Light of both high and low melanopic illuminance have positive effects on attention and alertness during daytime

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Abstract

Light exposure during the day exerts acute effects on attention, such as how alert and ready a person is for solving problems and goal-oriented behavior. However, to increase the understanding of how different light conditions during daytime affect our attention, there is a need for more studies. The current study tested the acute effects of daytime exposure to three experimental light conditions and one control light condition on attention and alertness with the Psychomotor Vigilance Task (PVT). Healthy, young adults (N = 39; mean age: 21.7, 61.5% females) performed the PVT three times in all four light conditions presented on separate days at the same time-of-day (09:00-11:00): three experimental light conditions of short-wavelength light [SWL, "blue", high melanopic illuminance], long-wavelength light [LWL, "red", low melanopic illuminance], and bright white light [BWL], and a dim light [DL] condition as control. Attention and alertness measures included fluctuations in attention, quantified as the number of lapses and Reaction Time (RT) variability; mean RT; and optimum response capability (10% fastest RTs). Compared to DL, participants had significantly fewer lapses and faster mean RT during SWL and LWL, and they enhanced their optimum response capability during LWL. There were no significant effects of BWL, and light did not appear to have effects on intra-individual RT variability. Surprisingly, SWL was not superior to LWL,

hence, our results suggest that light, irrespective of melanopic illuminance level, has the potential to increase alertness and attention during daytime.

Introduction

Impaired alertness is a common problem in everyday life and can arise from inadequate sleep related to work schedules and various societal/domestic demands. Irrespective of the cause, low alertness levels can be a risk factor for accidents and reduced performance in occupational and operational settings, especially during night shifts[1–7]. Exposure to light has been tested as an intervention to optimize alertness and performance during night shifts, however, most of these interventions have involved white light[8–10]. It is therefore of interest to better understand how different light conditions affect aspects of alertness, also during the day, to enhance cognitive performance.

Light is involved in a range of so-called Non-Image Forming (NIF) responses, including acute effects on alertness[11,12], melatonin suppression[13–15], pupil constriction[16,17], and synchronization of the "master" circadian clock in the brain to the environmental light-dark cycle[18]. NIF responses are likely driven by intrinsically photosensitive Retinal Ganglion Cells (ipRGCs), a subset of photoreceptors in the retina[19]. ipRGCs contain the photopigment melanopsin that is maximally sensitive to short-wavelength light (SWL) with a peak spectral wavelength (λ_{max}) at/near ~480 nm[20,21]. SWL with a narrow bandwidth (that is, with a narrow peak in some part of the visible electromagnetic spectrum) will appear blue to the human eye. Similarly, medium-wavelength light (MWL, with a peak spectral wavelength at ~550 nm) will appear green, and long-wavelength light (LWL, with a peak spectral wavelength at ~630 nm) will appear red. Polychromatic white light will also activate melanopsin, especially if the white light is bright enough, and/or "cool". "Cool" white light is often enriched in shorter wavelengths, resulting in high Correlated Color Temperature (CCT, measured in kelvin (K) degrees), whereas "warm" light is enriched in longer wavelengths, resulting in lower CCT. Light with high proportions of short wavelengths will typically also have a high melanopic-Equivalent Daylight Illuminance (m-EDI), a metric that has been proposed as the preferred metric (over the "traditional" photopic illuminance metric) when quantifying biological effects of light[22,23]. Given the role of light in various NIF responses it is crucial to understand how different light conditions influence attention and alertness. Alertness, a subfunction of attention, follows a circadian (~24 hour) rhythm, with low alertness levels immediately upon awakening, followed by increased and rather stable levels throughout the day and subsequent lower levels in the evening and night[24]. Levels of alertness are maintained by the alerting network, one of the three main attention networks of the human brain[25]. Adequate alertness levels throughout the day enable high sensitivity to incoming stimuli and facilitate more complex, cognitive tasks[26]. Systematic reviews have shown that exposure to SWL ("blue"), bright white light (BWL), and white light of high m-EDI during the day can increase neurobehavioral alertness, however, other studies report no significant effects (reviewed in[27–

[29]). Furthermore, some studies shown that exposure to LWL ("red") can have a positive effect on neurophysiological markers of alertness[11,30,31]. Importantly, acute effects of light on neurobehavioral alertness can be influenced by a range of factors, such as chronotype (inter-individual differences in preferred sleep and wake timing, e.g., whether one is a "morning lark" or an "evening owl")[32]. Additionally, poor sleep quality and sleep restriction (curtailed sleep duration) has been linked to alertness deficits in healthy individuals[33–36], and light exposure has the potential to counteract such deficits[37–39]. Seasonal changes in ambient light exposure can also affect NIF responses to light, probably due to changes in light sensitivity[40,41]. Hence, it is important to take these factors into consideration when assessing the alerting effects of light.

The Psychomotor Vigilance Task (PVT) is a widely used high signal-load reaction time (RT) task to assess alertness in laboratory contexts. It has minor learning effects, making it ideal for repeated measures[42]. The most reported PVT metrics are mean reaction time (RT) and the number of lapses in attention (often quantified as RTs≥500 ms). A less commonly reported PVT metric is the 10% fastest RTs, reflecting the most optimum responses on the task[43]. Studies using the PVT to assess alertness in different light conditions have reported faster mean RT and fewer lapses during SWL ("blue")[44], bright white light[12,45,46] and white light of high m-EDI[47]. However, other studies report no significant effects[48–54]. Also, most studies report no significant effects of white light on the 10% fastest RTs[12,45,48,50,51,53,55–58]. It is however unknown whether narrow bandwidth short- and long-wavelength light can affect this PVT metric. And, to our knowledge, no study has tested whether light affects another aspect of attention similar to lapses, namely intra-individual RT variability (RTV), which can be estimated with global measures such as the standard deviation (SD) in RTs [59]. As RTV on the PVT has hardly been reported, this metric might offer new insights into how light affects fluctuations in attention. Finally, relatively few studies have assessed light's impact on fatigue over time in testing, a factor that may increase RTs across sessions[12,46,48,52].

In sum, research on the acute effects of light during daytime on neurobehavioral alertness is inconclusive, and it is unknown how intra-individual fluctuations in RTs are acutely affected by light. Also, there is limited knowledge on how chronotype and season might affect neurobehavioral performance during light exposure. Therefore, the overall aim of the present study was to assess the impact of daytime exposure to different artificial light conditions on neurobehavioral alertness in healthy, young adults. Hypotheses were pre-registered at OSF (https://osf.io/m7gfh). Based on previous research and theory on the NIF acute effects of light, we hypothesized that:

- Short-wavelength ("blue") light (SWL), long-wavelength ("red") light (LWL) and bright white light (BWL), compared to dim light (DL), will reduce fluctuations in attention (quantified as the number of lapses and intra-individual RT variability) and overall mean RT on the PVT.
- SWL, LWL, and BWL, compared to DL, will not affect optimum response capability (quantified as the mean of the 10% fastest RTs).

As the differential effects between SWL, LWL, and BWL on alertness and attention are inconclusive in the literature[27], we tested the following explorative hypothesis:

- SWL will have a superior effect on lapses, intra-individual RTV and mean RT, compared to LWL, and BWL will have a superior effect on lapses, intra-individual RTV and mean RT, compared to LWL.

Last, we also hypothesized, exploratively, that:

- Participants tested in fall and winter will show stronger responses to light than participants tested in spring and summer.
- Individuals with a 'morning' chronotype or 'intermediate' chronotype will perform better than 'evening' chronotypes, and 'evening' chronotypes will benefit more from light with high m-EDI compared to DL, relative to 'morning' and 'intermediate' chronotypes.

