Diurnal effects of illuminance on performance

Citation for published version (APA):

Document license:
TAVERNE

DOI:
10.1177/1477153521990645

Document status and date:
Published: 01/12/2021

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 28. Sep. 2022
Diurnal effects of illuminance on performance: Exploring the moderating role of cognitive domain and task difficulty

T Ru PhD\textsuperscript{a,b,c}, KCHJ Smolders PhD\textsuperscript{b}, Q Chen MSc\textsuperscript{a}, G Zhou PhD\textsuperscript{a,c} and YAW de Kort PhD\textsuperscript{b}

\textsuperscript{a}Lab of Light and Physiopsychological Health, National Center for International Research on Green Optoelectronics, South China Normal University, Guangzhou, China
\textsuperscript{b}Human Technology Interaction, School of Innovation Sciences, and Intelligent Lighting Institute, Eindhoven University of Technology, Eindhoven, The Netherlands
\textsuperscript{c}Guangdong Provincial Key Laboratory of Optical Information Materials and Technology and Institute of Electronic Paper Displays, South China Academy of Advanced Optoelectronics, SCNU, Guangzhou, China

Received 23 March 2020; Revised 17 December 2020; Accepted 5 January 2021

Literature has occasionally reported acute effects of office illuminance on cognitive performance during daytime. The current study was conducted to systematically investigate whether the type of task and level of task difficulty moderate the effect of daytime illuminance on cognitive functioning. Thirty healthy participants were assigned to high (\(\sim1036\) lux at eye level; melanopic EDI = 904 lux) vs. low (\(\sim108\) lux at eye level, melanopic EDI = 87 lux) illuminance (at 6500 K) during working hours, in which participants were tested on both easy and difficult versions of tasks probing sustained attention, response inhibition, conflict monitoring and working memory. Subjective sleepiness and mood were also measured. Results revealed that exposure to high vs. low illuminance significantly improved speed on the response inhibition task, and accuracy and speed on the working memory tasks. Moreover, when effects arose, these were moderated by task difficulty, consistently showing more pronounced effects for easy than for difficult trials. Notably, subjective sleepiness and negative mood remained unaffected by illuminance, and no statistically significant effects emerged for sustained attention and conflict monitoring. This study demonstrates that the diurnal cognitive effects of illuminance may be moderated by both types of cognitive task and task difficulty.

1. Introduction

Office lighting is a vital environmental factor moderating human affective state and task performance in daily working life.\textsuperscript{1–4} The rod and cone-driven image-forming pathway affects visual performance and experiences such as atmosphere, aesthetic appeal and visual comfort.\textsuperscript{5–7} Beyond vision, non-image
forming (NIF) pathways have been implicated to play an important role in the light-induced moderations in subjective alertness, mood and cognitive function. Although we have come to understand better the retinal photoreceptors that mediate NIF responses to light (intrinsically photosensitive retinal ganglion cells, ipRGCs) and the neural mechanisms underlying circadian entrainment via their projections to the suprachiasmatic nucleus (SCN), we are, as yet, less well equipped to delineate the mechanisms by which lighting influences cognitive processes, particularly during the day. Recent research has indicated that ipRGCs project to multiple additional relevant brain regions, not necessarily mediated by the SCN, among which are subcortical (e.g. ventrolateral preoptic nucleus), brainstem (e.g. Locus Coeruleus) and cortical areas (e.g. frontal regions). Moreover, effects of light beyond vision are potentially also modulated by activation of the rods and cones, through their direct action on ipRGCs. This all points at a complex set of potential mechanisms and interactions that result in light-induced moderations in affective and cognitive states. Moreover, as the exact projections of light and the extent and conditions of their emergence are unknown, we currently are unable to predict exactly which cognitive tasks would be under stronger or weaker influence of light.

When we speak of light effects, there are many factors to take into consideration. Among them are illuminance, spectrum and duration, which all determine the ultimate dosage, in terms of specific photoreceptor activation, persons receive. In addition, timing (particularly where circadian effects are concerned, but also acute effects may be modulated by internal time), personal characteristics (e.g. age, chronotype) and light history may influence individuals' sensitivity to light. Illuminance and spectrum are two important properties of lighting that have been demonstrated to impact the direction and magnitude of light-induced moderations in alertness and cognitive performance in office-like contexts. As there are indications for more pronounced effects of the intensity vs. correlated color temperature of white light on daytime functioning (at least for realistic values in office environments), the current paper will particularly focus on the effects of illuminance.

Yet, the acute alerting and cognitive effects of illuminance are still inconclusive. In fact, results of studies revealed that daytime high vs. low illuminance was shown to either result in feelings of increased alertness, or no significant change in subjective alertness in healthy day-active people. In most of these studies, the influence of illuminance on cognitive performance was also examined by using one or more cognitive tasks, including psychomotor vigilance tests, response inhibition, task switching or working memory tasks, probing various cognitive functions. These studies, however, revealed even more inconclusive findings on acute cognitive effects of diurnal illuminance, showing not only positive and null effects, but also impaired performance under bright vs. dim light conditions.

