Different artificial light modalities during daytime have all positive effects on attention and alertness

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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 modalities during daytime affect our attention, there is a need for more studies. The current study tested the acute effects of daytime exposure to four artificial light modalities 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 four light modalities presented on separate days at the same time-of-day (09:00-11:00): short-wavelength light [SWL, “blue”], long-wavelength light [LWL, “red”], bright white light [BWL], and dim light [DL] 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 all three light conditions and enhanced optimum response capability during SWL and LWL. Light did not appear to have effects on intra-individual RT variability. Results suggest that 2 hours of exposure to artificial light during daytime can induce alerting effects and fewer attentional lapses in young, healthy adults. Surprisingly, neither SWL, LWL, nor BWL were significantly superior to one another.

Keywords: artificial light, NIF responses, attention, alertness, intra-individual variability, reaction time variability

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 (λ_{max}) to short-wavelength light (SWL) at/near ~480 nm [20,21]. SWL with a narrow bandwidth (that is, with a narrow peak in some part of the electromagnetic spectrum) will appear blue to the human eye. Similarly, medium-wavelength light (MWL, at ~550 nm) will appear green, and long-wavelength light (LWL, 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 lx) 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]. 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 [27]. The most reported PVT metrics are mean reaction time (RT) and the number of lapses in attention (often quantified as RTs≥500 ms) [28]. Studies using the PVT to assess alertness in different light conditions have reported faster mean RT and fewer lapses during SWL ("blue") [29], bright white light [12,30,31] and white light of high m-EDI [32]. However, other studies report no significant effects [33–39]. Also, most studies report no significant effects of white light on the 10% fastest RTs [12,30,33,35,36,38,40–43] – a less commonly reported metric from the PVT [28]. 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 also 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 [44]. 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 [12,31,33,37]. Chronotype (inter-individual differences

in preferred sleep and wake timing, e.g., whether one is a "morning lark" or an "evening owl") might affect alerting responses to light [45]. Also, poor sleep quality and sleep restriction (curtailed sleep duration) has been linked to alertness deficits in healthy individuals [46–49], and light exposure has the potential to counteract such deficits [50–52]. Finally, seasonal changes in ambient light exposure can affect NIF responses to light, probably due to changes in light sensitivity [53,54]. Hence, it is important to take these factors into consideration when assessing the alerting effects of light.

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. Based on previous research and theory on the NIF acute effects of light, the following pre-registered hypotheses (https://osf.io/m7gfh) were tested:

- 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 and overall mean RT on the PVT.

Additionally, we explored to what extent:

- SWL will have a superior effect on lapses and mean RT relative to BWL and LWL, and similarly, whether BWL will be superior to LWL,
- SWL, LWL, and BWL compared to DL, will reduce intra-individual RTV (quantified as the SD of RTs),

- SWL, LWL, and BWL affect optimum response capability (quantified as the mean of the 10% fastest RTs),
- Season and chronotype affect alerting responses.

Methods

Study Design and Setting

This study was a work package in a larger pre-registered study called the *ENLIGHT project* (https://osf.io/6nbr9). Using a within-subjects repeated measurements design, the *ENLIGHT project* investigates the acute effects of different light conditions on cognitive performance and mood. Data collection for the present study was conducted from November 2021 to October 2023, at a high latitude (60.39° N).

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, and they were allowed to consume their habitual number of caffeinated beverages. During in-laboratory testing, however, no caffeine consumption nor nicotine use was allowed.

Testing took place in a window-less laboratory (30 m^2) with five working stations equipped with a desk, keyboard, mouse, and PC. All computer screens had an overlay screen filter, blocking all wavelengths <520 nm (Metolight SFG-10, Asmetec, Germany). Participants arrived 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 four experimental light conditions. The experimental light conditions increased gradually in intensity during the last 10 minutes of dim light. Fig. 1 shows 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 in the following light conditions: 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), BWL (m-EDI = 1155.8±17.6 lx, CCT = 8035.7±42.8 K), and white DL (m-EDI = 9.7±6.4 lx). The two narrow bandwidth light conditions were matched on photon irradiance (= log 18.8/m^2/s). Light quantities were calculated using the open-access- and

source web platform *luox* [55]. Light-related quantities, including spectral power distributions, can be accessed in Supplementary Materials S1. The experimental light conditions except for DL were delivered through 20 ceiling-mounted 60x60 cm tunable Light Emitting Diode (LED) luminaires (Glamox AS, Norway). In the experimental 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 preceding light adaptation, DL was delivered through six portable Philips Hue Go lamps situated behind the computer screen at each workstation, facing away from the participants. At each workstation, light stimuli were measured at eye level (vertically, 120 cm above the floor, ~90 cm horizontally from the computer screen) with a calibrated spectroradiometer (GL Spectis 1.0 T Flicker, GL Optic, Poland), for approximately 30 minutes after the onset of the luminaires to allow the luminaires to adjust in temperature.