Methods

Study design and setting

This study used a within-subjects repeated measurements experimental design to test the acute effects of daytime exposure to different artificial light conditions on aspects of attention in healthy, young adults. Data collection was conducted from November 2021 to October 2023, at a high latitude (60.39° N), in a 30m^2 laboratory with no windows. The laboratory was equipped with 20 60x60 ceiling-mounted Light Emitting Diode (LED) luminaires (Glamox AS, Norway) and nine working stations in total, equipped with a desk, chair, a PC, keyboard and computer mouse. All computer screens had an overlay screen foil blocking all wavelengths <520 nm (Metolight SFG-10, Asmetec, Germany), to avoid potential alerting effects resulting from light radiating from the screens. More information about the laboratory setup is provided in Supplementary Materials S1.

Participants

Healthy, young adults (≤40 years old) were recruited in lectures at the University of Bergen, Norway, and through online and on-campus posters. Based on a screening procedure, participants were included if they had normal or corrected-to-normal vision. Participants were excluded if they were colorblind (as indicated with Isihara's Test for Color Deficiency), had traveled across three time zones within the last three weeks, had a severe psychiatric disorder (as indicated by the Symptom Check List-90 and module C from Mini International Neuropsychiatric Interview, probing symptoms of mania), or a severe medical disorder.

Procedures

Participants underwent one week of baseline at home, followed by four in-laboratory test sessions occurring from 08:00 to 11:00 on separate days during a two-week period. One light condition was presented in each session, in a block-stratified randomized cross-balanced order for each participant. There was at least one day in between sessions. During the entire three-week study period, participants were instructed to maintain a regular sleep-wake schedule, including on weekends. Adherence was ensured using sleep diaries and activity watches (Actiwatch Spectrum 2, Philips Respironics, Inc., United States) worn on participants' non-dominant hands. On the morning of scheduled test sessions, participants were instructed to wear short-wavelength light-blocking glasses (Honeywell International, Inc., United States) immediately upon awakening, to ensure that i) there were no alerting effects of light in the environment prior to assessment in the laboratory, and ii) to reduce variation in light history between participants and seasons. Prior to entering the laboratory at 08:00, participants were allowed to consume their habitual morning dosage of caffeine, however, during in-laboratory testing, no caffeine consumption nor nicotine use was allowed.

Participants arrived at the laboratory at 08:00 and were maintained in dim light (m-EDI = 4.8±6.2 lux (lx)) for one hour, followed by 30 minutes of adaptation to one of the three experimental light conditions or the control light condition. The experimental light conditions increased gradually in illuminance over the course of the last 10 minutes of dim light (see Fig. 1 for an overview of the experimental procedure). Pupils were not pharmacologically dilated prior to light exposure. During light adaptation, participants were seated comfortably in a chair and were provided with a snack. Water was available during the entire test session. After light adaptation, participants underwent neurobehavioral testing for approx. 1.5 hour during exposure to different light conditions: three experimental light conditions of narrow bandwidth SWL ("blue", λ_{max} = 455 nm, m-EDI = 1441.8±35.2 lx), narrow bandwidth LWL ("red", λ_{max} = 625 nm, m-EDI = 3.8±1.3 lx), and BWL (m-EDI = 1155.8±17.6 lx, CCT = 8035.7±42.8 K), and one control light condition of white DL (m-EDI = 9.7±6.4 lx). Hence, SWL and BWL were both of relatively high m-EDI, whereas the LWL condition had low m-EDI. SWL and LWL were matched on photon irradiance (= log 18.8/m^2/s). Light quantities were calculated using the open-access- and source web platform *luox* [22,60]. Light-related quantities, including spectral power distributions, can be accessed in Supplementary Materials S2. The three experimental light conditions were delivered through ceiling-mounted LED luminaires. In the control DL condition, all LED luminaires were off; the only light source in the room was light radiating from the computer screens. During the one-hour DL exposure from 08:00 to 09:00, preceding light adaptation, DL was delivered through six portable Philips Hue Go lamps situated behind the computer screen at each workstation, in an upward position facing away from the participants. At each workstation, light stimuli were measured with a calibrated spectroradiometer (GL Spectis 1.0 T Flicker, GL Optic, Poland) at eye level (vertically, 120 cm above the floor, ~90 cm horizontally from the computer screen in the direction of gaze – corresponding to the approximate seating of participants) with the screens turned on. The light measurements were performed approximately 30 minutes after the onset of the LED luminaires to allow the luminaires to adjust in temperature.

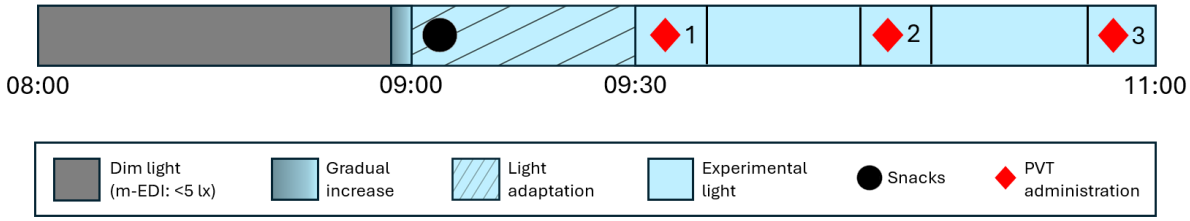

Figure 1. Overview of experimental in-laboratory design. Snacks included one serving of fruit, one whole grain crispbread, and one small bag (60 g) of mixed nuts. The number to the right of the red diamonds represents block number (PVT test administration). m-EDI = melanopic-Equivalent Daylight Illuminance. lx = lux. PVT = Psychomotor Vigilance Task.

Ethics

Participants provided written informed consent before participation and received 1000 NOK after completing the study. Ethics approval was provided by the Regional Committees for Medical and Health Research Ethics. All procedures contributing to this work comply with the Declaration of Helsinki.

Measures

Alertness

Alertness was assessed three times in each of the four light conditions (block 1-3, see Fig. 1) with a five-minute computerized version of the PVT [42,61], administered through E-Prime 3.0[62]. Participants monitored a red rectangular box on a white background. When a counting timer (stimulus, in black) appeared inside the box and started counting, participants were instructed to press the space bar as quickly as possible. The stimulus was presented at random intervals ranging from 2 to 7 s, and 1 s feedback on RT was provided after each trial. RTs <100 ms were considered false starts. Five practice trials were presented before each test. The mean number of trials in each PVT administration was 57. Outcome measures reported here are the number of lapses in attention (quantified as RTs ≥500 ms), overall mean RT, intra-individual RTV (quantified as the standard deviation (SD) in RTs), and optimum response capability (quantified as the mean of the 10% fastest RTs).

Covariates

Chronotype was assessed with a reduced version of the Horne & Östberg Morningness-Eveningness Questionnaire (r-MEQ) [63]. The r-MEQ has five questions probing individuals' circadian preferences, yielding a total score ranging from 4 to 25. A score of 4-7 = 'Definitely Evening Type', 8-11 = 'Moderately Evening Type', 12-17 = 'Intermediate Type', 18-21 = 'Moderately Morning Type', and 22-25 = 'Definitely Morning Type'. 'Definitely evening type' and 'definitely morning type' is often referred to as "extreme" chronotypes.

Season was not systematically manipulated between nor within subjects (each subject underwent laboratory testing in one season only, across a study period of three weeks) but

was entered as a covariate in statistical analyses. As there is substantial variation in annual photoperiod length at northern latitudes[64], all four seasons were included as categorical levels. December-February represented 'winter', March-May represented 'spring', June-August represented 'summer', and September-November represented 'fall'.

Sleep efficiency the night preceding each test session was derived from wrist actigraphy data, recorded in epochs of one minute duration. Threshold sensitivity was set to 'medium' (40 counts per minute) (Actiware version 6.0.9, Philips Respironics, Inc., United States). Rest intervals were scored based on i) the participants pushing an event button together with ii) raw data, and iii) information from sleep diaries. When the event button was not pushed, information from the two latter data sources were used. For each rest interval, sleep efficiency was calculated as total sleep time divided by interval duration minus total invalid time, multiplied by 100.