The potential mechanisms driving these (inconsistent) acute cognitive effects of illuminance during daytime remain largely unknown, apart from that they are separate from melatonin suppression due to light-induced responses, as diurnal circulating melatonin concentrations are generally negligible. Moreover, it is largely unclear under which conditions the beneficial effects manifest or are impeded in everyday life. Yet, in order to provide optimal lighting benefiting human work performance in daily life, it is essential to get more knowledge about factors mediating and moderating daytime effects of light level on cognitive functioning. To date, possible explanations for these inconsistent findings may – in part – be found in the differences in employed intensities, spectra, and/or duration of light exposures and
It should, however, be noted that there are also studies reporting differential cognitive effects of illuminance within one and the same study paradigm. In these investigations, various types of tasks were employed to test the acute effects of illuminance on specific cognitive aspects by comparing the same light conditions and employing the same protocol in each condition. The inconsistency in these findings suggests that the magnitude and/or the direction of effects of illuminance on cognition may depend on task characteristics, as different cognitive tasks may also engage brain regions differentially. This leaves the possibility open that the specific cognitive domain and/or task difficulty modulates light-induced effects on performance.

There are some indications that exposure to a relatively high illuminance might differentially benefit performance on difficult vs. easy levels of the same cognitive task. More specifically, Huiberts et al. revealed that accuracy in the 2-Back task was significantly impaired, whereas accuracy in the more difficult 3-Back and the easier 1-Back task was not significantly affected with exposure to a high vs. low illuminance. Also, accuracy for the relatively easy Digital Span task (forward digit span task [FDST]) mildly increased (after 1-hour light exposure) under exposure to higher illuminance, while no such performance improvement was found in a more difficult version of the Digital Span task (backward digit span task [BDST]). It should be noted, however, that there may have been a confound between type of task and task complexity (e.g. a backward digit span requires additional manipulations in working memory in comparison to a forward one), making it difficult to disentangle the potential moderating effect of cognitive domain and task difficulty. In a subsequent study, Huiberts et al. examined the effects of illuminance on a working memory task (BDST) with varying difficulty levels. In this study, performance on the easy level (short spans) of the BDST remained unaffected, while performance on the difficult level (long spans) of the BDST task significantly improved under high vs. low illuminance. The findings of these studies may suggest that the difficulty level of the task is, in addition to task type, another potential task characteristic moderating the effect of light on cognitive performance. Yet, the task difficulty manipulation was only employed in one specific cognitive domain of working memory. A recent study by Ru et al. also revealed – in addition to task-type dependent light-induced responses – moderations by task difficulty on the effect of illuminance on a task probing conflict monitoring. The findings indicated only faster reaction speed for the incongruent Flanker trials (relatively difficult) under high vs. low illuminance, but not for the congruent Flanker trials (relatively easy). To what extent or whether task difficulty could moderate the acute effect of illuminance on task performance in other cognitive domains is still unknown. Other studies investigating the diurnal effects of illuminance on different cognitive domains have restricted their cognitive tests to one difficulty level. No investigations have – at least to our knowledge – manipulated and tested the potential moderating role of the difficulty level within a particular task in light-induced modulations of task performance across a diverse set of tasks probing different cognitive domains.

All in all, we currently lack a clear view of how task difficulty and type of task moderate diurnal effects of illuminance on cognitive performance. The main aim of the current study, therefore, was to investigate the diurnal effect of light level on cognitive performance among tasks varying in cognitive domain as well as difficulty level. To this end, healthy adults were assigned to high vs. low illuminance conditions, during which participants were tested on both easy and difficult versions of the sustained...
attention task (psychomotor vigilance task [PVT]), response inhibition (Go/No-go) task, conflict-monitoring (Flanker) task and working memory tasks (paced visual serial addition task [PVSAT] and 2-Back task). In addition, the effects of light level on subjective sleepiness (Karolinska Sleepiness Scale), affective state (positive and negative affect schedule) and light appraisals were investigated.

2. Method

2.1 Design

The study followed a $2 \times 2$ within-subjects design with illuminance (high (~1000 lux at the eye) vs. low (~100 lux at the eye)) and task difficulty (easy vs. difficult) manipulated within each cognitive task (PVT, Go/No-go, Flanker, PVSAT and 2-Back) as independent factors. The two light conditions with either high illuminance or low illuminance were administered on two separate days with an interval of at least three days in between the experimental sessions, and the order randomly distributed across participants. Both difficulty levels of all the cognitive tasks were offered in each session. The order of the two difficulty levels was counterbalanced across participants and remained the same in the two experiment sessions within participants. Subjective indicators were measured during the baseline phase, as well as during the test phase.

The study was carried out during regular working hours in the winter, and each participant was scheduled to come to the laboratory on two visits during the same timeslot on both experiment days.

2.2 Participants

Thirty-two persons ($M_{age} = 20.46 \pm 1.81$, 10 males) participated in the laboratory study. Two of them quit prematurely for personal reasons, resulting in 60 complete experimental sessions. Participants had no hearing or visual impairments other than myopia, corrected by wearing contact lenses or glasses. None of them was extremely late or early chronotype according to the Munich Chronotype questionnaire (MCTQ). They had travelled to a different time zone or worked night-shifts during the month prior to the start of the first experimental session, nor did they suffer from general health-related problems.