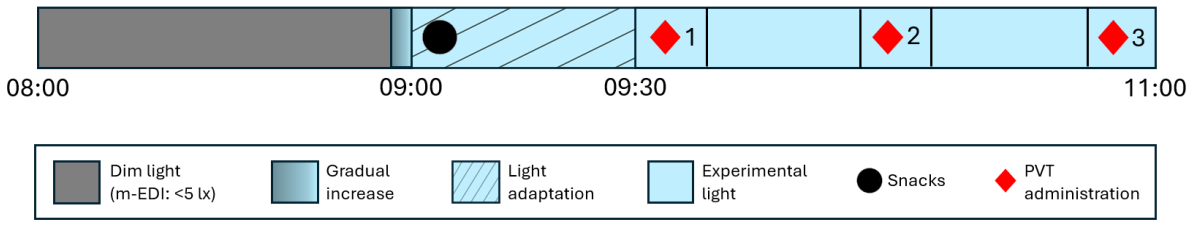

Figure 1. Overview of experimental in-laboratory design. Snacks included one serving of fruit, one whole grain crispbread, and one small bag (60 g) of mixed nuts. The number to the right of the red diamonds represents block number (PVT test administration). m-EDI = melanopic-Equivalent Daylight Illuminance. 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 light condition (block 1-3, see Fig. 1) with a five-minute computerized version of the PVT [27,56], administered through E-Prime 3.0 [57]. 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) [58]. 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 subjects but was entered as a covariate in statistical analyses. As there is substantial variation in annual photoperiod length at northern latitudes [59], 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 (https://osf.io/m7gfh). Missing data (<10%) were imputed with a Random Forest algorithm in the R package *mice* [60]. All analyses were performed in R version 4.4.1 [61] using the packages *tidyverse* [62], *glmmTMB* [63], *lme4* [64], *lmerTest* [65], *DHARMa* [66], *performance* [67], *emmeans* [68], *ggeffects* [69], and *effectsize* [70]. 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 modelled as fixed effects, and subject as random effect. 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 [71]. 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 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) [72], significant 'simple' effects of light and/or block in the initial model were modelled 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 [73]. In these analyses, light and biological sex were entered as fixed effects, using 'dim' and 'female', respectively, as reference levels, and subject was modelled as random effect. Alpha level was set to .05, two-tailed in all analyses. For the GLMMs on the number of lapses, Incidence Rate Ratio (IRR), 95% CI, SE, z-value, and p-value are reported. For the GLMMs on RTV, the estimate (β) 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 [74]. In the LMMs, the β together with 95% CI and SE, t-value, and p-value are reported. For significant effects in the LMMs, theoretical effect sizes include Cohen's f^2, as recommended by Lorah [75], as well as omega $(\omega)^2$, a less biased alternative to η^2 [76]. A Cohen's f^2 ≥.02 is considered a small effect, ≥.15 medium, and ≥.35 large [74]. An ω^2 <.01 is considered a very small effect, .01 – .05 = small effect, .06 – .13 = medium effect, and ≥ .14 = large effect [77]. All effect sizes were estimated using the test-statistic approximation method and were calculated using https://easystats4u.shinyapps.io/statistic2effectsize/, a Shiny app accompanying the *effectsize* package [70]. 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 effect of subject [78]. 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. A power analysis was conducted in the larger study only, assuming three subgroups of participants and multiple 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 random effect structure in addition to fixed 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 and 438 observations (Table 1).

Table 1. Study sample and laboratory characteristics

Total N (females)	39 (24)
Age [Mean (SD)]	21.7 (2.6)
r-MEQ (%)	
Definitely morningness	0
Moderately morningness	17.9
Intermediate type	56.4
Moderately eveningness	25.6
Definitely eveningness	0
Laboratory conditions*	
Temperature [Mean (SD), °C]	20 (1.2)
Humidity [Mean (SD), %]	39.8 (13.2)

Note: r-MEQ = Morningness-Eveningness Questionnaire reduced version. There were no extreme chronotypes. *Kruskal-Wallis Rank Sum Tests did not reveal any significant differences in temperature nor air humidity between light conditions.

Acute alerting effects of light

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 modelled 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 block; p's<.0001, see Supplementary Materials). Results from exploratory analyses, including interaction models exploring the interactions between light*chronotype and light*season, can be accessed in Supplementary Materials S2. Sensitivity analyses on a dataset with complete-cases only showed a similar overall pattern of results (see Supplementary Materials S3) as in analyses on imputed data, except for a significant main effect of light on RTV (larger variability in LWL compared to DL), 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<.001, LWL: p<.001, BWL: p<.01, Table 2). Post-hoc analyses showed that participants had significantly fewer lapses in SWL (p<.01, *EMM* = 0.99[0.72-1.37], *SE* = 1.18), LWL (p<.001, *EMM* = 0.98[0.71-1.36], *SE* = 1.18), and BWL (p<.05, *EMM* = 1.14[0.82-1.59], *SE* = 1.18), compared to DL (*EMM* = 1.67[1.23-2.27], *SE* = 1.17) (Fig. 2).

