A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures

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A B S T R A C T

Nocturnal white light exposure has shown marked results on subjective and objective indicators of alertness, vitality and mood, yet effects of white light during daytime and under usual office work conditions have not been investigated extensively. The current study employed a mixed-group design (N=32), testing effects of two illuminance levels (200 lx or 1000 lx at eye level, 4000 K) during one hour of morning versus afternoon exposure. In four repeated blocks, subjective reports, objective performance and physiological arousal were measured. Results showed effects of illuminance on subjective alertness and vitality, sustained attention in tasks, and heart rate and heart rate variability. Participants felt less sleepy and more energetic in the high versus the low lighting condition, had shorter reaction times on the psychomotor vigilance task and increased physiological arousal. Effects of illuminance on the subjective measures, as well as those on heart rate were not dependent on time of day or duration of exposure. Performance effects were most pronounced in the morning sessions and towards the end of the one-hour exposure period. The effect on heart rate variability was also most pronounced at the end of the one-hour exposure. The results demonstrate that even under normal, i.e., neither sleep nor light deprived conditions, more intense light can improve feelings of alertness and vitality, as well as objective performance and physiological arousal.

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1. Introduction

At work, people may experience fatigue and a depletion of mental resources. These increased feelings of sleepiness, lack of energy, psychological stress and decrements in performance may be the result of an accumulation of effort spent throughout the working day and of homeostatic and circadian regulation of sleep and wakefulness [1,2]. In this study, we investigate whether office lighting, and in particular the amount of light, i.e., illuminance, at eye level can improve office employees’ alertness, vitality and performance during daytime.

Research has established that light can have both direct and phase shifting effects on the circadian clock [3–4]. Direct effects of light on the human nervous system refer to instantaneous changes in physiological arousal, while phase shift effects refer to temporal changes in the circadian rhythm. In addition to these physiological effects, studies have shown that exposure to higher illuminance levels can result in feelings of increased alertness and better performance [5–12]. Importantly, most of these studies have assessed the effect of nocturnal light exposure on physiological and psychological measures of arousal and alertness. Moreover, the scarce diurnal data come from studies in which subjects were first substantially sleep and/or light deprived [10,12,13]. In contrast, little is known about such effects under the conditions many of us live and perform in: during daytime, under normal (or close to normal) sleep pressure, and without hours-long pretreatment exposure to darkness. Under such conditions, effects may be less pronounced or even disappear altogether, as alertness levels and brain activity may already be optimally tuned to daytime performance, hormonal levels of cortisol and melatonin are already in phase with task demands, and some may already have had substantial amounts of daylight while commuting or during a coffee or lunch break. Although controlled tests of illuminance levels under natural daytime conditions are scarce, a few recent studies do suggest effects of blue-enriched or high correlated colour temperature (CCT) lighting [14–16].

As one exception, Baadie and colleagues investigated the effect of illuminance on physiological arousal, subjective alertness and task performance during night time, but also during daytime without sleep deprivation or prior exposure to low illuminance levels [17]. Results revealed night-time effects of illuminance level on alertness, body temperature, EEG and performance; in contrast, the results in the afternoon showed a comparable, but non-significant trend. It should be noted, however, that the number of participants in this particular study was relatively low (N = 8). A field study employing fairly
subtle differences in illuminance levels (500 vs 700 lx) accompanied by CCT changes (3000–4700 K) during the working day did not render indications of alerting or vitalizing effects of brighter light [18]. On the other hand, a meta-analysis by Gifford and colleagues does suggest an effect of illuminance on visual performance tasks with a small to medium effect size [19]. Studies on the effect of natural light exposure also suggest that individuals may benefit from higher illuminance levels during daytime and under normal working day conditions in terms of subjective alertness, mood, and sleep quality [20–22], yet such effects are naturally confounded with effects of colour temperature, dynamic light conditions, as well as a view to the outside.

In addition to the effects of light on alertness and performance, diurnal exposure to a higher illuminance level might also improve mood. Research has shown that bright light of relatively high CCT improved feelings of vitality and reduced psychological distress of office workers [23], and can be beneficial for people suffering from mood disorders, such as seasonal affective disorder (SAD) [24]. In addition, short-term exposure to monochromatic light (blue vs. green) during daytime affects activity in the amygdala (and other regions), a brain area related to emotional responses, suggesting that light exposure can influence emotional brain processing [25,26].

In the current study, we investigated the alerting and vitalizing effect of illuminance (200 vs. 1000 lx at the eye) on subjective measures, sustained attention, and cognitive performance, also assessed with non-visual tasks, and physiological arousal during daytime. We monitored the occurrence and development of such effects during an hour of light exposure under natural conditions (i.e., no sleep deprivation or pre-treatment under extremely low light settings), after a 30-minute baseline exposure of 200 lx (horizontal). As levels of alertness, performance and heart rate seem to show diurnal variations [27–31], we distinguished between morning and afternoon exposure, and included chronotype characterization of participants as a control variable. In addition, we investigated the effects of illuminance at the eye on subjective evaluations of the lighting and experience of the space as these subjective appraisals and associations might mediate subjective alerting and vitalizing effects of light as suggested by Veitch and colleagues [32].