2.3 Setting

The laboratory room in which the experiment was conducted was a simulated office environment of $3.6 \times 3.6$ m. Four separate workstations with one white desk (1.2 m $\times$ 0.8 m) and one black chair were created. An All-in-One LCD PC (Lenovo, AIO300) with headphones, a keyboard and a mouse were placed on each of the desks.

The lab room was equipped with nine grille lamps in the ceiling. Six lamps were 1.2 m $\times$ 0.8 m containing three Philips LED tubes of 6500 K (T8-28 W/865), and three lamps were 1.2 m $\times$ 0.6 m and contained two Philips LED tubes of 6500 K(T8-28 W/865). Using a calibrated spectroradiometer (JETI Specbos 1201), the illuminance, spectral power distribution (SPD) and color-rendering index (CRI) were measured at eye level aimed in the gaze direction of participants. The CRI at 6500 K was $R_a = 81$. The SPDs of the light in the low and high illuminance conditions are depicted in Figure 1. After the baseline phase, lighting was set to either low illuminance (~108 lux at eye level, photon density: $8.99 \times 10^{13}$ photons*s$^{-1}$*cm$^{-2}$; irradiance: 33 $\mu$W*cm$^{-2}$) or high illuminance (~1036 lux at eye level, photon density: $9.28 \times 10^{14}$ photons*s$^{-1}$*cm$^{-2}$; irradiance: 341 $\mu$W*cm$^{-2}$). The $\alpha$-opic equivalent daylight illuminance (EDI) values at eye level, as well as the $\alpha$-opic irradiance for each of the photoreceptors per lighting condition, can be reviewed in Table 1.
2.4 Procedure

Before participating in the laboratory study, participants completed a set of online questionnaires, including questions regarding demographics, chronotype, physical and mental health. Participants were asked to adhere to their habitual sleep-wake schedule (based on sleep timing on work days as reported in the MCTQ, allowing a 30-min difference in time), and not to have drinks containing alcohol or caffeine prior to the session in the laboratory. All participants gave their written informed consent after their first arrival in the lab.

After participants arrived in the lab, they were guided to the workstation in the laboratory room with a relatively low illuminance (~80 lux at 6500 K at eye level) and had a short interview including questions on their sleep–wake timing of the preceding night,
whether they had taken caffeine containing drinks and how much time they had spent outside before their arrival in the lab. Next, participants’ baseline sleepiness and mood were measured with questionnaires. After that, the general procedure instruction followed, and the formal experimental session started.

The formal experiment started with a 10-min light adaptation phase, during which participants were free to read books under either the low or high illuminance condition at eye level. After this adaptation period, participants engaged in the five cognitive tests, with each test including one easy and one difficult measurement block, as well a brief questionnaire probing their ratings on task difficulty after each test block. These five cognitive tasks were programmed with two fixed orders (PVT–PVSAT–Go/No-go–Flanker–2-Back or PVT–Go/No-go–PVSAT–2-Back–Flanker), counterbalanced between participants. Participants were tested on the same task order on both experiment days. After 20 min (i.e. after the first task) and 35 min (after the third task) of light exposure, participants’ subjective sleepiness was assessed. After 50 min of light exposure (i.e. after the fifth task), participants’ subjective sleepiness and mood were both assessed by means of short questionnaires. Last, participants were asked to complete a questionnaire regarding their evaluation of the lighting environment in the laboratory. A schematic representation of one full experiment procedure is depicted in Figure 2.

2.5 Cognitive performance

The Auditory Psychomotor Vigilance Test (PVT) was used to assess sustained attention. The average reaction speed (inversed reaction time) on overall trials, the 10% fastest trials, and 10% slowest trials were used as markers for performance on this task. The visual Go/No-go task was employed to measure response inhibition capacities, the Flanker task was used to measure executive function of conflict monitoring, a Paced Visual Serial Addition Task (PVSAT) and a 2-Back task were used to measure short-term memory. Both reaction speed (1/RT) and accuracy were emphasised and investigated in Go/No-go, Flanker, PVSAT and 2-Back task. There were two versions of each task, varying in difficulty level. The manipulations of task difficulty for each cognitive task are described in the supplementary material (for additional details see Ru et al.).

2.6 Subjective measurement

Subjective sleepiness was assessed with the Karolinska Sleepiness Scale (KSS) ranging from (1) extremely alert to (9) extremely sleepy. Positive and negative mood were evaluated using the Positive and Negative Affect Schedule (PANAS), including 10 positive (α = 0.90) and 10 negative (α = 0.80)
Participants rated all items on a scale ranging from (1) extremely slight to (5) extremely strong.

After each test block, participants rated the difficulty level of the task version on a 9-point Likert scale ranging from (1) extremely easy to (9) extremely difficult.

The lighting environment in the laboratory room was evaluated by using six 5-point Likert-scale items adopted from Flynn et al., assessing participants’ appraisals of the lighting (intensity, color, pleasantness, comfort, disturbance and softness). In addition, three 9-point Likert-scale items were administered to probe participants’ subjective beliefs of lighting effects (energy/mood/work performance) adopted from Smolders and de Kort, and one 7-point Likert-scale item from (1) not at all to (7) very much was included probing to what extent the participant liked to apply the current light setting to their workplace.