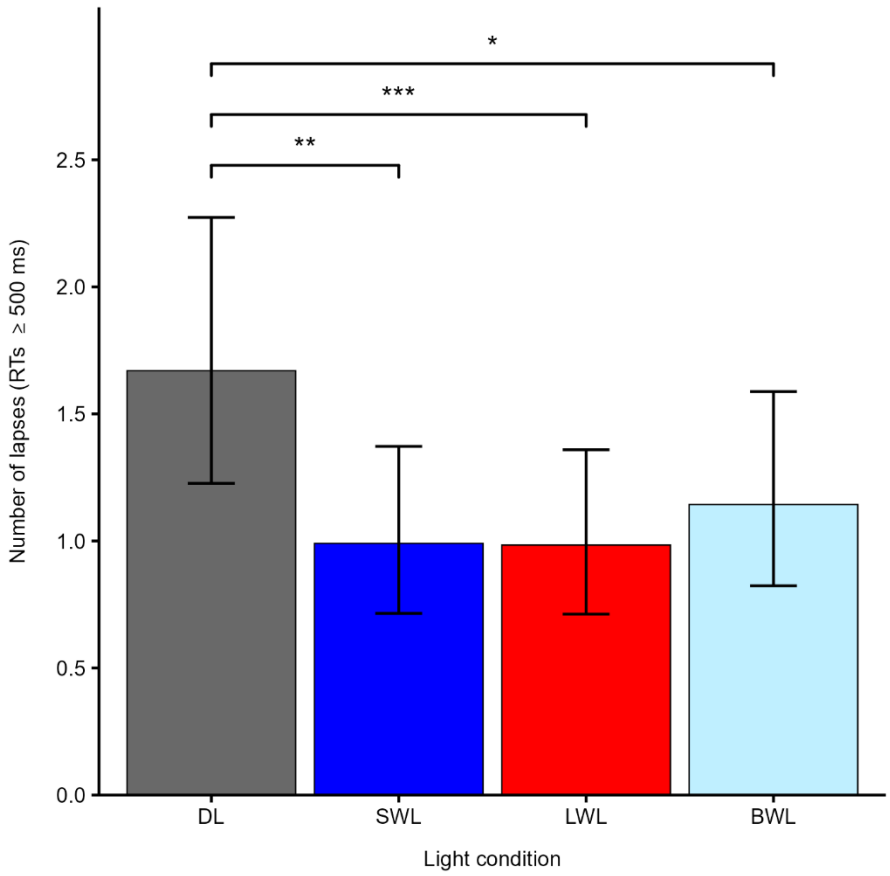

Figure 2. Estimated Marginal Means (EMMs) of the number of lapses in each light condition. Error bars = 95% Confidence Intervals (CIs). EMMs and CIs were back-transformed from log to original scale for visualization purposes. BWL = Bright White Light. DL = Dim Light. LWL = Long-Wavelength Light. ms = milliseconds. RTs = Reaction Times. SWL = Short-Wavelength Light. ***p<.001. **p<.01. *p<.05.

There was also a significant main effect of season (spring: p<.05), but the effect was no longer significant after correcting for multiple comparisons. Finally, the model with the interaction term light*season revealed that, in the fall, participants had fewer lapses in LWL vs. DL (p<.05, see Supplementary Materials S2).

Mean RT

The main effects model showed significant main effects of light (SWL: $p<.0001$, LWL: $p<.0001$, BWL: $p<.001$). Post-hoc analyses revealed that participants' mean RT was faster in SWL ($p<.001$, *EMM* = 304.20[293.67-315.11], *SE* = 1.02), LWL ($p<.001$, *EMM* = 305.33[294.72-316.31], *SE* = 1.02), and BWL ($p<.05$, *EMM* = 309.21[298.26-320.57], *SE* = 1.02), compared to DL (*EMM* = 318.82[307.51-330.53], *SE* = 1.02, Fig. 3).

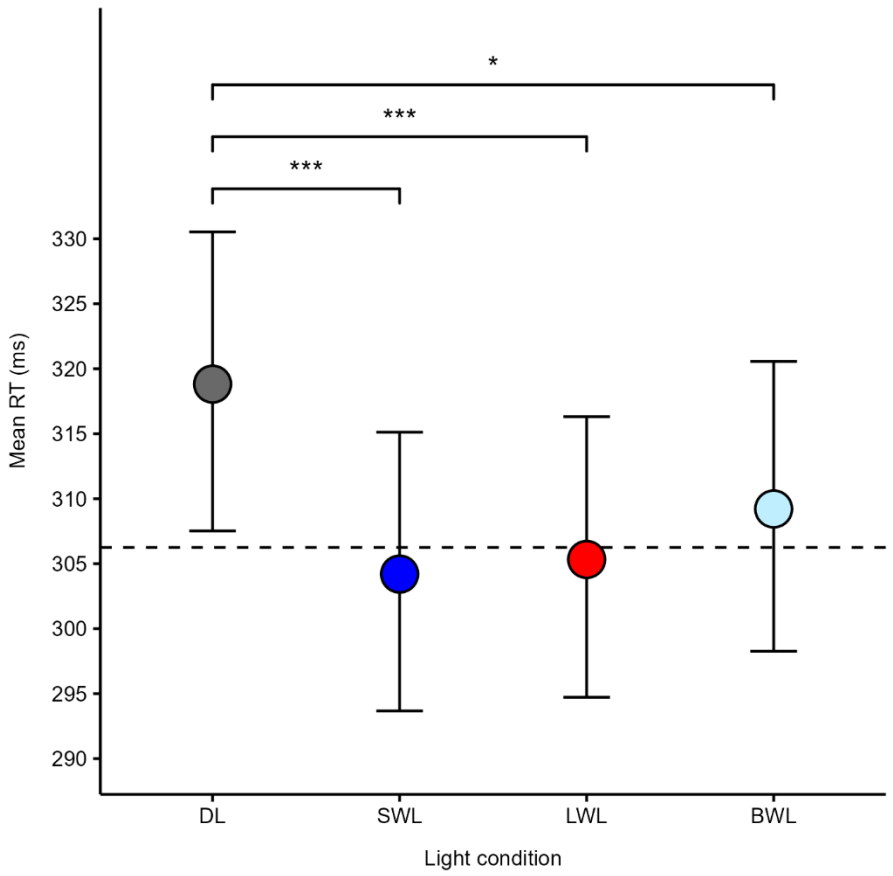

Figure 3. Estimated Marginal Means (EMMs) of Mean Reaction Time (RT) in each light condition. The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents mean estimated RT across SWL, LWL, and BWL. EMMs and CIs 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<0.001. *p<0.05.

Explorative analyses of the interaction between light and season and light and chronotype showed that in the fall, participants responded faster in SWL and LWL relative to DL, and 'morning types' responded faster in LWL than DL, whereas 'intermediate types' responded faster in SWL (see Supplementary Materials S2).