2. Method

2.1. Design

The study followed a 2 × 2 mixed design with illuminance at eye level (200 vs. 1000 lx) and time of day (morning vs. afternoon) as independent factors. Every session started with a 30-minute baseline phase (200 lx and 4000 K at work plane), followed by exposure to experimental conditions (at 4000 K) for 60 min, divided in four 15-minute blocks. The lighting conditions were counterbalanced across participants. The morning sessions started at 9 am or 11 am and the sessions in the afternoon started at 1 pm or 3 pm. There was no daylight contribution during this experiment.

2.2. Participants

Thirty-two students participated in this lab study, of which 19 were male and 13 female (mean age 22, SD = 4.0, range 18 to 35). None of these participants were extreme chronotypes according to the Munich Chronotype questionnaire (MCTQ) [33], had travelled to a different time zone two weeks prior to the experiment or had complaints about their general health. They participated two, three, or four times in different conditions, including at least both lighting conditions during the same time slot (either morning or afternoon).

Table 1 Overview number of participants in experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>200 lx</th>
<th></th>
<th>1000 lx</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>Morning</td>
<td>12</td>
<td>10</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Afternoon</td>
<td>10</td>
<td>9</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

Note. Total N = 32, of which 7 participated in all four conditions.

2.3. Setting

The room where the experiment took place was a simulated office environment and had a size of 3.6 m by 3.2 m. The room was equipped with surface-mounted Philips Strato luminaires (each containing six fluorescent tubes of 28 W, of which three tubes of 2700 K (T8 28 W/827) and three tubes of 6500 K (T8 28 W/865)) covering the walls and ceiling. Each luminaire was 1.2 × 1.2 m and had a translucent cover with an integrated diffuser. The spectral power distribution of the lighting at 4000 K is depicted in Fig. 1. During the baseline and throughout the experiment, three ceiling mounted luminaires provided basic room illumination (200 lx on the work plane). A wall-mounted luminaire was turned on when the experimental conditions started, resulting in either 200 or 1000 lx at the eye, depending on the experimental condition. The main furnishings of the room consisted of a desk with computer, chair and a cabinet. The walls were off-white and had a reflectance of 87%, the floor was grey-blue with a reflectance of 19% and the desk was grey and had a reflectance of 39%.

2.4. Procedure

At the beginning of each session, participants completed a short questionnaire with questions about time awake, hours of sleep, time spent outside, travelling time outside and whether they had coffee and/or ate something one hour before the experiment. During the baseline condition, participants applied electrodes for the heart rate and skin conductance measures according to the instructions given by the experimenter. Subsequently, the procedure of applying the EEG electrodes was explained and the experimenter placed the electrodes on the participant’s scalp. After applying the electrodes, participants read the instruction for the experiment and measurements started.

The experiment consisted of five measurement blocks with each part containing two performance tests and a (short) questionnaire. The first measurement block took place during the baseline phase; the remaining four measurement blocks (Block One to Block Four) comprised the experimental phase. Each block started with an EEG protocol to measure brain activity with eyes open and eyes closed. Subsequently, performance was measured with a 5-minute auditory Psychomotor Vigilance Test (PVT). In the baseline and Block Four, this task was followed by the Necker Cube Pattern Control task (NC) and a questionnaire. In Blocks One, Two and Three, participants performed a Letter Digit Substitution Test (LDST) after the auditory PVT and filled in a short version of the questionnaire. Every session lasted 90 min and the participants received a compensation of 15 Euros per session. The study was approved by the review board of the Human Technology Interaction group in Eindhoven and took place from June to September 2010.

1 The horizontal illuminance level measured at work plane was 233 lx in the 200 lx and 649 lx in the 1000 lx condition. The illuminance at eye level in the baseline was 118 lx.

2 The results on EEG will be reported elsewhere.
2.5. Measures

Both subjective measures and objective measures were employed to assess alerting and vitalizing effects of lighting (illuminance level at the eye).

2.5.1. Alertness and mood

Subjective alertness was assessed with the Karolinska Sleepiness Scale (KSS) [34]. The response options of this scale ranged from (1) ‘extremely alert’ to (9) ‘extremely sleepy – fighting sleep’. In each of the baseline and measurement blocks, mood was measured with items selected from the activation-deactivation adjective checklist [35]. Four items (energetic, lacking in energy, alert, sleepy) assessed subjective vitality and two items assessed tension (tension and calmness). The internal consistencies of these scales were α = .85 and α = .56, respectively. In addition, two items assessing positive and negative affect (happy and sad) were administered in this questionnaire. The response scales of the mood measures ranged from (1) ‘definitely not feel’ to (4) ‘definitely feel’.4

2.5.2. Cognitive performance

Three different tests were employed to test cognitive performance. In the baseline and in all measurement blocks of the experimental phase, a 5-minute auditory PVT was used to assess sustained attention [36]. The mean reaction time, 10% slowest responses and 10% fastest responses were used as dependent measures for performance on this task.