2.7 Data analysis

Before further statistical analyses were performed, the scores obtained for the individual items on the PANAS scale were averaged separately across positive and negative affective dimensions for each participant at baseline and at the end of the experimental phase. Likewise, all reaction time data were inverted to increase normality. Responses on error trials (omissions, false starts and trials following incorrect responses) and outliers (M ± 3SD; per participant and per dependent variable per session) were removed.

For all statistical analyses, R studio was used. Due to the hierarchical structure of the data, linear mixed model (LMM) analyses were conducted using an LMM model with Task difficulty (easy vs. difficult) and Cognitive domain (PVT, Go/No-go, Flanker, 2-Back and PVSAT) as fixed factors, and Participant ID as random intercept for subjective ratings on task difficulty. To further check the effectiveness of the task difficulty manipulations, LMMs with Task difficulty as fixed factor and Participant ID and Experimental session (nested within Participant ID; for repeatedly measured performance across the two test blocks varying in task difficulty level) as random intercepts were performed with the actual task performance on the PVT, Go/No-go task, 2-Back and PVSAT as outcome measures (separate models per variable). Similar LMMs were performed for the Flanker task, but with Congruency (Congruent vs. Incongruent) as additional fixed factor and Block as additional random intercept (nested within Experimental session, which in turn was nested within Participant ID), since congruent trials and incongruent trials were nested within the easy and difficult block of the Flanker task, within each experimental session for each participant.

In the LMM analyses to assess the effect of the light manipulation on measures of performance in PVT, Go/No-go task, 2-Back task and PVSAT, Illuminance (low vs. high) and Task difficulty (easy vs. difficult) were added as fixed factors. Moreover, Participant ID and Experimental session (nested within Participant ID) were added as random intercepts to cluster the data per participant and per experimental session. In the LMMs for the Flanker task, Congruency (congruent vs. incongruent) was added as third fixed factor and Block was added as additional random intercept (nested within Experimental session, which in turn was nested within Participant ID). In case a significant interaction emerged between Illuminance and Task difficulty, post hoc contrasts were performed to investigate the nature of these interaction effects.
Post hoc comparisons were Bonferroni corrected.

To test the effect of the lighting condition on subjective sleepiness as well as the time course of subjective sleepiness under the two illuminance conditions, Illuminance and Time in session (20 min, 35 min vs. 50 min) were added as fixed factors and Participant ID and Experimental session were added as random intercepts in the LMM analyses on the repeated measures of sleepiness. In addition, subjective mood, light appraisal, beliefs and preferences were analysed with LMM including only Illuminance as fixed factor and Participant ID as random intercepts, as these were only measured once at the end of each session. Effect sizes ((partial) R²-values) were calculated using the r2glmm package.

3. Results

3.1 Baseline and manipulation check

3.1.1 Baseline sleepiness and mood

LMM analysis on the baseline data indicated that participants’ sleepiness did not significantly differ prior to the 1000 lux compared to the 100 lux condition \( [EMM_{\text{Bright}} = 3.17, \ SE = 0.20; \ EMM_{\text{Dim}} = 3.37, \ SE = 0.20, \ F(1, 30) = 0.68, \ p = 0.42, \ R^2 = 0.01] \). In addition, neither positive mood \( [EMM_{\text{Bright}} = 1.85 \pm 0.11; \ EMM_{\text{Dim}} = 1.99, \ SE = 0.11, \ F(1, 60) = 0.72, \ p = 0.40, \ R^2 = 0.01] \) nor negative mood \( [EMM_{\text{Bright}} = 1.18, \ SE = 0.05; \ EMM_{\text{Dim}} = 1.23, \ SE = 0.05, \ F(1, 60) = 0.37, \ p = 0.54, \ R^2 = 0.01] \) significantly differed between the baseline phase of the two illuminance conditions.

3.1.2 Subjective task difficulty manipulation check

The LMM analyses for subjective ratings of task difficulty showed that both Task difficulty and Cognitive domain elicited significant main effects \( [F(1, 238) = 28.71, \ p < 0.01, \ R^2 = 0.11; \ F(4, 210) = 61.27, \ p < 0.01, \ R^2 = 0.54, \text{ respectively}] \), see Figure 3. Self-rated difficulty was, on average, lower for the easy blocks \( (EMM = 4.53, \ SE = 0.15) \) compared to the difficult blocks \( (EMM = 5.53, \ SE = 0.18) \). In addition, the post hoc comparisons to assess differences in self-rated task difficulty across the tasks addressing different cognitive domains indicated that the average self-rated difficulty of the PVT was significantly lower than that of the other four tasks (all \( p < 0.05 \)). The average difficulty of the Go/No-go test was not significantly different from that of the Flanker task \( (t = -1.62, \ p = 0.11) \). Both of them appeared to be significantly easier than the 2-Back task and PVSAT (all \( p < 0.05 \)). The average difficulty did not significantly differ between 2-Back task and PVSAT \( (t = 1.04, \ p = 0.30; \text{ see Figure 3}) \). No statistically significant interaction between Task difficulty and Cognitive domain was found \( [F(4, 210) = 2.06, \ p = 0.09, \ R^2 = 0.04] \), suggesting that the difficulty manipulations were comparable across tasks (which was confirmed by the post hoc comparisons between the two difficulty levels per cognitive performance task (all \( p < 0.01 \)).
3.1.3 Task difficulty manipulation check on task performance markers

