedrich, A., Gendolla, G. H. E. Task difficulty effects on cardiac activity. Psychophysiology. 2008,45:869-75.
[38] Wright, R. A. Presidential address 2013: Fatigue influence on effort-considering implications for self-regulatory restraint. Motivation and Emotion. 2014,38:183-95.
[39] Wright, R. A., Martin, R. E., Bland, J. L. Energy resource depletion, task difficulty, and cardiovascular response to a mental arithmetic challenge. Psychophysiology. 2003,40:98–105.
[40] Schmidt, R. E., Richter, M., Gendolla, G. H. E., Van der Linden, M. Young poor sleepers mobilize extra effort in an easy memory task: Evidence from cardiovascular measures. Journal of Sleep Research. 2010,19:487–95.
[41] Dawson, M. E., Schell, A. M., Filion, D. L. The electrodermal system. In: Cacioppo JT, Tassinary LG, Berntson G, eds. Handbook of Psychophysiology. New York: 3rd Cambridge University Press; 2007. p. 159–81.
[42] Fowles, D. C. Motivational effects on heart rate and electrodermal activity: Implications for research on personality and psychopathology. Journal of Research in Personality. 1983,17:48–71.
[43] Roenneberg, T., Wirz-Justice, A., Merrow, M. Life between Clocks: Daily Temporal Patterns of Human Chronotypes. Journal of Biological Rhythms. 2003,18:80-90.
[44] Zavada, A., Gordijn, M. C. M., Beersma, D. G. M., Daan, S., Roenneberg, T. Comparison of the Munich Chronotype Questionnaire with the Horne-Ostberg's Morningness-Eveningness Score. Chronobiology International. 2005,22:267-78.
[45] Lucas, J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., et al. Measuring and using light in the melanopsin age. Trends in Neurosciences. 2014,37:1-9.
[46] Dinges, D. F., Powell, J. W. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. Behavior Research Method, Instruments & Computers. 1985,17:652–5.
[47] Drummond, S. P. A., Bischoff-Grethe, A., Dinges, D. F., Ayalon, L., Mednick, C. M., Meloy, M. J. The neural basis of the psychomotor vigilance task. Sleep. 2005,28:1059–68.
[48] Dorrian, J., Rogers, N. L., Dinges, D. F. Psychomotor vigilance performance neurocognitive assay sensitive to sleep loss. In: Kushida CA, ed. Sleep Deprivation: Clinical Issues, Pharmacology and Sleep Loss Effects. New York: Marcel Dekker Inc.; 2005.
[49] The Psychological Corporation. Updated WAISIII–WMS-III technical manual. San Antonio, TX: Author; 2002.
[50] Hamilton, P. S. "Open source ECG analysis". Proceedings of Computers in Cardiology. 2002,29:101–4.
[51] Fung, P., Dumont, G., Ries, C., Mott, C., Ansermino, M. Continuous noninvasive blood pressure measurement by pulse transit time. Engineering in Medicine and Biology Society, 2004. IEMBS '04. 26th Annual International Conference of the IEEE. 2004,1:738 - 41.
[52] Gesche, H., Grosskurth, D., Küchler, G., Patzak, A. Continuous blood pressure measurement by using the pulse transit time: Comparison to a cuff-based method. European Journal of Applied Physiology. 2012,112:309-15.
[53] Beurer. Beurer BM44 User guide. 2012.
[54] Åkerstedt, T., Gillberg, M. Subjective and objective sleepiness in the active individual. International Journal of Neuroscience. 1990,52:29-37.
[55] Thayer, R. E. Measurement of activation through self-report. Psychological Reports. 1967,20:663-78.
[56] Flynn, J. E., Spencer, T. J., Martyniuk, O., Hendrick, C. Interim study of procedures for investigating the effect of light on impression and behavior. Journal of the Illuminating Engineering Society. 1973,3.

[57] Buysse, D. J., Reynolds III, C. F., Monk, T. H., Berman, S. R., Kupfer, D. J. The pittsburgh sleep quality index: A new instrument for psychiatric practice and research. Psychiatry Research. 1989,28:193-213.
[58] Vercoulen, J. H. M. M., Alberts, M., Bleijenberg, G. De Checklist Individual Strength (CIS). Gedragstherapie. 1999,32:131-6.
[59] Ryan, R. M., Frederick, C. On energy, personality and health: Subjective vitality as a dynamic reflection of well-being. Journal of Personality. 1997,65:529–65.
[60] Raudenbush, S. W., Bryk, A. S. Hierarchical linear models (2nd ed.). Thousand Oaks: Sage Publications; 2002; 2002.
[61] Revell, V. L., Skene, D. J. Impact of age on human non-visual responses to light. Sleep and Biological Rhythms. 2010,8:84-94.

Table 1: Spectrally-weighted α-opic lux levels at eye level for each lighting condition based on calculations of Lucas et al. [44]

	λ max	α-opic lux value (165 lux)	α-opic lux value (600 lux)	α-opic lux value (1700 lux)
Melanopsin	480.0	130	465	1267
S-cone	419.0	135	495	1303
M-cone	530.8	153	559	1575
L-cone	558.4	158	585	1662
Rods	496.3	142	511	1413

Highlights

- We investigated paralel non-image forming effects of illuminance level on task performance and physiology
- Bright (vs. dim) light exposure (BLE) improved performance on a difficult working memory task
- Illuminance level did not impact vigilance and easy working memory performance
- BLE significantly increased heart rate and skin conductance, but not during each task
- No relationships between light-induced changes in performance and physiology were found