In Blocks One to Three, a letter digit substitution test (LDST) was used as measure for sustained attention, visual search and working memory [37]. The performance indicators correspond to the number of correctly substituted digits, the number of errors and percentage correct.

In the baseline and last measurement block, the Necker cube pattern control test was also administered to assess the capacity to direct attention [38]. Participants indicated every single reversal in pattern control test was also administered to assess the capacity to maintain attention [38]. Participants indicated every single reversal in pattern control test was also administered to assess the capacity to maintain attention [38]. The percentage of instruction to try to hold on to one perspective. The percentage of instructions as they indicated more reversals in part two than in part one. Therefore, we will not report on these data.

2.5.3. Physiological measures

Heart rate and heart rate variability (HRV) were measured continuously during the experiment using TMSi software. The electrodes for the ECG measurements were placed at V1 and V6 using Kendall Arbo H124SG ECG electrodes. A sampling frequency of 2048 Hz was used. ECG measurements of 5 min during the auditory PVT tasks were used for the analyses. To minimize poor signal quality, artefacts in the ECG signals were removed following a procedure for EEG described by Van de Velde and colleagues [39]. Time domain and frequency domain (Fast Fourier Transform) analyses were performed with Kubios analysis software [40] using adequate RR intervals in a segment of at least 3 min. Mean heart rate (bpm), low frequency band (LF: .04–.15 Hz) and high frequency band (HF: .15–.40 Hz) power in normalized units (n.u.), and the LF/HF power ratio were used in this study. Difference scores between the lighting condition and baseline measures were computed considering potential inter- and intra-individual differences in heart rate and HRV.

2.5.4. Evaluation of lighting condition

Four self-report items assessed pleasantness of the lighting (α = .85). Four items assessed the subjective perception of the colour, intensity, distribution, and stimulation of the lighting. Three items probed beliefs regarding the effects of the lighting on work performance (α = .80). One item related to whether lighting affected their mood. Two items probed the adequacy of the amount and colour of light for an office environment. Three items measured visual comfort on the work plane, on the screen and in the space (α = .65) [41].

2.5.5. Evaluation of office environment

Four items measured participants’ evaluation of the overall impression of the environment (α = .88). Attitude towards the office environment was measured with four items probing what it would be like to work in a comparable environment (α = .95).

2.5.6. Confounding variables

Time awake, minutes of sleep, time spent outside, travelling time outside and whether participants had coffee and/or ate something one hour before the experiment were investigated at the beginning of each session. In addition, person characteristics were assessed prior to the first session in which the subject participated.

2.5.7. Light sensitivity

Light sensitivity was measured with the three items ‘How much trouble do your eyes give when you are exposed to bright light?’ ‘How much do you suffer from headaches when you are exposed to bright light?’, and ‘How often do you wear sunglasses because light is too bright?’ (α = .63).

2.5.8. Subjective trait vitality

Trait subjective vitality was measured with the trait level subjective vitality scale (α = .90) [42].

2.5.9. Health and sleep quality

General health was assessed with five items from the Dutch version of the SF-36 Health Survey (RAND-36) [43]. Sleep quality was measured with the Pittsburg Sleep Quality Index (PSQI) [44].

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The complete set of twenty items was employed in the baseline and last measurement block, but only the data from the short version are used here as they allow comparison over the five blocks. The short version of these scales showed a large overlap with the longer versions employed in the baseline and Block Four, as indicated by high bivariate correlations (all r > .79).

The response option (2) ‘cannot decide’ in the original activation-deactivation adjective checklist was changed into ‘very little’ to create a more consistent labelling of scale points.

More than one-third of the participants did not appear to comply with the instructions as they indicated more reversals in part two than in part one. Therefore, we will not report on these data.

The results on EEG and skin conductance will be reported elsewhere. Note that we did not include respiratory measures.
2.5.10. Chronotype

Chronotype was assessed with the Dutch translation of the Munich Chronotype questionnaire (MCTQ) [33].

2.6. Statistical analyses

Linear Mixed Model (LMM) analyses were performed to investigate the effect of illuminance at eye level, Time of day and Measurement block on subjective measures of alertness and mood, cognitive performance, heart rate measures and evaluation of the lighting and environment (separate LMM analyses were run for each dependent variable). In these analyses, participant was added as random variable to group the data per participant, i.e., to indicate that the same participant was measured multiple times. This implies that the intercept is not constant but is a random variable, i.e. the intercept varies between persons. Person characteristics, such as light sensitivity and chronotype, were added as covariates to control for these variables. The model used is a two-level model with Lighting condition, Time of day and Measurement block as predictors for the dependent measures of each session (Level 1) and person characteristics as predictors for the dependent measures of each participant (Level 2). For more details about LMM analyses, see e.g., Raudenbush and Bryk [45] and Hox [46].