Table 2 provides the descriptive and test statistics for the LMM analyses with Task difficulty as a predictor for performance on each of the tasks. LMM analyses on PVT performance (speed) disclosed that the main effect of Task difficulty reached significance on overall reaction speed, as well as on the 10% slowest responses, with the contrary to our expectations — lower speed in easier vs. more difficult trials. The average speed in the 10% fastest responses was not significantly influenced by Task difficulty. The average accuracy and reaction speed in the Go/No-go task were both significantly influenced by Task difficulty, with higher accuracy and speed for the easier vs. more difficult Go/No-go trials. LMM analyses revealed statistically significant differences in accuracy and reaction speed between easier trials and more difficult trials in the Flanker task. The interaction effects between Task difficulty and Congruency were not statistically significant [Accuracy: F < 1, ns; Speed: F(1, 120) = 1.22, p = 0.27, R² < 0.01]. Accuracy on the 2-Back task was higher for easier trials than more difficult trials, while reaction speed was not significantly influenced by task difficulty. LMM analyses revealed a significantly better performance (in terms of both accuracy and speed) for easier PVSAT trials than more difficult PVSAT trials (see Table 2).

3.2 Effects of lighting condition on subjective sleepiness and mood

A LMM analysis on the KSS scores during the test phase revealed no significant main effect of Illuminance, nor an Illuminance × Time in session interaction [F(1, 30) = 2.06, p = 0.16, R² = 0.06; F(2, 120) = 0.68, p = 0.51, R² = 0.01]. The main effect of Time in session did reach significance [F(2, 120) = 15.47, p < 0.01, R² = 0.21]. Post hoc comparisons showed that participants felt significantly more sleepy after 35 min (EMM = 4.28, SE = 0.27) and 50 min (EMM = 4.15, SE = 0.27) than after 20 min (EMM = 3.38, SE = 0.27) in the session (both p < 0.01). Participants’ sleepiness did not significantly differ between the assessments after 35 min and 50 min (t = 0.76, p = 0.45; see Figure 4(a)).

Table 2 Results of linear mixed model analyses for task difficulty

<table>
<thead>
<tr>
<th>Task</th>
<th>Easy</th>
<th>Difficult</th>
<th>Test Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMM</td>
<td>SE</td>
<td>EMM</td>
</tr>
<tr>
<td>PVT task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall reaction speed</td>
<td>2.91</td>
<td>0.04</td>
<td>2.99</td>
</tr>
<tr>
<td>10% Fastest reaction speed</td>
<td>3.49</td>
<td>0.05</td>
<td>3.54</td>
</tr>
<tr>
<td>10% Slowest reaction speed</td>
<td>2.27</td>
<td>0.05</td>
<td>2.37</td>
</tr>
<tr>
<td>Go/No-go task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.90</td>
<td>0.01</td>
<td>0.87</td>
</tr>
<tr>
<td>Reaction speed</td>
<td>2.72</td>
<td>0.04</td>
<td>2.60</td>
</tr>
<tr>
<td>Flanker task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.96</td>
<td>0.01</td>
<td>0.95</td>
</tr>
<tr>
<td>Reaction speed</td>
<td>2.21</td>
<td>0.03</td>
<td>2.19</td>
</tr>
<tr>
<td>2-Back task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.85</td>
<td>0.01</td>
<td>0.82</td>
</tr>
<tr>
<td>Reaction speed</td>
<td>1.33</td>
<td>0.04</td>
<td>1.34</td>
</tr>
<tr>
<td>PVSAT task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.63</td>
<td>0.04</td>
<td>0.54</td>
</tr>
<tr>
<td>Reaction speed</td>
<td>1.25</td>
<td>0.04</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Significant effects are indicated in bold.
Likewise, LMM analyses on the PANAS scores during the test phase (see Figure 4(b)) revealed no significant main effect of Illuminance on positive affect or negative affect \[ F(1, 60) = 1.14, p = 0.29; R^2 = 0.02; F(1, 60) = 0.86, p = 0.36, R^2 = 0.02, \] respectively.

### 3.3 Effects of lighting condition on task performance

#### 3.3.1 Psychomotor vigilance task

LMM analyses did not reveal any statistically significant differences between Illuminance conditions for overall reaction speed, the average speed in the 10% fastest responses or the 10% slowest responses \[ F(1, 30) = 3.21, p = 0.08, R^2 = 0.02; F(1, 30) = 2.31, p = 0.14, R^2 = 0.02; F(1, 86) = 1.50, p = 0.22, R^2 = 0.01, \] respectively. In addition, no statistically significant Illuminance x Task difficulty interaction effect was found for any measure of PVT performance \[ F < 1, ns, R^2 < 0.01; F(1, 59) = 1.25, p = 0.27, R^2 = 0.01; F(1, 86) = 1.21, p = 0.28, R^2 = 0.01, \] respectively (see Figure 5).