RTV

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

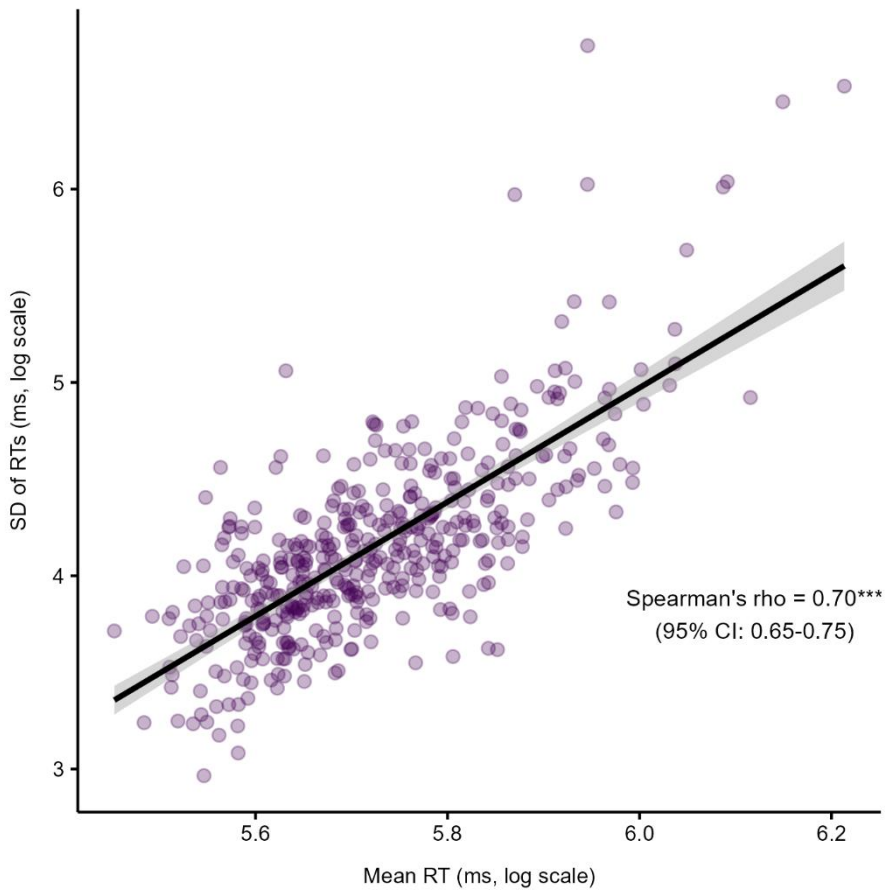

Figure 4. Scatter plot of the relationship between standard deviations in reaction time (RT) and mean RT. Values are on log scale. Error band = 95% Confidence Interval (CI). ms = milliseconds. ***p<.001.

There were also significant main effects of measurement blocks (p's<.001, Table 2). Post-hoc analyses showed that participants expressed lower variability in block 2 (p<.001, *EMM* = 60.72[55.96-65.89], *SE* = 1.04) and 3 (p<.0001, *EMM* = 58.15[53.51-63.20], *SE* = 1.04), relative to block 1 (*EMM* = 69.72[64.16-75.76], *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 and LWL: p's<.01), chronotype (p's<.05), and season (summer: p<.05), see Table 3. Post-hoc analyses showed that participants responded faster in SWL (p<.05, *EMM* = 243.85[237.67-250.20], *SE* = 1.01) and LWL (p<.01, *EMM* = 243.01[236.83-249.35], *SE* = 1.01) compared to DL (*EMM* = 248.43[242.02-255.02], *SE* = 1.01), see Fig. 5. Post-hoc analyses on the main effect of season showed that participants tested in winter responded faster (p<.05, *EMM* = 234.65[222.23-247.76], *SE* = 1.03) compared to participants tested in summer (*EMM* = 261.33[246.20-277.39], *SE* = 1.03), see Supplementary Materials S2. Post-hoc analyses of the main effect of chronotype did not remain significant after correction for multiple comparisons. The interaction models showed no significant interaction between light and season, but there was a significant interaction between light and chronotype (p<.05, see Supplementary Materials S2).