3. Results

First, we investigated whether there were no differences in sleep, time spent outside and consumption prior to the experiment between the conditions. Subsequently, the effects of illuminance at eye level on subjective measures of alertness and mood, then on cognitive performance, heart rate and HRV, and lastly on evaluations of the lighting and environment were assessed.

3.1. Confounding variables: sleep, time spent outside and consumption

LMM analyses with Lighting condition, Time of day and the interaction between Lighting condition and Time of day as fixed factors were performed to explore whether there were differences in sleep duration, time awake, time spent outside and consumption prior to the experiment. The results revealed that there were no differences in sleep duration, time awake, time spent outside and consumption prior to the experiment. The results revealed that time awake and sleep duration in minutes did not differ between lighting conditions (p = .89 and p = .61, respectively). There were also no differences in minutes spent outside between the lighting conditions (p = .83). Time awake, sleep duration and time spent outside in minutes did differ between the morning and afternoon sessions, as would be expected (all p < .05). Participants were awake for longer in the afternoon (EMM = 207; SE = 15) than in the morning sessions (EMM = 132; SE = 14). Participants had also slept longer when participating in the afternoon (EMM = 462; SE = 14) compared to the morning session (EMM = 421; SE = 13). In addition, participants had spent more minutes outside in the afternoon (EMM = 61; SE = 9) than in the morning (EMM = 30; SE = 9). These effects were not moderated by condition (all p > .10). Whether the participants had had coffee or eaten something during the hour before the experiment also did not differ between the sessions (all p > .10).

3.2. Subjective measures

3.2.1. Baseline comparisons

LMM analyses were performed on feelings of alertness and mood at baseline with Lighting condition, Time of day, and their interaction as fixed factors. Light sensitivity, Chronotype, Trait vitality, and Global sleep quality were added as covariates to control for these person characteristics. The results revealed that there were no significant differences between the lighting conditions in sleepiness, feelings of vitality, tension, positive, or negative affect at baseline (all p > .10).

3.2.2. Effects of Lighting, Time of day and Measurement block on subjective alertness and mood

LMM analyses were performed to investigate the effect of Lighting condition, Time of day and Measurement block on sleepiness, vitality, tension, happiness, and sadness with Lighting condition, Time of day, and Measurement block as fixed factors. The interaction between Lighting condition and Measurement block was also added to the model. In addition, the interaction between Lighting condition and Time of day was added to assess whether Time of day moderated the effects of illuminance. Table 2 reports the results for the comparison between the 200 lx and 1000 lx conditions (at the eye).

The results showed an effect of Lighting condition on subjective sleepiness, measured with the KSS, and feelings of vitality. Participants felt less sleepy and more energetic in the 1000 lx condition compared to the 200 lx condition. There was no main effect of Time of day on these variables (p > .05). Measurement block had a significant effect on feelings of vitality [F(3,299) = 3.79; p = .01]: in both light conditions participants’ feelings of vitality decreased during the experiment. Post-hoc tests with Bonferroni correction showed that participants felt less energetic in the last measurement block (EMM = 2.53, SE = .08) than in Block One (EMM = 2.77, SE = .08) and Block Two (EMM = 2.73, SE = .08) with p = .01 and p = .05 respectively. The difference between Block Three (EMM = 2.71, SE = .08) and the last measurement block approached significance (p = .06).

The interaction effects between Lighting condition and Time of day and between Lighting condition and Measurement block on subjective sleepiness and vitality were not significant (F<1, NS), indicating that the effects of illuminance level were consistent across the day and across measurement blocks (see Fig. 2). Our manipulations did not induce significant effects on other dimensions of mood — happiness, sadness and tension (all p > .05).

3.3. Performance measures

3.3.1. Baseline comparisons

LMM analyses on auditory PVT performance at baseline with Lighting condition, Time of day, and their interaction as fixed factors and person characteristics as covariates revealed that there were no significant differences in overall reaction times, the 10% fastest or the 10% slowest reaction times in the baseline condition (all p > .10), indicating that performance at baseline did not differ between the conditions.

LDST measures were only taken in Blocks One, Two and Three, hence we cannot compute baseline comparisons for this indicator of cognitive performance.

3.3.2. Effects of Lighting, Time of day and Measurement block on performance

LMM analyses were performed to investigate the effect of Lighting condition, Time of day, and Measurement block on reaction time measures of the auditory PVT, controlling for person characteristics. Table 2 reports the F-statistics of these analyses and the estimated marginal means for the overall reaction times, the 10% fastest and the 10% slowest reaction times in both the 200 lx and 1000 lx conditions (at the eye).

We also performed the analyses with the three-way interaction between Lighting condition, Time of day and Measurement block added to the model, but this interaction did not have significant effects on the dependent variables (all p > .10) and did not change the results.