#### 3.3.2 Go/No-go task

LMM analyses revealed that the main effect of Illuminance on reaction speed reached significance \[ F(1, 30) = 5.60, p = 0.03, R^2 = 0.06, \] while the effect on accuracy was not statistically significant \[ F(1, 30) = 0.69, p = 0.41, R^2 = 0.01. \] The interaction between Illuminance and Task difficulty was significant for reaction speed \[ F(1, 59) = 5.31, p = 0.02, R^2 = 0.02, \] but not for accuracy \[ F(1, 55) = 1.24, p = 0.27, R^2 = 0.01. \] Post hoc contrasts revealed that high vs. low illuminance significantly increased the reaction speed only for the easy version but not for the difficult version of Go/No-go task.

#### 3.3.3 Flanker task

LMM analyses revealed no statistically significant main effect of Illuminance on Flanker performance \[ Speed: F(1, 30) = 1.41, p = 0.24, R^2 = 0.03, Accuracy: F(1, 207) = 1.34, p = 0.25, R^2 = 0.01. \] No statistically significant two-way or three-way interactions were found \( p > 0.05), except for a significant Illuminance x Congruency interaction effect on speed \[ F(1, 120) = 7.28, p < 0.01, R^2 = 0.02. \] However, post hoc contrasts revealed no statistically significant differences in response speed between the two lighting conditions for congruent trials \[ t(38) = 0.92, p = 0.77 \] nor
Figure 5 PVT task performance average reaction speed across (a) all trials, (b) 10% fastest responses and (c) 10% slowest responses on easy and difficult trials in the low (dark bars) and high illuminance conditions (light bars). Error bars indicate ±1 standard error of the mean.

Figure 6 Go/No-go task performance (a) Average reaction speed and (b) Average accuracy on easy and difficult trials in the low (dark bars) and high illuminance conditions (light bars). Error bars indicate ±1 standard error of the mean. *p < 0.05
3.3.4 2-Back task

LMM analyses disclosed a statistically significant main effect of Illuminance on both accuracy and reaction speed in the 2-Back task $[F(1, 85) = 10.24, p < 0.01, R^2 = 0.07$, and $F(1, 30) = 23.45, p < 0.01, R^2 = 0.22$, respectively]. The accuracy and response speed were, on average, higher in the high vs. the low

Incongruent trials $[t(38) = 1.93, p = 0.06]$. The main effect of Congruency was significant, such that both the reaction speed and accuracy were, on average, higher for the congruent vs. incongruent Flanker trials $[F(1, 120) = 929.93, p < 0.01, R^2 = 0.66; F(1, 207) = 163.36, p < 0.001, R^2 = 0.42$, respectively] (see Figure 7).
illuminance condition. The Illuminance × Task difficulty interaction effect was significant on reaction speed but not on accuracy [speed: F(1, 59) = 5.91, p = 0.02, R^2 = 0.02; accuracy: F(1, 85) = 2.28, p = 0.13, R^2 = 0.02]. Post hoc contrasts revealed that the difference in reaction speed between the two lighting conditions was significant for the relatively easy as well as the more difficult version of 2-Back task, but that the difference in participants’ reaction speed between the high and low illuminance condition was more pronounced on the easier compared to the difficult trials of the 2-Back task [estimated difference = 0.21, t(47) = 5.36, p < 0.01; estimated difference = 0.13, t(49) = 3.13, p < 0.01, respectively] (see Figure 8).

### 3.3.5 PVSAT

LMM analyses revealed that the main effect of Illuminance, and the Illuminance × Task difficulty interaction were significant for PVSAT accuracy [F(1, 30) = 13.64, p < 0.01, R^2 = 0.15; F(1, 60) = 6.79, p = 0.01, R^2 = 0.02, respectively]. The post hoc contrasts showed that participants’ accuracy was, on average, higher in the high vs. low illuminance condition for both relatively easy and difficult PVSAT trials, but that the difference in accuracy between the high vs. low illuminance condition was more pronounced for the easier PVSAT trials [estimated difference = 0.18, t(48) = 4.40, p < 0.01] than the more difficult PVSAT trials [estimated difference = 0.08, t(48) = 2.06, p = 0.05]. Neither the main effect of Illuminance nor the Illuminance × Task difficulty interaction elicited a statistically significant difference in terms of reaction speed on the PVSAT [F(1, 29) = 2.50, p = 0.12, R^2 = 0.03; F(1, 57) = 0.92, p = 0.34, R^2 < 0.01, respectively] (see Figure 9).

### 3.4 Evaluation of the lighting

LMM analyses investigating the effect of high vs. low illuminance level on participants’ subjective appraisals, beliefs and preference of the lighting conditions revealed a statistically significant difference for participants’ evaluations of the brightness and softness of the lighting as well as their beliefs regarding the...
influence of the lighting on task performance. These findings suggest that participants in high vs. low illuminance condition evaluated the lighting much brighter and, interestingly, somewhat softer. In addition, the lighting in the high illuminance condition was believed to benefit their task performance (see Table 3).

4. Discussion

Multiple studies have investigated the diurnal effects of light exposure on subjective alertness and cognitive performance, but the collective results suggest a rather inconsistent alerting as well as cognitive effect of illuminance. The current study was conducted in an
effort to systematically explore – for the first time – whether the cognitive effects of illuminance are moderated by the cognitive domain and the level of task difficulty within one experimental paradigm. Moreover, the time course of subjective alertness and mood during the light condition, as well as participants’ subjective appraisals of the light conditions were investigated.