Statistical analyses

The analysis plan was also pre-registered at OSF, together with the hypotheses (https://osf.io/m7gfh). Missing data (<10%) were imputed with a Random Forest algorithm in the R package *mice*[65]. All analyses were performed in R version 4.4.1[66] using the packages *tidyverse*[67], *glmmTMB*[68], *lme4*[69], *lmerTest*[70], *DHARMa*[71], *performance*[72], *emmeans*[73], *ggeffects*[74], and *effectsize*[75]. Data from the five practice trials on the PVT were excluded from analyses. The distribution of residuals was evaluated with Q-Q plots, and model assumptions were checked. The number of lapses were analyzed with a Generalized Linear Mixed-Effects Model (GLMM) using a generalized Poisson distribution, as the number of lapses did not exhibit significant zero-inflation nor overdispersion. RTV was also analyzed with a GLMM due to right-skewness in the data. In the GLMMs, 95% Confidence Intervals (CIs) and p-values were computed using a Wald z-distribution approximation. Mean RT for all trials and the mean of the 10% fastest RTs were each analyzed with a Linear Mixed Effects-Model (LMM) using Restricted Maximum Likelihood (REML). In the LMMs, 95% CIs and p-values were computed using a Wald t-distribution approximation. As the residuals of RTV, mean RT, and mean 10% fastest RTs deviated slightly from a normal distribution, variables were log-transformed prior to analysis to increase normality and stabilize variance in the models. In all analyses on PVT variables, light*block, chronotype, season, and sleep efficiency were modeled as fixed effects, subject was modeled with random intercept, and the two other within-subjects factors of light and block were modeled using complex random intercepts[76], as models with a maximum random-effects structure justified by the data did not converge[77]. In the analysis of RTV, mean RT was added as an additional predictor, as the mean and SD of RTs are often correlated to some extent[78]. The following reference levels for the categorical predictors were used in the analyses: dim (light), 1 (block), fall (season), and intermediate type (chronotype). First, an initial model with the interaction term light*block and the other fixed effects and complex random intercepts specified above were tested. As the interpretation of significant simple effects that are part of one or more interaction terms is conditioned on the levels of each predictor in the interaction(s)[79], significant 'simple' effects of light and/or block in the

initial model were modeled as main effects in a subsequent model. We also constructed two models with the interaction term light*chronotype in one model and light*season in another model, controlling for the other fixed effects, including block as main effect. Finally, we also explored sex differences on all PVT measures, as there are some indications that sex influences acute alerting responses[80]. In these analyses, light and biological sex were entered as fixed effects, using 'dim' and 'female', respectively, as reference levels, and subject was modeled with random intercept. Alpha level was set to .05, two-tailed in all analyses. For the GLMMs on the number of lapses, we report each estimate as Incidence Rate Ratio (IRR, the exponentiated model coefficient) as appropriate for count data, together with 95% CI, SE, z-value, and p-value. For the GLMMs on RTV, estimates in terms of exponentiated model coefficients (as the model provide estimates on the log-scale) together with 95% CI, SE, z-value, and p-value are reported. Partial r (r_p) is reported as the theoretical effect size in the GLMMs. An r_p <.3 is considered a small effect, <.5 is considered moderate, and ≥.5 is considered a large effect[81]. In the LMMs, exponentiated model coefficients together with 95% CI and SE, t-value, and p-value are reported. Theoretical effect sizes in the LMMs include Cohen's partial f^2, as recommended by Lorah[82]. A Cohen's f^2 ≥.02 is considered a small effect, ≥.15 medium, and ≥.35 large [81]. All effect sizes were estimated using the test-statistic approximation method and were calculated using the *effectsize* package[75]. Explained variance statistics for each model include Nakagawa's adjusted (conditional) R^2 for the total model, Nakagawa's marginal R^2 for the combined influence of the fixed effects, as well as the adjusted Intra-class Correlation Coefficient (ICC) for the random effects[83]. In case of significant main and/or interaction effects, post-hoc analyses using Tukey's Honest Significant Difference (HSD) were used to control the Family-Wise Error Rate (FWER). In these post-hoc analyses, t-values and the degrees of freedom were computed using a Kenward-Roger approximation, and Estimated Marginal Means (EMMs) together with 95% CI, and corrected p-values are reported. An *a priori* power analysis was conducted in the larger study only, named *ENLIGHT*, consisting of several work packages (the current study being one of them), assuming three subgroups of participants (young, healthy adults, healthy seniors, and seniors with mild dementia/mild cognitive impairment) and multiple non-hierarchical regression analyses (see https://osf.io/6nbr9), and hence does not apply to the mixed model analyses in this study with a sample consisting of only one of the three subgroups and a hierarchical structure of both fixed and random effects.

Results

Descriptive statistics

40 healthy, young adults participated in the study. 42 out of a total of 480 observations were excluded from analyses due to measurement errors, resulting in a sample of 39 participants (mean age: 21.7, SD = 2.6, range: 18-28) and 438 observations (Table 1). Mean rMEQ score was 13.8 (SD = 3.3), corresponding to an 'intermediate' chronotype. On the PVT, irrespective

of light manipulation and measurement block, participants' median number of lapses were 1 (range: 0-16), mean overall RT was 308.40 ms (SD: 40.50 ms), mean intra-individual RTV was 75.31 ms (SD: 71.27 ms), and the mean of the 10% fastest RTs was 242.96 ms (SD: 21.79 ms). 64% of the study sample habitually consumed one or more caffeinated beverages on a normal day. As caffeine consumption can affect attention[84], we checked whether there were any significant differences in PVT performance among participants who habitually consumed caffeine vs. those who did not. GLMMs (lapses and intra-individual RTV) and LMMs (mean RT and 10% fastest RTs) with each PVT metric as outcome, controlling for whether participants habitually consumed caffeine or not ("Yes", "No", respectively) and with subject as random intercept, confirmed that caffeine consumption did not affect performance (lapses: p=.541, mean RT: p=.377, intra-individual RTV: p=.974, 10% fastest RTs: p=.140).

Total N (females)	39 (24)
Age [Mean±SD]	21.7±2.6
Caffeinated beverages [Median (range)]	1 (0-5)
Sleep efficiency [Mean±SD, %]	83.5±8.9
Chronotype N (%)	
Definitely morningness	0 (0)
Moderately morningness	7 (17.9)
Intermediate type	22 (56.4)
Moderately eveningness	10 (25.6)
Definitely eveningness	0 (0)
Season N (%)	
Spring	10 (25.6)
Summer	5 (12.8)
Fall	18 (46.2)
Winter	6 (15.4)
Laboratory conditions*	
Temperature [Mean±SD, °C]	20±1.2
Humidity [Mean±SD, %]	39.8±13.2

Table 1. Descriptive statistics of study sample and laboratory characteristics. Chronotype was assessed with a reduced version of the Morningness-Eveningness Questionnaire. There were no extreme chronotypes. Sleep efficiency was derived from wrist actigraphy. Caffeinated beverages represent the median number of caffeinated beverages (coffee, caffeinated tea, energy drink) habitually consumed on a normal day. *Kruskal-Wallis Rank Sum Tests did not reveal any significant differences in temperature nor air humidity between light conditions.

Acute alerting effects of light

Line plots of the progress in RTs from trial 1 to 54 in each light condition, stratified by measurement block, are provided in Supplementary Materials S3.

As the initial models with the interaction term light*block revealed significant simple effects of light and/or block but no significant interactions, light and block were modeled as separate fixed effects in subsequent main effects models. Results from these models are

described below. Model estimates, effect sizes, and explained variance statistics are provided in Table 2 (GLMMs) and Table 3 (LMMs).

On all PVT measures except for RTV, participants responded slower over time (main effects of measurement blocks; p's<.001, see Supplementary Materials S3. Additional figures from main-effects analyses can be accessed in Supplementary Materials S4. Sensitivity analyses on a dataset with complete-cases only showed a similar overall pattern of results (see Supplementary Materials S4) as in analyses on imputed data, except for a significant main effect of light on RTV (larger variability in LWL compared to DL; $p_{corrected}$=.031), which did not appear in analyses on imputed data. However, this result should be interpreted with caution, as estimates are often biased in complete-case analyses when data is not missing completely at random.