7 General health and gender were not added to the model to avoid multicollinearity as these variables correlated (r > 3) with the other covariates.
The results of the PVT revealed significant main effects of Lighting condition on cognitive performance assessed with the overall reaction times and with the 10% slowest responses. Participants performed better on the PVT in the 1000 lx compared to the 200 lx condition (at the eye). The main effect of Measurement block on overall reaction times was also significant indicating increasing reaction times during the experiment. Post-hoc tests with Bonferroni correction showed that the overall reaction time in Block One ($EMM = 283.12; SE = 8.08$) was shorter than in Block Four ($EMM = 291.09; SE = 8.08$) with $p < .05$. The reaction times in Blocks Two ($EMM = 289.30; 8.08$) and Three ($EMM = 289.94; SE = 8.08$) were not significantly different from the last block (both $p > .10$). The interaction between Lighting condition and Time of day on overall reaction time, 10% slowest reaction times and 10% fastest reaction times was significant (all $p < .01$). Responses in the morning (but not in the afternoon) were slower in the 200 lx condition versus the 1000 lx condition (see Fig. 3). In addition, the interaction between Lighting condition and Measurement block on overall reaction time and 10% slowest reaction times was significant (both $p < .01$). From Block Three onward, responses got slower in the 200 lx condition (see Fig. 3). The interaction effects show that the effect of illuminance level on reaction times is moderated by time of day and the duration of the experiment. From Fig. 3, it even appears that the main effect of Lighting condition is fully qualified by these interactions.

The LDST was administered as an additional cognitive performance indicator in Blocks One, Two and Three. LMM analyses showed no significant main effects of Lighting condition and Time of day on the number of correct answers, the number of errors, or the percentage of correct answers (all $p > .10$; see Table 2), controlling for person characteristics. There was, however, a significant main effect of Measurement block on the number of correct answers, with increasing numbers of correct answers during the experiment [$F(2,216) = 13.79; p < .01$]. Post-hoc tests with Bonferroni correction showed that the number of correct answers in Blocks One ($EMM = 29.04; SE = 1.40$) and Two ($EMM = 31.85; SE = 1.40$) were lower than in Block Three ($EMM = 34.42; SE = 1.40$) with $p < .01$ and $p < .05$, respectively. The interactions between Lighting condition and Time of day and between Lighting condition and Measurement block had no significant effect on the number of correct answers ($p = .29$ and $p = .85$, respectively). There was a significant interaction effect between Lighting condition and Measurement block on number of errors [$F(2,219) = 3.92; p = .02$] and on the percentage of correct answers [$F(2,218) = 3.94; p = .02$]. Although participants in the 1000 lx condition made more errors and had a lower percentage of correct answers in Block One, they made fewer errors and had a higher percentage of correct answers in Blocks Two and Three than those in the 200 lx condition (see Fig. 4). The interaction between Lighting condition and Time of day had no significant effect on the percentage correct or the number of errors ($p = .86$ and $p = .45$, respectively).

### 3.4. Heart rate and HRV

#### 3.4.1. Baseline comparisons

LMM analyses on the heart rate measures at baseline with Lighting condition, Time of day, and their interaction as fixed factors and person characteristics as covariates revealed that there were no significant differences in mean heart rate, power in LF and HF, and LF/HF power ratio (all $p > .10$), indicating that heart rate and HRV at baseline did not differ between the conditions.

#### 3.4.2. Effects of Lighting, Time of day and Measurement block on heart rate and HRV

LMM analyses were performed to explore the effect of Lighting condition, Time of day and Measurement block on heart rate and HRV, controlling for person characteristics. The F-statistics and the estimated marginal means for these measures are reported in Table 2. Results revealed that heart rate increased compared to baseline in the 1000 lx (at the eye) condition, while the heart rate decreased compared to baseline in the 200 lx (at the eye) condition. This effect was not moderated by Time of day or Measurement block (both $F < 1, ns$; see Fig. 5). Lighting condition did not have a significant main effect on the normalized power in the LF and HF bands, nor were the interaction effects of Lighting condition with Time of day or Measurement block on the normalized power in these bands significant (all $F < 1, ns$). Lighting condition, however, did have a main effect on the LF/HF power ratio with a higher increase compared to baseline in the 1000 lx condition (at the eye). The interaction between Lighting condition and Time of day was not significant ($F < 1, ns$), but the interaction between Lighting condition and Measurement block was significant [$F(3,152) = 3.37; p < .05$] suggesting that the effect of Lighting condition was moderated by duration of the exposure. Post hoc comparisons with Bonferroni correction revealed that the effect of Lighting condition on the LF/HF power ratio was only significant in the last measurement block ($p < .01$; see Fig. 5).

### 3.5. Evaluations of the lighting and environment

LMM analyses were performed to investigate the effect of Lighting condition and Time of day on the appraisals of the lighting, the environment, and visual comfort assessed in the last measurement block. In these analyses Lighting condition, Time of day and the interaction between Lighting condition and Time of day were added

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**Table 2**

Results of linear mixed model analyses for subjective and objective measures.