The current data did not reveal any statistically significant effect of illuminance on participants’ sustained attention performance in either version of the PVT. This finding is actually quite well in line with the majority of the literature: in the review by Souman et al., only two out of sixteen studies that tested effects on a PVT found significant results; in the review by Lok et al., only five out of ten studies rendered significant results on PVT performance. In four of these cases, these effects were moderated by factors such as time of day (only in the morning), prior light exposure (only after blue-enriched or dim evening light, but not after orange evening light50) and duration of exposure (only after prolonged exposure5,16). The null effects in the current study may be attributed to the fact that the PVT was always performed first during each session, so after relatively brief exposure and when participants experienced less mental fatigue than later in the test session. In fact, subjective sleepiness scores in the current study were, on average, lower when assessed after the PVT than after completing two or four additional tasks. Both the present study and existing literature, therefore, suggest that PVT performance is not very sensitive to light exposure and that, if an effect on simple sustained attention performance exists, this effect would be moderated by exposure time and participants’ prior state. Whether task difficulty would moderate such effects on vigilance could not be firmly established, as the manipulation check showed some inconsistencies: the difficult trials, although indeed rated as more difficult by participants, showed faster response speed than easy trials.

Light’s effect on conflict monitoring (i.e. a Flanker task) was – at least to our knowledge – only investigated in one previous study. They reported faster response speed for relatively difficult (incongruent) Flanker trials under high vs. low illuminance but not for the relatively easy (congruent) Flanker trials. In contrast to this earlier study, no statistically significant influence of illuminance on conflict monitoring performance emerged in the present study.

Response inhibition accuracy on the Go/No-go task was also not significantly affected by the high vs. low illuminance, yet response speed was facilitated by the high vs. low illuminance condition. This effect on response speed was moderated by task difficulty, with the speed improvement only being observed for the easy level of the Go/No-go task. Earlier studies had reported better speed and accuracy under dim rather than bright screen light5,16 and illuminance. This appears to be in contrast with the current study’s findings. However, the difficulty levels in both studies were comparable with the current difficult Go/No-go version rather than the easy version. Also, differences in light level and individual characteristics could also explain the above inconsistent effect of illuminance on inhibitory capacity. Less bluish white light (4000 K) was employed in Smolders and de Kort and participants were exposed to quite low light levels (80 lux vs. 1 lux at the eye) in the study by Heath et al. Moreover, participants in the study by Heath et al. were exposed to the lighting manipulation during the one hour before habitual bedtime when both homeostatic and circadian need for sleep are generally high. Based on the above, task difficulty appears to modulate the effect of illuminance on response inhibition ability, with either negative or null effects being found on the more difficult versions and
positive effects of high illuminance on the easier version of the task.

With respect to the effect of daytime light exposure on working memory, the current results revealed an overall improvement of 2-Back accuracy (PVSAT) under the high vs. low illuminance condition. Moreover, the current study confirmed, for response speed on the 2-Back task and accuracy on the PVSAT, the hypothesis that the performance-enhancing effect of illuminance on a working memory task is moderated by the difficulty level of the task.\textsuperscript{26,31,33,52} More precisely, the effect of high illuminance on 2-Back response speed was more pronounced for the easy vs. difficult trials. Results on the PVSAT also revealed larger light-induced improvements in accuracy for the easy vs. difficult trials. The effect of illuminance on PVSAT response speed was not statistically significant. These findings suggest that exposure to high vs. low light level may elicit selective beneficial effects on intellectual working memory tasks. While the current results showed only positive or null results, two recent studies by Huiberts and her colleagues found positive and null effects, but also negative effects of daytime high vs. low illuminance condition on working memory.\textsuperscript{26,33} More precisely, these studies revealed lower accuracy on the 2-Back, but not 3-Back, version of the n-Back task under high vs. low illuminance condition in the afternoon,\textsuperscript{33} and higher accuracy under high vs. low illuminance condition for BDST trials with relatively long spans (i.e. relatively difficult trials).\textsuperscript{33} These results contrast with our current findings. Apart from the differences in study paradigm and light properties, the differences in task characteristics (type of working memory task and difficulty level) may – at least partly – explain these divergent results on working memory performance. Together with the results by Huiberts \textit{et al.},\textsuperscript{26,33} the current findings suggest that both the type of working memory task and the task difficulty of the task itself could moderate the effect of daytime illuminance on working memory capacity. Additionally, earlier studies indicated that the diurnal effect of illuminance on working memory performance was reported to – at least for some (versions of the) tasks – depend on time of day. The current study did not test the moderation of time of day. It was only conducted in the afternoon, so whether the current findings directly translate to other times of the day is still unknown.