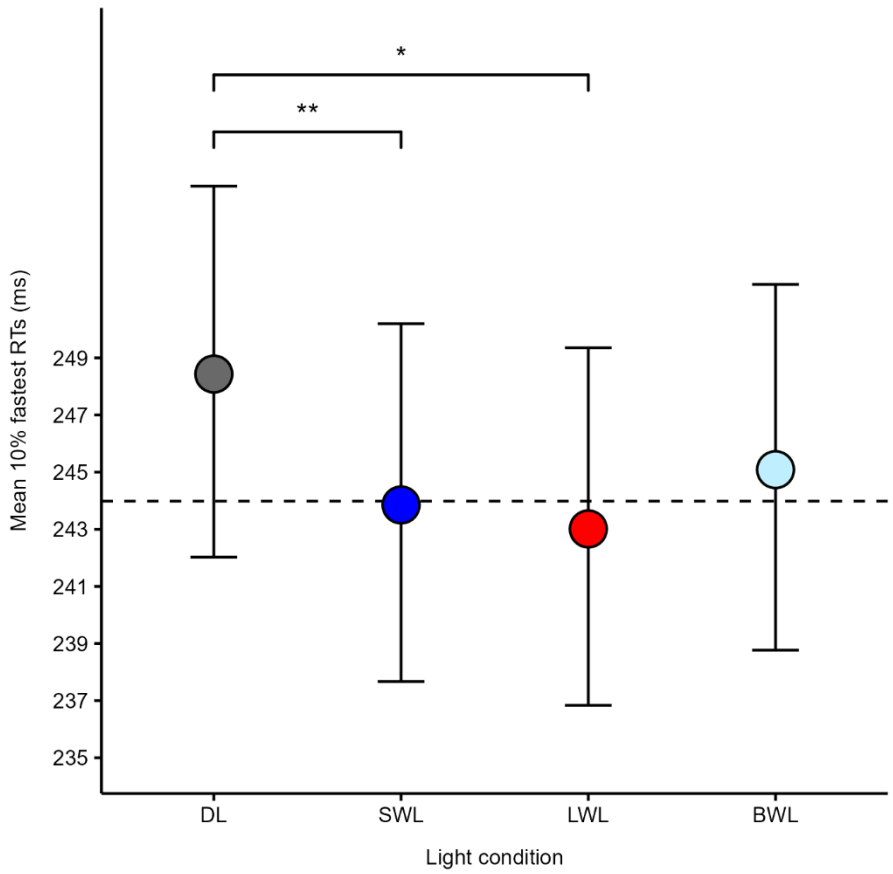

Figure 5. Estimated Marginal Means (EMMs) of the Mean 10% fastest Reaction Times (RTs). The y axis limit has been adjusted so that group differences appear more clearly. Error bars = 95% Confidence Intervals (CIs). Dashed line represents mean estimated 10% fastest RT across SWL, LWL, and BWL. EMMs and 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<0.01. *p<0.05.

Table 2. Generalized Linear Mixed Effects Model analyses of the number of lapses and intra-individual reaction time variability on the Psychomotor Vigilance Task

	Lapses					**RTV**				
Parameters	*IRR (95% CI)*	*SE*	*z*	*p*	r_p	*Estimate (95% CI)*	*SE*	*z*	*p*	r_p
Intercept	1.53 (0.37 - 6.38)	1.11	0.58	0.562		2.43e-8 (0.00 - 0.00)	2.40E-08	-17.73	<.001	
Light										
SWL	0.59 (0.45 - 0.78)	0.08	-3.73	**<.001**	-0.513	1.07 (0.99 - 1.16)	0.04	1.80	0.073	
LWL	0.59 (0.45 - 0.77)	0.08	-3.81	**<.001**	-0.521	1.07 (0.99 - 1.15)	0.04	1.67	0.094	
BWL	0.68 (0.52 - 0.90)	0.10	-2.70	**<.01**	-0.397	1.03 (0.95 - 1.11)	0.04	0.78	0.433	
Block										
Block 2	2.22 (1.68 - 2.93)	0.31	5.65	**<.001**	0.671	0.87 (0.81 - 0.93)	0.03	-3.96	**<.001**	-0.536
Block 3	2.41 (1.84 - 3.15)	0.33	6.38	**<.001**	0.715	0.83 (0.78 - 0.89)	0.03	-5.05	**<.001**	-0.629
Chronotype										
Eveningness	1.11 (0.70 - 1.76)	0.26	0.45	0.654		0.94 (0.83 - 1.06)	0.06	-1.08	0.280	
Morningness	1.09 (0.62 - 1.91)	0.31	0.28	0.777		0.92 (0.79 - 1.06)	0.07	-1.17	0.241	
Season										
Spring	1.77 (1.01 - 3.09)	0.50	2.00	**<.05**	0.305	1.08 (0.92 - 1.26)	0.09	0.91	0.364	
Summer	1.36 (0.68 - 2.72)	0.48	0.86	0.389		0.84 (0.69 - 1.03)	0.09	-1.69	0.091	
Winter	0.94 (0.49 - 1.80)	0.31	-0.19	0.848		1.09 (0.91 - 1.31)	0.10	0.95	0.340	
		0.01								
Sleep efficiency	0.99 (0.98 - 1.01)		-1.06	0.289		1.00 (0.99 - 1.00)	0.00	-1.26	0.209	
Mean RT						46.99 (33.79 - 65.35)	7.91	22.88	**<.001**	0.943

Random Effects				
Subject (Intercept)	1.74 (1.44 - 2.10)		0.18 (0.13 - 0.24)	
Residual	0.60 (0.44 - 0.82)		0.28 (0.26 - 0.30)	
Adjusted / Unadjusted ICC		0.291 / 0.239		0.303 / 0.104
Conditional / Marginal R^2		0.417 / 0.177		0.760 / 0.657

Note: BWL = Bright White Light. CI = Confidence Interval. ICC = Intra-Class Correlation Coefficient. IRR = Incidence-Rate Ratio. LWL = Long-Wavelength Light. RTV = Reaction Time Variability. SE = Standard Error. SWL = Short-Wavelength Light. Significant p-values are highlighted in bold.

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

	Mean RT						**Mean of the 10% Fastest RTs**					
Parameters	*Estimate (95% CI)*	*SE*	*t*	*df*	*p*	*f² / ω²*	*Estimate (95% CI)*	*SE*	*t*	*df*	*p*	*f² / ω²*
Intercept	306.36 (268.92 - 349.01)	20.32	86.33	354.02	<.001		244.75 (225.05 - 266.17)	10.45	128.87	349.18	<.001	
Light												
SWL	0.95 (0.93 - 0.98)	0.01	-4.16	394.39	**<.001**	0.04 / 0.040	0.98 (0.97 - 1.00)	0.01	-2.66	393.75	**<.01**	0.02 / 0.015
LWL	0.96 (0.94 - 0.98)	0.01	-3.82	395.52	**<.001**	0.04 / 0.033	0.98 (0.96 - 0.99)	0.01	-3.15	394.73	**<.01**	0.03 / 0.022
BWL	0.97 (0.95 - 0.99)	0.01	-2.65	392.95	**<.01**	0.02 / 0.015	0.99 (0.97 - 1.00)	0.01	-1.90	392.67	0.059	
Block												
Block 2	1.08 (1.06 - 1.10)	0.01	8.09	392.4	**<.001**	0.17 / 0.141	1.04 (1.03 - 1.05)	0.01	6.71	392.38	**<.001**	0.12 / 0.100
Block 3	1.10 (1.08 - 1.12)	0.01	9.75	391.75	**<.001**	0.24 / 0.193	1.05 (1.03 - 1.06)	0.01	7.76	391.78	**<.001**	0.15 / 0.131
Chronotype												
Eveningness	1.01 (0.97 - 1.06)	0.02	0.65	154.56	0.519		1.03 (1.00 - 1.06)	0.02	2.16	215.42	**<.05**	0.02 / 0.017
Morningness	1.02 (0.97 - 1.08)	0.03	0.71	169.63	0.476		1.04 (1.01 - 1.08)	0.02	2.26	233.32	**<.05**	0.02 / 0.017
Season												
Spring	1.04 (0.97 - 1.11)	0.04	1.07	36.47	0.285		1.01 (0.96 - 1.06)	0.03	0.35	36.20	0.723	
Summer	1.09 (1.00 - 1.19)	0.05	1.86	34.42	0.064		1.08 (1.01 - 1.16)	0.04	2.37	34.90	**<.05**	0.16 / 0.111
Winter	0.99 (0.91 - 1.07)	0.04	-0.34	33.51	0.732		0.97 (0.91 - 1.03)	0.03	-0.92	34.09	0.356	