<table>
<thead>
<tr>
<th></th>
<th>200 lx</th>
<th>1000 lx</th>
<th>Statistics</th>
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<tbody>
<tr>
<td></td>
<td>EMM SE</td>
<td>EMM SE</td>
<td>F df p R²</td>
</tr>
<tr>
<td>Subjective measures</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sleepiness</td>
<td>4.50 .24</td>
<td>4.10 .24</td>
<td>2.21 (1,300) &lt;.01 .03</td>
</tr>
<tr>
<td>Vitality</td>
<td>2.59 .07</td>
<td>2.78 .07</td>
<td>12.52 (1,301) &lt;.01 .00</td>
</tr>
<tr>
<td>Tension</td>
<td>1.74 .08</td>
<td>1.74 .08</td>
<td>08 &lt;.01 (1,299) .06 .02</td>
</tr>
<tr>
<td>Happy</td>
<td>2.49 .10</td>
<td>2.55 .10</td>
<td>14.8 (1,300) .23 .04</td>
</tr>
<tr>
<td>Sad</td>
<td>1.30 .07</td>
<td>1.31 .07</td>
<td>04 (1,299) .84 .01</td>
</tr>
<tr>
<td>PVT</td>
<td></td>
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<tr>
<td>Overall reaction time</td>
<td>291.29 7.96 285.44 7.96 8.65 (1,298) &lt;.01 .16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10% slowest reaction times</td>
<td>390.18 12.62 377.72 12.62 6.10 (1,299) &lt;.01 .12</td>
<td></td>
<td></td>
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<tr>
<td>10% fastest reaction times</td>
<td>277.61 5.35 225.13 5.35 3.24 (1,298) &lt;.01 .12</td>
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<tr>
<td>LDST</td>
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<tr>
<td>Number correct</td>
<td>32.32 1.33 31.23 1.33 1.67 (1,217) .20 .12</td>
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<td>Number of errors</td>
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<td>.67 .11</td>
<td>.03 (1,221) .87 .04</td>
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<td>Percentage correct</td>
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<td>.97 .80</td>
<td>.25 (1,221) .02 .04</td>
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<tr>
<td>Heart rate (variability)</td>
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<tr>
<td>Δ Heart rate</td>
<td>−3.04 2.60 4.73 2.82 9.72 (1,177) &lt;.01 .10</td>
<td></td>
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<tr>
<td>Δ LF power (n.u.)</td>
<td>3.48 2.60 6.02 2.82 12.2 (1,177) .27 .05</td>
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<tr>
<td>Δ HF power (n.u.)</td>
<td>−3.48 2.60 −6.02 2.82 12.2 (1,177) .27 .05</td>
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<tr>
<td>Δ LF/HF power ratio</td>
<td>.06 .10 .24 .10 4.13 (1,174) .04 .10</td>
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</table>

Note. EMM stands for estimated marginal means and SE stands for standard errors. Significant differences are indicated in bold. Adjusted R-Squared are given for the total mixed model at level 1, i.e., within sessions. This measure is the proportion reduction in variance of residuals. Note that this measure can also have negative values [45].

9 The main effect of Lighting condition on 10% fastest reaction times approached significance ($p = .07$).
10 The interaction between Lighting condition and Measurement block on the 10% fastest responses approached significance ($p = .10$) suggesting a similar trend as for the overall and 10% slowest reaction times.
11 We also performed the analyses with the three-way interaction between Lighting condition, Time of day and Measurement block added to the model, but this interaction did not have significant effects on the PVT measures (all $p > .10$) and did not change the results.
as fixed factors. In Table 3, the F-statistics of the LMM analyses on the subjective appraisals for Lighting condition and the estimated marginal means for the subjective evaluations in both the 200 lx and 1000 lx conditions are reported.

The results revealed that illuminance level had a significant effect on the pleasantness of the lighting: participants evaluated the 200 lx (at the eye) condition as more pleasant than the 1000 lx (at the eye) lighting condition. In addition, participants evaluated the colour of the lighting to be cooler in the high lighting condition than in the low illuminance level condition. The lighting in the high lighting condition was experienced as brighter and more activating than in the low lighting condition. In addition, the illuminance had a significant effect on the experienced distribution of the lighting: the light was evaluated to be distributed less evenly in the high lighting condition than in the low lighting condition. The illuminance also had a significant effect on visual comfort with 200 lx at eye level just above the optimum whereas 200 lx at the eye was just below the optimum. There was no significant difference in experienced adequacy of the lighting for of office spaces in terms of illuminance or colour between the lighting conditions. The main effects of Time of day and the interaction effects between Lighting condition and Time of day were not significant for the subjective evaluations of the lighting (all F < 1; ns). This suggests that the evaluations did not differ between the morning or afternoon sessions nor was the effect of lighting condition on these evaluations moderated by time of day.

LMM analyses were also performed to explore whether the beliefs concerning the effect of lighting on performance and mood differed between the conditions. The results of these analyses showed no significant main or interaction effects, suggesting that the beliefs concerning the effects of lighting on performance and mood did not differ between the two lighting conditions nor between the morning or afternoon sessions (all p > .10).