Lapses

The analysis of the number of lapses showed significant main effects of light (SWL: p=.004, r_p = -0.42; LWL: p=.002, r_p = -0.44; BWL: p=.044, r_p = -0.31, Table 2). Post-hoc analyses showed that participants had significantly fewer lapses in SWL (p=.023, *EMM* = 0.89[0.63-1.27], *SE* = 1.20) and LWL (p=.010, *EMM* = 0.85[0.59-1.22], *SE* = 1.20), compared to DL (*EMM* = 1.48[1.05-2.10], *SE* = 1.20) (Fig. 2).

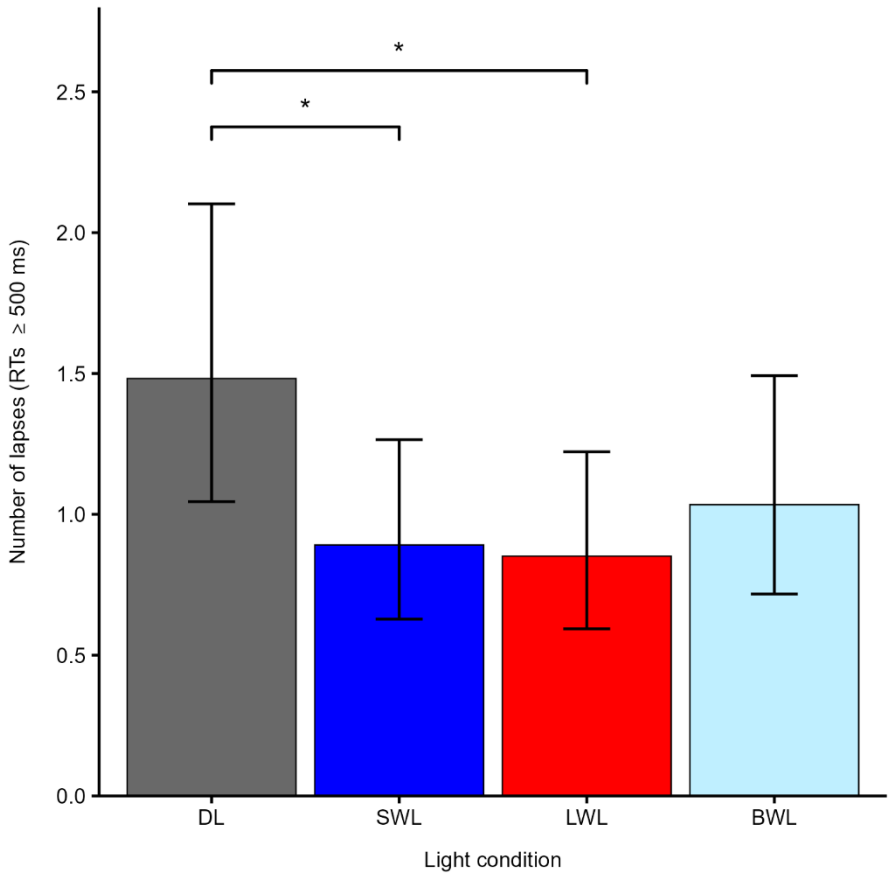

Figure 2. Estimated Marginal Means (EMMs) of the number of lapses in each light condition. Error bars = 95% Confidence Intervals (CIs). EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. RTs = Reaction Times. SWL = Short-Wavelength Light. *p<.05.

There was also a significant main effect of season (spring vs. fall: p=.027, r_p = 0.33, fig. S3.2.2), but the effect was no longer significant after correcting for multiple comparisons. Also, the model with the interaction term light*season revealed a significant interaction between SWL and winter (p=.025), but this effect was also no longer significant after correcting for multiple comparisons. There were no significant light*chronotype interactions.

Mean RT

The main effects model showed significant main effects of light (SWL: p=.001, f^2 = 0.11; LWL: p=.004 f^2 = 0.09; BWL: p=.038 f^2 = 0.04). Post-hoc analyses revealed that participants' mean RT was faster in SWL (p=.008, *EMM* = 303.89[293.05-315.14], *SE* = 1.02) and LWL (p=.018, *EMM* = 305.12[294.20-316.45], *SE* = 1.02) compared to DL (*EMM* = 318.81[307.05-331.02], *SE* = 1.02, Fig. 3). Exploratory analyses showed no significant interactions between light and season nor between light and chronotype.

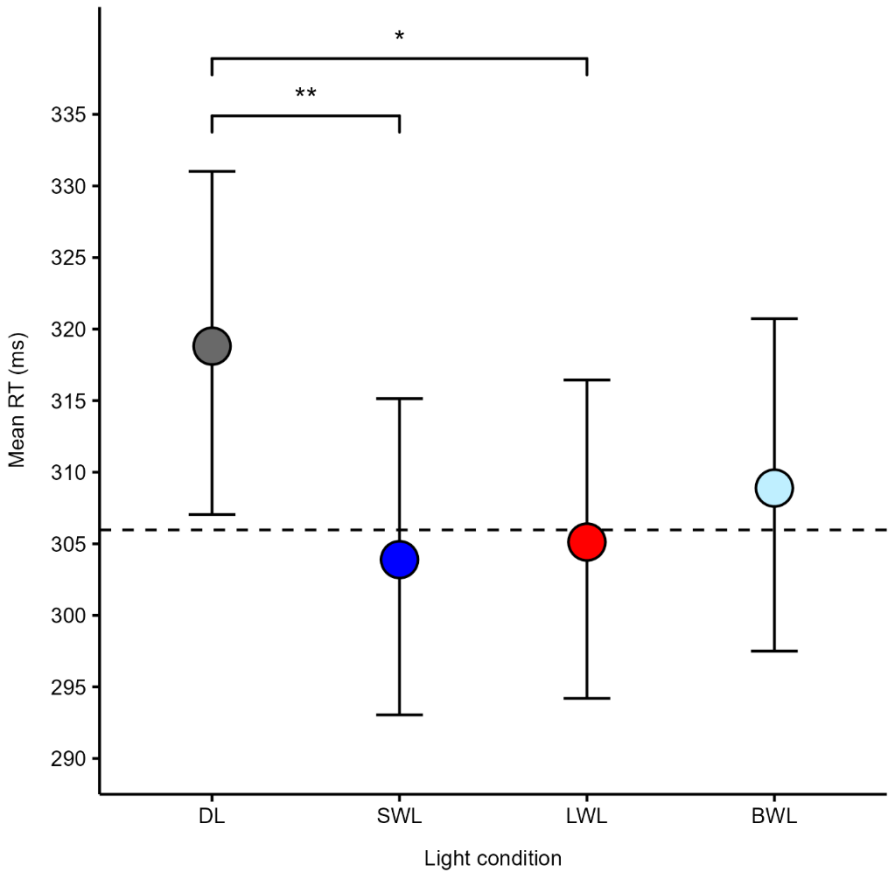

Figure 3. Estimated Marginal Means (EMMs) of Mean Reaction Time (RT) in each light condition. The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents

mean estimated RT across SWL, LWL, and BWL. EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. SWL = Short-Wavelength Light. **p<0.01. *p<0.05.

RTV

The main effects model showed a significant main effect of mean RT (p<.0001, r_p = 0.943), in that variability in RT increased with longer RTs (p<.001, Spearman's ρ =.70 [95% CI: .65-.75], Fig. 4).