Previous studies reported that daytime exposure to more intense light may (differentially) influence numerous domains of cognitive performance, including sustained attention, executive control and working memory.\textsuperscript{16,26,31,33,52} Here, we provided evidence that exposure to high illuminance during the daytime working hours rendered different effects in terms of performance in tasks probing sustained attention, executive functioning and working memory within one study paradigm. More precisely, exposure to high vs. low illuminance did not significantly influence performance in the sustained attention (PVT) and the conflict monitoring (Flanker) tasks but did facilitate response speed to easy trials of the Go/No-go task and relatively easy and difficult trials of 2-Back task (although more pronounced effects among easy trials), and accuracy on the 2-Back task and accuracy on easy trials of the PVSAT. When the effect of light was moderated by task difficulty, the results consistently revealed more beneficial effects of high vs. low illuminance for the relatively easy vs. difficult versions of the tasks.

Notably, the present data revealed no statistically significant effects of exposure to a higher illuminance on subjective sleepiness or mood. This contrasts with several studies reporting effects of bright light on sleepiness.\textsuperscript{16,28,53,54} Yet, as was also concluded from recent reviews,\textsuperscript{24,25} although the majority of studies did report significant light-induced differences in subjective alertness, a substantial group (38%, according to Souman \textit{et al.}\textsuperscript{24}) did not. Similarly, earlier studies
have reported null effects for the effect of light level on mood,\textsuperscript{16,26,33} but also beneficial effects of illuminance on subjective mood during daytime hours.\textsuperscript{5,16,55,56} Differences in the light manipulation (i.e. intensity and duration), spectrum and timing (time of day and season), light history as well as statistical power may – at least partly – also account for the mixed results. The effect of light on lighting appraisals was also investigated at the end of the experimental sessions, with the results indicating that participants evaluated the lighting in the laboratory as much brighter and more soft in the high vs. low illuminance condition, while no statistically significant differences in perceived pleasantness and comfort were found. The lighting in the high illuminance condition was believed to benefit performance more than in the low illuminance condition. These subjective ratings regarding the expected effect of light on performance are in contrast with the null effects on PVT performance, but largely in line with the objective task performance data of Go/No-go task, 2-Back task and PVSAT. The null results for subjective sleepiness, mood and perceived pleasantness and comfort of the lighting suggest that the light-induced modulations in executive functioning and working memory cannot be explained by reduced subjective sleepiness, better mood or the lighting being experienced as more pleasant or comfortable. Additional research, including assessment of brain modulations and autonomic nervous activity, is required to establish the potential underlying physiological mechanism.

Some limitations of the current study need to be kept in mind when drawing conclusions. First, the five tasks were presented in one of two fixed orders and the PVT was always presented first. Earlier research has demonstrated that the onset of cognitive effects of light may show some delay relative to the onset of bright light.\textsuperscript{5,16} Moreover, differences in the timing of the tasks during the experimental session may have introduced a change in arousal or mental fatigue across the different tasks, which need to be considered when comparing the results between tasks. Secondly, several other potential confounding factors such as sleep quality of preceding night(s) and light history prior to experimental sessions were not objectively monitored or well-controlled, respectively. Thirdly, several tasks employed in the current study were also visual-pathway dependent, which might lead to potential interference by activation of the visual response to light. Lastly, the gender-induced moderation of the cognitive effects of daytime light exposure that was addressed in earlier studies\textsuperscript{32,57} was not the focus of the current study and hence was not investigated due to power considerations.

5. Conclusion

To conclude, the current findings demonstrate that the effect of illuminance on cognitive performance appears to be moderated by the type of task as well as task difficulty level, and that cognitive effects are not necessarily reflected in subjective affective experiences. Exposure to a higher illuminance of blue-enriched white light for short periods (10–50 min) significantly improved speed on a response inhibition task (Go/No-go task), both speed and accuracy on a working memory task (2-Back task), and accuracy in a second working memory task (PVSAT). Importantly though, task difficulty moderated light-induced benefits on response speed to targets in the Go/No-go task and the 2-Back task, and accuracy in the PVSAT: consistently, effects were only observed for the relatively easy version of the response inhibition task and were more pronounced on relatively easy versions of the working memory tasks. Notably, no statistically significant effects emerged for sustained attention (PVT) and conflict monitoring (Flanker), nor for subjective sleepiness and negative mood, although participants did
expect that the high illuminance condition had more beneficial effects in terms of work performance. Overall, these findings contribute to the current literature, suggesting that task characteristics (e.g. the nature of the task and the difficulty level of the task) need to be considered when people aim to optimise performance with office lighting in daytime work setting.

**Declaration of conflicting interests**

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Education Science 13th Five-year Plan-Ministry of Education Youth Project (EBA190467).

**ORCID iDs**

T Ru https://orcid.org/0000-0002-6097-4160
Q Chen https://orcid.org/0000-0002-5458-0210

**Supplemental material**

Supplemental material for this article is available online.

**References**

1 van Bommel WJM, van den Beld GJ. Lighting for work: a review of visual and biological effects. *Lighting Research & Technology* 2004; 36: 255–266.


16 Smolders KCHJ, de Kort YAW, Cluitmans PJM. 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.


31 Santhi N, Groeger JA, Archer S, Gimenez MC, Schlangen LJM, Dijk D. Morning sleep inertia in alertness and performance: effect of


51 Heath M, Sutherland C, Bartel K, Gradisar M, Williamson P, Lovato N, Micic G. Does one hour of bright or short-wavelength filtered tablet screenlight have a meaningful effect on adolescents’ prebedtime alertness, sleep, and daytime...
Office lighting and cognitive performance