LMM analysis of the general evaluation of the room revealed no significant main or interaction effects of illuminance and Time of day (all F < 1; ns). In addition, Lighting condition and Time of day did not have an effect on the attitude towards working in a comparable environment (all F < 1; ns).

4. Discussion

Several studies have explored – and reported – alerting effects of light during night time, under extreme sleep pressure, or after light deprivation. In contrast, the current study investigated whether such effects also appear under regular conditions during daytime and office work conditions. We found that indeed a higher illuminance during daytime can have an effect on subjective measures of alertness and vitality, as well as objective measures of performance, heart rate, and HRV.

4.1. Subjective reports

Daytime exposure to a higher illuminance had a positive effect on subjective alertness and vitality: participants felt more alert and energetic in the high lighting condition (1000 lx at eye level) compared to the lower lighting condition (200 lx at eye level). These findings are in line with findings reported in earlier studies [10,12,13]. Even during daytime, light has an immediate (i.e. visible in first measurement block, 10 min into the exposure) and persistent effect on subjective alertness and vitality. These effects are not moderated by time of day or duration of exposure.

Results on additional mood dimensions (tension, positive, and negative affect) revealed no significant effect of illuminance. This result is comparable to earlier studies by Baron et al. and Daurat et al. [47,48] who also revealed no significant effects of a higher illuminance on
positive or negative affect during daytime and night time, respectively. Although it does contrast studies showing beneficial effects of bright light on mood [23,49], these differences may be explained by the fact that both studies employed lighting of higher illuminance (2500 vs. 1000 lx) and correlated colour temperature (6500 K vs. 4000 K), and studied effects over prolonged periods of time. Moreover, in the current study persons already felt, on average, quite happy and did not suffer from tension or sadness in the baseline phase, which suggests that there was little to improve.

Subjective evaluations of the office lighting revealed that the participants rated the two lighting conditions differently. They experienced the 1000 lx condition as more bright and activating, although less pleasant, but judged both illuminance conditions equally adequate for working. Nevertheless, they felt more alert and vital in the 1000 lx (at the eye) condition compared to the 200 lx condition.

4.2. Cognitive performance

The light manipulation demonstrated an effect on participants’ performance in the auditory PVT, with shorter responses in the 1000 lx at the eye condition compared to the 200 lx at the eye condition. These effects were moderated by two variables: time of day and duration of the experiment. The effect of illuminance on performance was most pronounced towards the end of the experiment. Similarly, the interaction between illuminance and measurement block for the LDST task suggested that the participants in the 1000 lx condition, although starting off worse than those in the 200 lx condition, performed better during the later part of the experiment.

Participants reported that they became more fatigued and depleted during the experiment as indicated by an effect of measurement block on subjective feelings of vitality. Therefore, a potential explanation for the delayed effect of illuminance on cognitive performance is that

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**Fig. 3.** Overall reaction times (a), 10% slowest reaction times (b) and 10% fastest reaction times (c) for the high and low lighting conditions per measurement block (left panel) and for time of day (right panel). The whiskers represent the 95% confidence interval. Note. "p < .01, *p < .05 and †p < .10.
more intense light improves cognitive performance mainly when participants suffer from mental fatigue. This suggests that more intense light can help overcome tiredness and decreased vitality during the day. This is consistent with research showing that light exposure at night or among sleep-deprived participants can improve reaction times immediately \cite{10, 50}. Furthermore, a lab study showed that participants who did not respond to exposure to a higher illuminance already had faster response times than participants who did, suggesting that they already were very alert \cite{13}.

The effect of illuminance on auditory PVT performance was most pronounced in the morning sessions. In contrast, this interaction was absent for LDST measures. The data did however demonstrate a learning effect on speed in the LDST. Results on this task should therefore be considered with caution. Earlier research has shown that persons have lower alertness levels and performance in the morning than in the afternoon (e.g. see \cite{30}), which would appear to be in line with our results as the PVT is an objective measure of alertness and sustained attention. However, we did not find significant differences in self-reported alertness and vitality or cognitive performance between the morning and afternoon baseline sessions, which actually invalidates this explanation. We also controlled for relevant person characteristics such as, chronotype, light sensitivity, sleep quality and trait vitality. Adding these variables to the analyses did not change the results suggesting that, for example, chronotype cannot explain the time of day dependent effect of illuminance on cognitive performance in this study.\textsuperscript{12}

4.3. Heart rate and HRV

Results on the heart rate measures suggest that illuminance level also has an influence on autonomic nervous activity. Heart rate increased compared to baseline in the 1000 lx (at the eye) condition, while it decreased in the 200 lx condition. In addition, a higher illuminance increased the LF/HF power ratio compared to baseline suggesting a relative increase in sympathetic activity in the 1000 lx condition. The effect on heart rate was independent of time of day or duration of exposure, while the effect on the LF/HF power ratio was most pronounced at the end of the light exposure. These results suggest that a higher illuminance level can increase physiological arousal. Earlier studies had shown inconsistent effects of light on autonomic nervous system. Some studies only reported effects of illuminance levels on heart rate during night time (e.g., \cite{12, 51}).