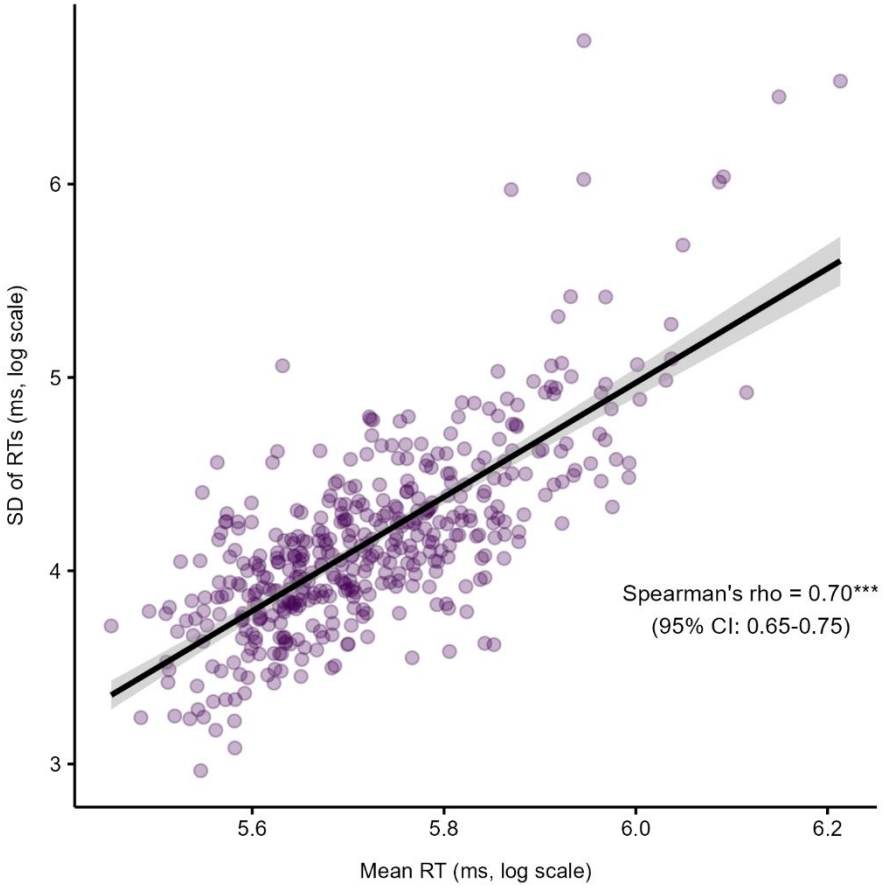

Figure 4. Scatter plot of the relationship between standard deviations in reaction time (RT) and mean RT. Values are on log scale. Error band = 95% Confidence Interval (CI). ms = milliseconds. ***p<.001.

There were also significant main effects of measurement blocks (block 1: p<.001, r_p = -0.51; block 2: p<.001, r_p = -0.61, Table 2). Post-hoc analyses showed that participants expressed lower variability in block 2 (p<.001, *EMM* = 60.61[55.76-65.88], *SE* = 1.04) and 3 (p<.0001, *EMM* = 58.03[53.30-63.18], *SE* = 1.04), relative to block 1 (*EMM* = 69.70[64.04-

75.87], *SE* = 1.04), see Supplementary Materials S2. There were no significant main effects of light, season, and chronotype, and no significant interactions.

Mean of the 10% fastest RTs

The main effects model on the mean of the 10% fastest RTs showed significant main effects of light (SWL: p=.017, f^2 = 0.06; LWL: p=.005, f^2 = 0.08), chronotype (eveningness: p=.019, f^2 = 0.03; morningness: p=.023, f^2 = 0.02), and season (summer: p=.018, f^2 = 0.16), see Table 3. Post-hoc analyses showed that participants responded faster in LWL (p=.030, *EMM* = 243.11[236.88-249.51], *SE* = 1.01) compared to DL (*EMM* = 248.57[242.08-255.24], *SE* = 1.01), see Fig. 5. Post-hoc analyses on the main effect of season showed that participants tested in winter responded faster (p=.048, *EMM* = 234.68[222.32-247.73], *SE* = 1.03) than participants tested in summer (*EMM* = 261.25[246.19-277.23], *SE* = 1.03, fig. S3.5.2). Post-hoc analyses of the main effects of chronotype did not remain significant after correction for multiple comparisons, and the interaction models of light*season and light*chronotype showed no significant interactions.

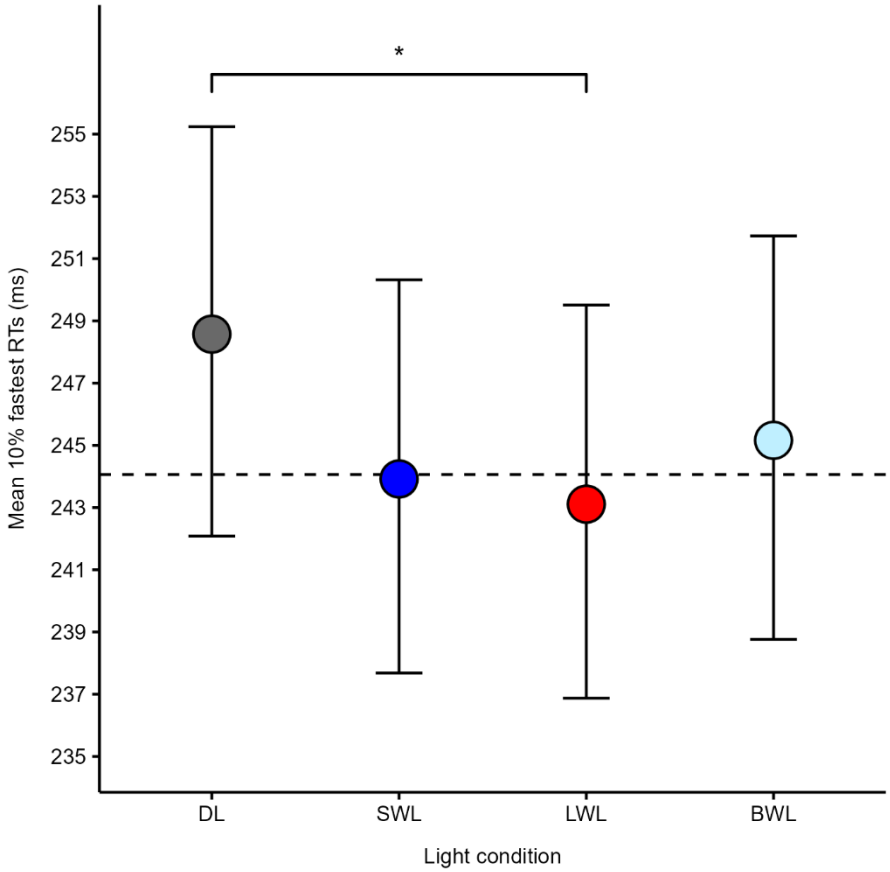

Figure 5. Estimated Marginal Means (EMMs) of the Mean 10% fastest Reaction Times (RTs). The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents mean estimated 10% fastest RT across SWL, LWL, and BWL. EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. SWL = Short-Wavelength Light. *p<0.05.