Sleep Efficiency	1.00 (1.00 - 1.00)	0.00	-0.91	424.42	0.363	1.00 (1.00 - 1.00)		-1.39	425.43	0.164
Random Effects									
Subject (Intercept)	0.08 (0.06 - 0.11)	0.01				0.06 (0.05 - 0.08)	0.01			
Residual	0.08 (0.08 - 0.09)	0.00				0.05 (0.05 - 0.05)	0.00			
Adjusted / Unadjusted ICC		0.613 / 0.480					0.515 / 0.420			
Conditional / Marginal R^2		0.697 / 0.217					0.604 / 0.183			

Note: 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. Significant p-values are highlighted in bold.

Discussion

This study tested whether daytime exposure to different artificial light conditions could enhance alertness in healthy, young adults. The results supported our main hypothesis, showing that narrow bandwidth SWL, narrow bandwidth LWL, and BWL reduced lapses and shortened overall mean RT, compared to DL. However, neither SWL, LWL, nor BWL were significantly superior to one another. Notably, our design differs from other studies in terms of light stimuli characteristics. Relatively few prior studies have assessed PVT performance during/immediately following exposure to narrow bandwidth light during daytime, and none reported m-EDI [29,34,39].

Although different designs and light stimuli characteristics complicate comparison, our findings of no differential effects between light conditions align partly with Killgore et al. [34] who found no significant difference in lapses following 30 minutes of SWL versus LWL exposure in the late morning. The alerting effect we found of LWL contrasts with Sahin et al. [79], where 110 minutes of LWL vs. DL did not affect performance on a task probing sustained attention (alertness over time). Similarly, van der Meijden et al. [39] found no significant difference in mean RT when comparing LWL and darkness, though their intermittent light exposure pattern (5-minute light intervals separated by varying periods of darkness) differed from our continuous exposure.

We also found alerting effects of BWL (m-EDI: ~1000 lx), consistent with Lok et al. [32] and Yang et al. [31], who reported fewer lapses in response to high m-EDI white light compared to DL. However, te Kulve et al. [38] found no significant effect of BWL on lapses. Despite similar light exposure duration and assessment timing, their BWL stimulus was ~3800 K, while our BWL was considerably “cooler” (~8000 K).

To our knowledge, the current study is the first to test whether light influences intra-individual variability in RTs, indexed by the SD in RTs [44]. RTV reflects attentional fluctuations similar to lapses and has been proposed as a neurophysiological marker of lapses [80]. Hence, one could expect similar acute alerting effects 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. [81] 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 [44,80,82]. 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 modelling techniques. Unfortunately, we did not have enough trials to reliably estimate the exponential component of RTs.

We also found that light significantly impacted optimum response capability (mean of the 10% fastest RTs), with faster responses during SWL and LWL compared to DL. No significant effect was found for BWL, which is consistent with previous studies [12,30,33,35,36,38]. As this is the first study to test the acute effects of short- and long-wavelength light on optimum response capability, future research is needed to confirm these effects.

In addition to the alerting effects of light, we examined changes in alertness over time within each light condition. All response metrics except for RTV deteriorated over time, reflecting a time-on-task effect [83], likely due to fatigue or boredom. Light exposure did not counteract this effect, as there were no significant interactions between light and measurement

block, consistent with some previous findings [30,33,37]. However, other studies report significant interactions [12,31].

Inter-individual differences like chronotype may influence how light exposure affects attention [45,84]. Overall, we found no consistent pattern of effects, but there were some significant interactions (see Supplementary Materials S2). While alerting effects did not vary widely across chronotypes, they may have been masked by sleep inertia, which can reduce alertness for hours, even in rested individuals [85,86]. Although participants maintained regular sleep schedules, we did not individually time light exposure. Hence, some participants might have been sleep-deprived, possibly amplifying the alerting effects of light.

In addition to the acute effect of light on optimum response capability, season also influenced performance: optimum responses were faster in winter than in summer. Additionally, for participants tested in the fall, we observed fewer lapses in LWL vs. DL, and faster mean RT in LWL and SWL vs. DL. This could be due to increased light sensitivity in seasons with shorter photoperiods [54,87]. Humans are also very sensitive to evening light, with substantial interindividual variability [88]. Without controlling evening light exposure prior to cognitive testing, the performance-enhancing effects of light may have been less pronounced. Finally, the alerting effects of light likely involve complex interactions between season, chronotype, and sleep factors, but our sample size limited the assessment of three-way interactions.