\textsuperscript{12} It should be noted that in this experiment no extreme chronotypes participated, therefore the results apply for people of average and moderate chronotypes, but should not be generalized to extreme morning or evening types.
exposure than before. Whether illuminance affects heart rate and HRV may
be due to the current study were induced by less extreme illuminance differences
which thus coincided with higher heart rates and higher LF/HF ratios.

5. Conclusion

These performance effects emerged particularly in the morning and
results of the performance measures suggest that white light can have
improvement in brain activity under 'natural' conditions.

5. Conclusion

The current study shows that even under natural conditions, i.e.
neither sleep nor light deprived, a higher illuminance (measured at
the eye) can improve not only employees’ subjective feelings of
alertness and vitality, but also objectively measured performance.

The results of the performance measures suggest that white light can have
an activating effect, i.e. improve performance and result in faster
responses and higher accuracy on relatively simple cognitive tasks.

These performance effects emerged particularly in the morning and
after prolonged exposure (> 30 min). In addition, the results on heart
rate and HRV showed that exposure to a higher illuminance can also
increase physiological arousal.

The light exposure in the current study was relatively brief (i.e., one
hour). As exposure to a higher illuminance level in workplaces would be
less energy efficient, future research should investigate the effects of
prolonged exposure periods and/or the effects of exposure to bright
light only when activation is needed (e.g., when a person is suffering
from mental fatigue). This would also render a better understanding
of the underlying mechanisms of the alerting and vitalizing effect of
bright light. Recently, two possible mechanisms by which light might
influence alertness and performance during daytime have been
proposed [13,54–56]. In addition to the circadian system, a possible
mechanism for the alerting and vitalizing effects of light might be the
activation and modulation of alertness-related (e.g., brainstem,
thalamus) and mood-related pathways (e.g., amygdala, hippocampus).
In addition, beliefs or expectations regarding effects of bright light may
have contributed to the findings. Thus, the effect can be purely
biological, i.e. through activation of the central nervous system
[26,56,57], but can also be more psychological in nature.

The current study suggests that levels of 1000 lx on the eye (as
compared to 200 lx, under normally entrained conditions) are sufficient
to (temporarily) help overcome tiredness and decreased vitality, and
improve performance on vigilance and sustained attention tasks during
daytime. These results complement earlier studies to the positive effects
of illuminance on alertness and performance at night and after sleep
depression. They also complement research reporting effects of blue
enriched light during daytime on subjective measures of alertness and
vitality [15,16].

Declaration of interest

The authors report no conflicts of interest. The authors alone are
responsible for the content and writing of the paper.

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Table 3

<table>
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<tr>
<th>EMM</th>
<th>SE</th>
<th>EMM</th>
<th>SE</th>
<th>F</th>
<th>df</th>
<th>p</th>
<th>R²</th>
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<td>200 lx</td>
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<td>1000 lx</td>
<td></td>
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<tr>
<td>Pleas</td>
<td>2.34</td>
<td>0.25</td>
<td>2.55</td>
<td>0.15</td>
<td>16.50 (1.47)</td>
<td>&lt;0.01</td>
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<td>Activat</td>
<td>2.81</td>
<td>0.13</td>
<td>3.60</td>
<td>0.13</td>
<td>20.10 (1.44)</td>
<td>&lt;0.01</td>
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<td>Colour of lighting</td>
<td>2.90</td>
<td>0.16</td>
<td>3.47</td>
<td>0.17</td>
<td>11.16 (1.48)</td>
<td>&lt;0.01</td>
<td>21</td>
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<tr>
<td>Amount of lighting</td>
<td>3.11</td>
<td>0.12</td>
<td>4.35</td>
<td>0.12</td>
<td>121.31 (1.48)</td>
<td>&lt;0.01</td>
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<td>Distribution of lighting</td>
<td>2.61</td>
<td>0.20</td>
<td>2.08</td>
<td>0.20</td>
<td>6.29 (1.44)</td>
<td>&lt;0.02</td>
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<td>Adequacy of amount of light</td>
<td>2.79</td>
<td>0.16</td>
<td>2.55</td>
<td>0.16</td>
<td>1.41 (1.56)</td>
<td>&lt;0.24</td>
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<tr>
<td>Adequacy of colour of light</td>
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<td>3.15</td>
<td>0.17</td>
<td>0.80 (1.48)</td>
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<td>Visual comfort</td>
<td>2.82</td>
<td>0.10</td>
<td>3.20</td>
<td>0.10</td>
<td>29.35 (1.50)</td>
<td>&lt;0.01</td>
<td>38</td>
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</table>

Note. EMM stands for estimated marginal means and SE stands for standard errors. Significant differences are indicated in bold. Adjusted R-Squared are given for the
total mixed model at level 1, i.e. within sessions. This measure is the proportion
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[45].

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