	Lapses					RTV				
Parameters	*IRR (95% CI)*	*SE*	*z*	*p*	r_p	*Coefficient (95% CI)*	*SE*	*z*	*p*	r_p
Intercept	1.04 (0.19 – 5.68)	0.90	0.50	0.562		2.04e-8 (0.00 - 0.00)	2.40E-08	-17.67	<.001	
Light										
SWL	0.60 (0.42 – 0.85)	0.11	-2.87	**.004**	-0.42	1.07 (0.99 - 1.16)	0.04	1.75	.081	0.27
LWL	0.57 (0.40 – 0.82)	0.10	-3.10	**.002**	-0.44	1.07 (0.99 - 1.15)	0.04	1.63	.104	0.25
BWL	0.70 (0.49 – 0.99)	0.12	-2.01	**.044**	-0.31	1.03 (0.95 - 1.11)	0.04	0.75	.452	0.12
Block										
Block 2	2.41 (1.82 – 3.19)	0.34	6.18	**<.001**	0.70	0.87 (0.81 - 0.93)	0.03	-3.75	**<.001**	-0.51
Block 3	2.48 (1.89 – 3.26)	0.35	6.50	**<.001**	0.72	0.83 (0.78 - 0.89)	0.03	-4.79	**<.001**	-0.61
Chronotype										
Eveningness	1.09 (0.68 – 1.75)	0.26	0.37	.714	0.06	0.94 (0.83 - 1.06)	0.06	-1.19	.235	-0.19
Morningness	1.07 (0.60 – 1.91)	0.32	0.22	.830	0.04	0.92 (0.79 - 1.06)	0.07	-1.19	.234	-0.19
Season										
Spring	1.92 (1.08 – 3.44)	0.57	2.21	**.027**	0.33	1.08 (0.92 - 1.26)	0.09	0.87	.384	0.14
Summer	1.38 (0.68 – 2.81)	0.50	0.89	.373	0.14	0.84 (0.69 - 1.03)	0.09	-1.71	.087	-0.26
Winter	0.97 (0.97 – 1.01)	0.35	-0.08	.934	-0.01	1.09 (0.91 - 1.31)	0.10	0.96	.338	0.15
Sleep efficiency	0.99 (0.97 - 1.01)	0.01	-0.64	.519	-0.10	1.00 (0.99 - 1.00)	2.42e-03	-1.14	.253	-0.18
Mean RT						46.99 (33.79 - 65.35)	8.24	22.76	**<.001**	0.96
Random effects	*Coefficient*					*Coefficient*				
SD (Residual)	1.29					0.26				
SD (Intercept: Subject)	0.56					0.17				
SD (Intercept: Subject:Light)	0.47					0.08				
SD (Intercept: Subject:Block)	0.22					0.08				
Adjusted / Unadjusted ICC	0.396 / 0.330					0.381 / 0.130				
Conditional / Marginal R^2	0.497 / 0.168					0.789 / 0.660				

Table 2. Generalized Linear Mixed-Effects Model analyses of the number of lapses and intra-individual reaction time variability on the Psychomotor Vigilance Task. Incidence Rate Ratio (IRR) values represent the exponentiated coefficients. The coefficients in the model of RTV are also exponentiated, as the model provides estimates on the log-scale. Significant p-values are highlighted in bold. BWL = Bright White Light. CI = Confidence Interval. ICC = Intra-Class Correlation Coefficient. LWL = Long-Wavelength Light. RTV = Reaction Time Variability. SE = Standard Error. SWL = Short-Wavelength Light.

	Mean RT					Mean of the 10% fastest RTs				
Parameters	*Coefficient (95% CI)*	*SE*	*t*	*p*	f^2	*Coefficient (95% CI)*	*SE*	*t*	*p*	f^2
Intercept	291.97 (250.83 – 339.85)	22.56	73.47	<.001		241.40 (220.52 - 264.27)	11.11	119.17	<.001	
Light										
SWL	0.95 (0.93 - 0.98)	0.01	-3.27	**.001**	0.11	0.98 (0.97 - 1.00)	7.76e-03	-2.39	**.017**	0.06
LWL	0.96 (0.93 - 0.99)	0.01	-2.99	**.003**	0.09	0.98 (0.96 - 0.99)	7.75e-03	-2.81	**.005**	0.08
BWL	0.97 (0.94 – 1.00)	0.01	-2.10	**.036**	0.04	0.99 (0.97 - 1.00)	7.98e-03	-1.71	.088	0.03
Block										
Block 2	1.08 (1.06 - 1.10)	9.20e-03	9.10	**<.001**	1.10	1.04 (1.03 - 1.05)	6.68e-03	6.16	**<.001**	0.51
Block 3	1.10 (1.08 - 1.12)	9.34e-03	10.95	**<.001**	1.60	1.05 (1.03 - 1.06)	6.71e-03	7.12	**<.001**	0.68
Chronotype										
Eveningness	1.02 (0.97 - 1.06)	0.02	0.75	.452	e.78e-03	1.04 (1.01 - 1.07)	0.02	2.35	**.019**	0.03
Morningness	1.01 (0.96 - 1.06)	0.03	0.30	.764	5.44e-04	1.04 (1.01 - 1.08)	0.02	2.29	**.023**	0.02
Season										
Spring	1.04 (0.97 - 1.12)	0.04	1.24	.285	0.04	1.01 (0.96 - 1.06)	0.03	0.42	0.676	4.82e-03
Summer	1.09 (1.00 - 1.19)	0.05	1.92	.064	0.11	1.08 (1.01 - 1.16)	0.04	2.37	**.018**	0.16
Winter	0.99 (0.91 - 1.07)	0.04	-0.30	.732	2.73e-03	0.97 (0.92 - 1.03)	0.03	-0.93	.355	0.03
Sleep Efficiency	1.00 (1.00 - 1.00)	0.00	-0.09	.363	4.24e-05	1.00 (1.00 - 1.00)	4.99e-04	-0.96	.337	5.76e-03
Random Effects	*Coefficient*					*Coefficient*				
SD (Residual)	0.07					0.05				
SD (Intercept: Subject)	0.08					0.06				
SD (Intercept: Subject:Light)	0.05					0.02				
SD (Intercept: Subject:Block)	8.70e-03					0.02				
Adjusted / Unadjusted ICC	0.633 / 0.516					0.685 / 0.534				
Conditional / Marginal R^2	0.701 / 0.185					0.754 / 0.220				

Table 3. Linear Mixed-Effects Model analyses of mean reaction time and the mean of the 10% fastest reaction times on the Psychomotor Vigilance Task. Significant p-values are highlighted in bold. Model coefficients are exponentiated, as the models provide coefficients on the log-scale. BWL = Bright White Light. CI = Confidence Interval. df = degrees of freedom. ICC = Intra-Class Correlation Coefficient. LWL = Long-Wavelength Light. RT = Reaction Time. SE = Standard Error. SWL = Short-Wavelength Light.

Discussion

This study tested whether daytime exposure to artificial light conditions of high and low melanopic illuminance, against a control condition of DL (<10 melanopic lux), could enhance alertness and attention in healthy, young adults. Overall, the results partly supported our main hypothesis, showing that narrow bandwidth SWL and narrow bandwidth LWL, compared to the DL control condition, reduced lapses and shortened overall mean RT. Surprisingly, there were no significant effects of BWL, despite that this light condition was also of relatively high melanopic illuminance. Contrary to our explorative hypothesis, SWL was not significantly superior to LWL. Hence, irrespective of melanopic illuminance level, both SWL and LWL induced acute alerting effects.

Notably, our design differs from other studies in terms of light stimuli characteristics, including illuminance level and exposure duration. Also, relatively few prior studies have assessed PVT performance during or immediately following exposure to narrow bandwidth light during daytime[44,49,54] and none of these have reported the melanopic-Equivalent Daylight Illuminance (m-EDI) of the light conditions. Hence, a direct comparison of results across studies is challenging. Nevertheless, our finding of an acute alerting effect of SWL (compared to DL) on lapses and mean RT are in line with findings in Rahman et al.[85], although this study had a control condition of medium-wavelength light rather than DL, and the duration of light exposure was 6.5 hours. Additionally, Laszewska et al. reported that 40 minutes of exposure to SWL in the early afternoon reduced EEG markers of drowsiness/sleepiness[30]. Hence, it appears that SWL of different exposure durations can exert positive effects on alertness during daytime. However, van der Meijden et al.[54], who also used DL as a control condition, found no significant effect of SWL on lapses and mean RT. It should be noted that the intermittent light exposure pattern in this study (5-minute light intervals separated by varying periods of darkness) differed from our continuous exposure. In the evening and during nighttime, acute alerting effects of SWL in humans have been linked to mechanisms involving the suppression of melatonin[13,86], a neurohormone involved in the biological timing of sleep[87]. As the spectral sensitivity of melatonin suppression (at least in young adults) lies close to the spectral sensitivity of ipRGCs/melanopsin[88], it has been hypothesized and demonstrated that light which activates melanopsin to a large extent (light with high melanopic-Equivalent Daylight Illuminance (m-EDI) or high melanopic irradiance) is a strong predictor of light's alerting effects during times-of-day where circadian clocks promote sleepiness and relaxation[89]. However, although it has been shown that light of high m-EDI prior to bedtime can suppress melatonin by ~14% compared to low m-EDI light, behavioral and self-report measures of sleepiness and alertness were not significantly different between the two light conditions[90]. Notably, LWL which has low m-EDI can also suppress nighttime melatonin levels[91], hence, the mechanistic effects underlying alerting effects of light during nighttime cannot be entirely attributed to melatonin suppression alone. During daytime, when the circadian clock promotes wakefulness and there is hardly any melatonin present in the human body[87], other mechanistic explanations are needed to