This study has several limitations. First, the sample size and the number of predictors likely reduced statistical power, and effect sizes in the LMMs were mostly small. Reported effect sizes, particularly ω^2, should be interpreted cautiously, due to challenges in estimating them accurately in multilevel models with random variance components [75]. Although most findings remained significant after correction for multiple comparisons, some confidence intervals were wide, indicating uncertainty in estimates. Additionally, while we matched SWL

and LWL on photon irradiance, we cannot attribute alerting responses purely to melanopsin/ipRGCs. Melanopsin and other photopigments follow the principle of univariance (the output of a given photoreceptor is dependent on the total amount of photons absorbed – the photoreceptor does not distinguish between differences in wavelength vs. intensity) [19,89]. As we did not use metamers, light conditions that appear visually similar but differ in melanopsin stimulation [90], the SWL and BWL condition used in the current study probably activated melanopsin to a similar extent. The use of metamers could also have ruled out potential placebo effects arising from participants' expectations about what light conditions would increase alertness.

Conclusion

Our findings suggest that 2 hours of artificial light exposure during daytime can enhance alertness and attention in healthy, young adults, by reducing lapses and improving overall mean RT and optimum response capability. Notably, high m-EDI light (short-wavelength- and bright white light) was not superior to low m-EDI light (long-wavelength light) – all three light conditions 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. Given that BWL exerted effects similar to SWL, BWL may serve as a practical and ecologically valid intervention for increasing daytime alertness levels in everyday settings. Lastly, 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.

References

1. Barger, L. K. *et al.* Impact of Extended-Duration Shifts on Medical Errors, Adverse Events, and Attentional Failures. *PLOS Medicine* **3**, e487 (2006).
2. Bell, T., Sprajcer, M., Flenady, T. & Sahay, A. Fatigue in nurses and medication administration errors: A scoping review. *Journal of Clinical Nursing* **32**, 5445–5460 (2023).
3. Ganesan, S. *et al.* The Impact of Shift Work on Sleep, Alertness and Performance in Healthcare Workers. *Sci Rep* **9**, 4635 (2019).
4. Gold, D. R. *et al.* Rotating shift work, sleep, and accidents related to sleepiness in hospital nurses. *American Journal of Public Health* (2011) doi:10.2105/AJPH.82.7.1011.
5. Mulhall, M. D. *et al.* Sleepiness and driving events in shift workers: the impact of circadian and homeostatic factors. *Sleep* **42**, zsz074 (2019).
6. Pack, A. I. *et al.* Characteristics of crashes attributed to the driver having fallen asleep. *Accident Analysis & Prevention* **27**, 769–775 (1995).
7. Vedaa, Ø. *et al.* A longitudinal study on the association between quick returns and occupational accidents. *Scandinavian Journal of Work, Environment & Health* **46**, 645–649 (2020).
8. Motamedzadeh, M., Golmohammadi, R., Kazemi, R. & Heidarimoghadam, R. The effect of blue-enriched white light on cognitive performances and sleepiness of night-shift workers: A field study. *Physiology & Behavior* **177**, 208–214 (2017).
9. Sletten, T. L. *et al.* Randomised controlled trial of the efficacy of a blue-enriched light intervention to improve alertness and performance in night shift workers. *Occup Environ Med* **74**, 792–801 (2017).
10. Sunde, E. *et al.* Blue-Enriched White Light Improves Performance but Not Subjective Alertness and Circadian Adaptation During Three Consecutive Simulated Night Shifts. *Frontiers in Psychology* **11**, (2020).
11. Sahin, L. & Figueiro, M. G. Alerting effects of short-wavelength (blue) and long-wavelength (red) lights in the afternoon. *Physiol. Behav.* **116–117**, 1–7 (2013).

12. Smolders, K. C. H. J., de Kort, Y. A. W. & Cluitmans, P. J. M. A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures. *Physiology & Behavior* **107**, 7–16 (2012).
13. Cajochen, C. *et al.* High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. *J. Clin. Endocrinol. Metab.* **90**, 1311–1316 (2005).
14. Chellappa, S. L. *et al.* Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert? *PLOS ONE* **6**, e16429 (2011).
15. Hanifin, J. P. *et al.* Randomized trial of polychromatic blue-enriched light for circadian phase shifting, melatonin suppression, and alerting responses. *Physiol. Behav.* **198**, 57–66 (2019).
16. de Zeeuw, J. *et al.* Living in Biological Darkness: Objective Sleepiness and the Pupillary Light Responses Are Affected by Different Metameric Lighting Conditions during Daytime. *J. Biol. Rhythms* **34**, 410–431 (2019).
17. Spitschan, M. Photoreceptor inputs to pupil control. *Journal of Vision* **19**, 5 (2019).
18. Roenneberg, T., Kumar, C. J. & Merrow, M. The human circadian clock entrains to sun time. *Current Biology* **17**, R44–R45 (2007).
19. Spitschan, M. Melanopsin contributions to non-visual and visual function. *Current Opinion in Behavioral Sciences* **30**, 67–72 (2019).
20. Bailes, H. J. & Lucas, R. J. Human melanopsin forms a pigment maximally sensitive to blue light ($\lambda max \approx 479$ nm) supporting activation of Gq/11 and Gi/o signalling cascades. *Proceedings of the Royal Society B: Biological Sciences* **280**, 20122987 (2013).
21. Provencio, I. *et al.* A novel human opsin in the inner retina. *J. Neurosci.* **20**, 600–605 (2000).
22. Commission Internationale de l'Eclairage (CIE). CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. CIE S026/E:2018. (2018).
23. Vetter, C. *et al.* A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions. *LEUKOS* **18**, 387–414 (2022).
24. Dijk, D.-J., Duffy, J. F. & Czeisler, C. A. Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance. *Journal of Sleep Research* **1**, 112–117 (1992).