account for light's alerting effects. The alerting potential of SWL during daytime can be explained by acute effects on brain activity in areas associated with the alerting network, one of the three main attention networks in the human brain[92]. The alerting network comprises several frontal and parietal areas, including the dorsolateral prefrontal cortex (DLPFC) and the anterior cingulate cortex (ACC), as well as the Locus Coeruleus (LC) in the brain stem, providing the main source of norepinephrine to the brain though a range of projections to multiple cortical areas[92–94]. During or immediately following exposure to SWL, studies using functional Magnetic Resonance Imaging (fMRI) have shown activations in the DLPFC, the ACC, and an area in the brain stem compatible with the LC [95,96], pointing towards activation of the alerting network. Moreover, stable performance on the PVT has been linked to greater functional connectivity between the DLPFC and other cortical areas[49]. To date, only one study[97] has tested whether SWL affects the efficiency of the alerting network, as assessed with the Attention Network Test (ANT), a behavioral test utilizing the Eriksen Flanker paradigm[98]. This study found no significant effect of SWL on the efficiency of the alerting network. However, the duration of light exposure was five minutes only, hence, it is possible that longer exposure durations (such as 30 minutes as in the fMRI study by Alkozei et al.[96]) are needed to enhance alertness. At the same time, another fMRI study by Vandewalle et al.[95] showed activations in brain areas associated with the alerting network during 50 seconds of light exposure. Notably, these fMRI studies examined brain responses to light in association with a working memory task probing executive processes more than alertness, and no study has yet combined light stimuli, fMRI and the Attention Network Test. Therefore, it remains unknown whether SWL, and of which exposure duration(s), modulates the alerting network at a neurophysiological level sufficient to affect alertness at the behavioral level.

In addition to acute alerting effects of SWL on lapses and mean RT, we also observed similar acute alerting responses during LWL, including a positive effect on the most optimum responses (10% fastest RTs). An acute alerting effect of LWL on mean RT contrasts with findings from other studies. Sahin et al.[31], despite having similar light exposure duration (110 minutes) and control light condition (and DL of <5 photopic lx) as our study, found no significant effects of LWL on a neurobehavioral task probing sustained attention. However, the photopic illuminance level of LWL in this study was 213 lx, whereas our LWL stimulus was considerably brighter (~560 photopic lx). Similarly, van der Meijden et al.[54] did also not find any significant effect of LWL in one of their two experiments, however, as previously mentioned, the light exposure pattern was entirely different from that in our study, as was the light exposure duration (40 minutes) and illuminance level (40 photopic lux). No study has yet tested the acute effects of LWL on other PVT metrics such as lapses and the 10% fastest RTs, hence, future studies are needed to confirm our findings. A recent fMRI study reported that narrow bandwidth "orange" light (λ_{max} = 590 nm) did not modulate the connectivity between a subcortical and cortical brain region involved in regulating attention[99], and a pilot study utilizing resting-state fMRI showed that narrow bandwidth LWL ("red") disrupted brain regions associated with goal-oriented behavior[100]. However, none of these studies investigated brain responses to tasks probing alertness as a subfunction of attention, nor the

490 efficiency of the alerting network, and light exposure duration was brief (30 and 60 seconds,
491 respectively). Although several studies have shown that LWL (with exposure durations
492 ranging from 40 to 110 minutes) reduces EEG markers of drowsiness during the day[11,30,31], it
493 remains to be tested with fMRI and the ANT in combination, whether LWL can activate brain
494 regions in the alerting network in a similar extent to SWL.

495 Interestingly, and contrary to our exploratory hypothesis, SWL was not significantly
496 superior to LWL on any of the PVT measures. This finding of no differential effects between
497 SWL and LWL align with Killgore et al.[49] who also did not observe any significant difference in
498 lapses following 30 minutes of SWL versus LWL in the late morning. One possible explanation
499 for no differential effects between SWL and LWL in our study is that the two light conditions
500 were approximately matched on photon irradiance, hence, the photopic illuminance of LWL
501 had to be considerably high as to match the photon flux in SWL. As melanopsin and other
502 photopigments follow the 'principle of univariance' (the output of a given photoreceptor is
503 dependent on the total amount of photons absorbed), the photoreceptor does not
504 distinguish between differences in wavelength vs. intensity[19,101].

505 Contrary to our main hypothesis, BWL, which was also of relatively high melanopic
506 illuminance (~1000 melanopic lx), did not induce significant alerting effects. This is in contrast
507 to findings from two other studies testing the effects of BWL or short-wavelength-enriched
508 white light at a similar time-of-day as that in our study[45,55]. However, as shown in a recent
509 systematic review by our research group[27], most studies do not report significant effects of
510 BWL on PVT measures. Although it has been recommended that daytime light should have at
511 least 250 melanopic lx at eye level[102], dose-response curves for the acute alerting effects of
512 light during daytime have not yet been firmly established. No dose-response curves for
513 neurobehavioral alertness have been established for SWL and LWL, and for BWL, Smolders et
514 al.[103] did not find any clear dose-response relationships between 1h of exposure to white
515 light (intensity range: ~14-1000 melanopic lx) during daytime on alertness. Irrespective of the
516 spectrum of light, dose-response curves for alerting responses to light will depend not only
517 on exposure duration, but probably also on the specific time-of-day during the biological
518 day, e.g., morning versus afternoon. We might have observed alerting effects of BWL with an
519 exposure duration extending into the post-lunch dip[56,104], a time-of-day where some people
520 experience a dip in core body temperature, which can have negative impacts on performance
521 on some cognitive tasks[105]. Alternatively, BWL might have induced alerting effects if we had
522 included a longer light adaptation than 30 minutes prior to cognitive testing. Even though 30
523 minutes of light adaptation aligns with durations in other studies and physiological responses
524 to light, showing that the half-maximum electroencephalographic (EEG) gamma response
525 (associated with cognitive processes and attention) is achieved after approx. 12 minutes of
526 light exposure[106], most studies assessing the acute effects of light on cognition do not
527 include a light adaptation prior to cognitive testing. Rather, they include a dark adaptation
528 only, and/or "standardize" previous light history in terms of a brief exposure to BWL[27]. Hence,

529 it might be shown in future studies that a longer light adaptation time than 30 minutes will
530 be more optimal for acute effects of light on cognitive functioning.

531 In addition to acute alerting effects, light can also indirectly affect alertness during the
532 day by modulating circadian (~24-h) rhythms and sleep. Melanopsin-containing ipRGCs,
533 sensing environmental light, send projections to the "master" circadian clock, the
534 SupraChiasmatic Nucleus (SCN) in the hypothalamus. The SCN further projects to nuclei
535 involved in regulating melatonin and sleep-related processes (reviewed in[107]), as well as
536 regulating alertness/arousal through a pathway connecting the SCN, the dorsomedial
537 hypothalamic nucleus and the LC[108]. One prominent role of ipRGCs when it comes to
538 circadian rhythms is phase shifting of the biological clock[109,110] . Depending on the timing of
539 light exposure relative to the trough of core body temperature, light can either phase-
540 advance the biological clock if light exposure occurs in the morning (after the core body
541 temperature trough), or phase-delay the clock if light exposure occurs in the evening or at
542 night (before the trough in core body temperature). As we did not control light exposure in
543 the evening, there is a possibility that light emitted from evening displays (e.g., smartphones,
544 tablets, laptops) phase-delayed participants' circadian clock and disrupted their sleep[111],
545 potentially amplifying the alerting effects of light in the morning hours. Also, even though
546 there were no extreme 'evening' chronotypes in our sample (who have a later circadian
547 phase[112]) and we did not observe any significant main effects of chronotype on alertness and
548 attention, alerting effects of light in the morning hours can still have been masked by sleep
549 inertia (drowsiness immediately upon awakening from sleep), which can reduce alertness for
550 hours, even in rested individuals[113,114]. Although participants maintained regular sleep
551 schedules, we did not time light exposure individually, hence, some participants might still
552 have been sleep-deprived and/or suffering from sleep inertia at the time of testing, making
553 them more sensitive to alerting effects of light.

554 Acute alerting effects of light during daytime can also be influenced by season, the length
555 of the photoperiod. With shorter photoperiods (fall and winter), particularly at high latitudes
556 where there are larger variations in the amount of daylight throughout the year, light
557 sensitivity is increased[41,115], thus potentially enhancing alerting responses to light. Indeed, we
558 found that participants tested in the fall had fewer lapses than participants tested in spring,
559 and that participants tested in winter had faster optimum responses (10% fastest RTs) than
560 participants tested in summer. However, we found no significant interactions between light
561 condition and season, hence, we cannot conclude on whether particular light conditions are
562 more optimal than others for different seasons of the year. As participants were tested in one
563 season only and the number of participants tested in each season was rather small and
564 unbalanced in groups, future research should be conducted with large enough sample sizes
565 enabling the manipulation of season between-subjects or with enough resources enabling
566 repeated testing of the same individual across all four seasons of the year.

567 Apart from assessing alerting responses to light with the influence of chronotype, of
568 which we found no significant main effects, and season, we also examined changes in

alertness and attention over time within each light condition. All PVT response metrics except for RTV deteriorated over time, reflecting a time-on-task effect[116], likely due to fatigue or boredom. Light exposure, however, did not counteract this effect, as there were no significant interactions between light and measurement block, consistent with some previous findings[45,48,52]. Other studies on the other hand, report significant interactions[12,46]. However, as previously pointed out, there is large heterogeneity across studies in terms of light spectrum, illuminance and duration of light exposure, hence direct comparisons of results across studies are challenging.

To our knowledge, the current study is the first to test whether light influences intra-individual variability in RTs (RTV), indexed by the SD in RTs[59]. RTV reflects attentional fluctuations similar to lapses and has been proposed as a neurophysiological marker of lapses[117]. Hence, one could expect similar acute alerting effects of light on both measures. However, our results did not support this. Instead, much of the variation in RTV was explained by mean RT (Spearman's ρ =.70), with increasingly slower mean RT associated with increasingly higher variability. Additionally, unlike other PVT metrics, RTV did not worsen over time, rather, variability decreased across assessments, suggesting a stable response pattern, possibly due to ceiling effects in our young, healthy sample (see e.g., MacDonald et al.[118] for an overview of changes in RTV across the life span and in relation to brain disorders). RTV can also be estimated with Ex-Gaussian modeling which separates RT distributions into two gaussian and one exponential component, addressing some limitations of global measures such as SD[59,117,119]. Our findings suggest that 1) lapses may be more sensitive to light than RTV, and/or 2) acute effects of light on RTV might have emerged with Ex-Gaussian modeling techniques. Unfortunately, we did not have enough trials to reliably estimate the exponential component of RTs.

This study has several limitations. First, to be able to conclude more on ipRGC/melanopsin-mediated responses to light, we should have used 'metamers', light conditions that appear visually similar but differ in melanopsin stimulation[120]. Unfortunately, the set-up in our LED lab did not have this design option. The use of metameric light conditions could also have ruled out potential placebo effects arising from participants' expectations about what light conditions would increase alertness. Still, it can be argued that positive and negative effects of light when it comes to health and sleep (e.g., getting enough daylight and avoiding the use of visual LED displays in the evening and night) are more known in public discourse than neurobehavioral effects of more "extreme" light conditions as those of SWL and LWL used in our study. Hence, it is unlikely that our results stem from placebo alone. Second, we might have observed acute alerting effects of BWL with a cognitive test assessing the vigilance aspect of sustained attention, rather than just 'alertness'. Even though the PVT is commonly described as a test of 'vigilance' in chronobiology and somnology, the typical durations of 5 to a maximum of 10 minutes will predominantly measure alertness but will not meet the definition typically used in cognitive psychology as a measure of vigilance[121]. To assess vigilance, longer performance durations of

14-20 minutes are needed. Hence, the PVT used in our study is not an adequate measure of the vigilance aspect of sustained attention. Therefore, the field are in need of more studies that assess how light acutely impacts vigilance, by using tests such as the Sustained Attention Task or the Continuous Performance Task. Finally, although most findings remained significant after correction for multiple comparisons, some confidence intervals were wide, indicating uncertainty in estimates. Also, the sample size and the number of predictors in the models likely reduced statistical power, and effect sizes for the significant main effects of light were small to moderate. However, these indices should be interpreted cautiously, due to challenges in estimating them accurately in multilevel models with random-effect variance components[82]. This is especially relevant for the results reported in our study, as the statistical models were constructed with multiple random-effect terms to account for all sources of random variance associated with repeated testing on the same subjects.

Conclusion

Our findings suggest that exposure to artificial light of both low and high melanopic illuminance during daytime can enhance alertness and attention in healthy, young adults, by reducing lapses and improving overall mean RT and optimum response capability. Notably, light of high melanopic illuminance was not superior to light of low melanopic illuminance – both SWL and LWL improved alertness and attention. This finding challenges the traditional theoretical assumptions underlying the NIF effects of light and suggests that the relationship between light and attention may be more complex than previously understood. Surprisingly, despite having relatively high melanopic illuminance, BWL did not induce alerting effects, and light exposure did not impact short-term intra-individual variability in performance. However, future research with higher sample sizes should test whether intra-individual variability, indexed with various measures, is acutely affected by light.

Data availability

Aggregated behavioral data is available from the corresponding author upon request.

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Figure legends

Figure 1. Overview of experimental in-laboratory design. Snacks included one serving of fruit, one whole grain crispbread, and one small bag (60 g) of mixed nuts. The number to the right of the red diamonds represents block number (PVT test administration). m-EDI = melanopic-Equivalent Daylight Illuminance. lx = lux. PVT = Psychomotor Vigilance Task.

Figure 2. Estimated Marginal Means (EMMs) of the number of lapses in each light condition. Error bars = 95% Confidence Intervals (CIs). EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. RTs = Reaction Times. SWL = Short-Wavelength Light. *p<.05.

Figure 3. Estimated Marginal Means (EMMs) of Mean Reaction Time (RT) in each light condition. The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents mean estimated RT across SWL, LWL, and BWL. EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. SWL = Short-Wavelength Light. **p<0.01. *p<0.05.

Figure 4. Scatter plot of the relationship between standard deviations in reaction time (RT) and mean RT. Values are on log scale. Error band = 95% Confidence Interval (CI). ms = milliseconds. ***p<.001.

Figure 5. Estimated Marginal Means (EMMs) of the Mean 10% fastest Reaction Times (RTs). The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents mean estimated 10% fastest RT across SWL, LWL, and BWL. EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. SWL = Short-Wavelength Light. *p<0.05.

Author contributions

Writing original draft, planning and conducting statistical analyses, preparing figures and tables: LBB. Methodology and conceptualization: EF-G, EV, IHN, LBB, LS. Funding acquisition: EF-G, IHN, LS. Recruitment of participants: LBB, OBK, MEH, EF-G, EV, IHN. Data collection: LBB, OBK, MEH. Reviewing draft and approving final manuscript for submission: all authors.

Acknowledgements

We would like to thank Erlend Sunde for assisting with a pre-processing script of PVT raw data, and Mattan S. Ben-Shachar for consulting on multi-level modeling.

Funding

The study was supported by a grant from the Research Council of Norway (grant number: 275305) and LBB's PhD grant from the University of Bergen.

Competing Interests

The authors declare no competing interests.