25. Posner, M. I. & Petersen, S. E. The Attention System of the Human Brain. *Annual Review of Neuroscience* **13**, 25–42 (1990).
26. Posner, M. I. Measuring Alertness. *Annals of the New York Academy of Sciences* **1129**, 193–199 (2008).
27. Dinges, D. F. & Powell, J. W. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers* **17**, 652–655 (1985).
28. Basner, M. & Dinges, D. F. Maximizing Sensitivity of the Psychomotor Vigilance Test (PVT) to Sleep Loss. *Sleep* **34**, 581–591 (2011).
29. Rahman, S. A. *et al.* Diurnal spectral sensitivity of the acute alerting effects of light. *Sleep* **37**, 271–281 (2014).
30. Huiberts, L. M., Smolders, K. C. H. J. & De Kort, Y. A. W. Seasonal and time-of-day variations in acute non-image forming effects of illuminance level on performance, physiology, and subjective well-being. *Chronobiology International* **34**, 827–844 (2017).
31. Yang, M. *et al.* The Acute Effects of Intermittent Light Exposure in the Evening on Alertness and Subsequent Sleep Architecture. *International Journal of Environmental Research and Public Health* **15**, 524 (2018).
32. Lok, R., Joyce, D. S. & Zeitzer, J. M. Impact of daytime spectral tuning on cognitive function. *Journal of Photochemistry and Photobiology B: Biology* **230**, 112439 (2022).
33. Huiberts, L. M., Smolders, K. C. H. J. & de Kort, Y. A. W. Non-image forming effects of illuminance level: Exploring parallel effects on physiological arousal and task performance. *Physiology & Behavior* **164**, 129–139 (2016).
34. Killgore, W. D. S. *et al.* Blue light exposure increases functional connectivity between dorsolateral prefrontal cortex and multiple cortical regions. *NeuroReport* **33**, 236 (2022).
35. Ru, T., de Kort, Y. A. W., Smolders, K. C. H. J., Chen, Q. & Zhou, G. Non-image forming effects of illuminance and correlated color temperature of office light on alertness, mood, and performance across cognitive domains. *Building and Environment* **149**, 253–263 (2019).

36. Ru, T., Smolders, K., Chen, Q., Zhou, G. & de Kort, Y. Diurnal effects of illuminance on performance: Exploring the moderating role of cognitive domain and task difficulty. *Lighting Research & Technology* **53**, 727–747 (2021).

37. Smolders, K. C. H. J. & de Kort, Y. A. W. Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal. *Journal of Environmental Psychology* **39**, 77–91 (2014).

38. te Kulve, M., Schlangen, L. J. M., Schellen, L., Frijns, A. J. H. & van Marken Lichtenbelt, W. D. The impact of morning light intensity and environmental temperature on body temperatures and alertness. *Physiology & Behavior* **175**, 72–81 (2017).

39. van der Meijden, W. P. *et al.* Sustained effects of prior red light on pupil diameter and vigilance during subsequent darkness. *Proc. Biol. Sci.* **285**, (2018).

40. Münch, M. *et al.* Blue-Enriched Morning Light as a Countermeasure to Light at the Wrong Time: Effects on Cognition, Sleepiness, Sleep, and Circadian Phase. *NPS* **74**, 207–218 (2016).

41. Slama, H., Deliens, G., Schmitz, R., Peigneux, P. & Leproult, R. Afternoon Nap and Bright Light Exposure Improve Cognitive Flexibility Post Lunch. *PLOS ONE* **10**, e0125359 (2015).

42. Smolders, K. C. H. J. & de Kort, Y. A. W. Investigating daytime effects of correlated colour temperature on experiences, performance, and arousal. *Journal of Environmental Psychology* **50**, 80–93 (2017).

43. te Kulve, M., Schlangen, L., Schellen, L., Souman, J. L. & van Marken Lichtenbelt, W. Correlated colour temperature of morning light influences alertness and body temperature. *Physiology & Behavior* **185**, 1–13 (2018).

44. Kofler, M. J. *et al.* Reaction time variability in ADHD: A meta-analytic review of 319 studies. *Clinical Psychology Review* **33**, 795–811 (2013).

45. Rodríguez-Morilla, B., Madrid, J. A., Molina, E., Pérez-Navarro, J. & Correa, Á. Blue-Enriched Light Enhances Alertness but Impairs Accurate Performance in Evening Chronotypes Driving in the Morning. *Front. Psychol.* **9**, (2018).

46. Gibbings, A. *et al.* EEG and behavioural correlates of mild sleep deprivation and vigilance. *Clinical Neurophysiology* **132**, 45–55 (2021).

47. Gobin, C. M., Banks, J. B., Fins, A. I. & Tartar, J. L. Poor sleep quality is associated with a negative cognitive bias and decreased sustained attention. *Journal of Sleep Research* **24**, 535–542 (2015).

48. Van Dongen, H. P. A., Maislin, G., Mullington, J. M. & Dinges, D. F. The Cumulative Cost of Additional Wakefulness: Dose-Response Effects on Neurobehavioral Functions and Sleep Physiology From Chronic Sleep Restriction and Total Sleep Deprivation. *Sleep* **26**, 117–126 (2003).

49. Vgontzas, A. N. *et al.* Adverse Effects of Modest Sleep Restriction on Sleepiness, Performance, and Inflammatory Cytokines. *The Journal of Clinical Endocrinology & Metabolism* **89**, 2119–2126 (2004).

50. Faraut, B. *et al.* Daytime Exposure to Blue-Enriched Light Counters the Effects of Sleep Restriction on Cortisol, Testosterone, Alpha-Amylase and Executive Processes. *Front. Neurosci.* **13**, (2020).

51. Grant, L. K. *et al.* Supplementation of ambient lighting with a task lamp improves daytime alertness and cognitive performance in sleep-restricted individuals. *Sleep* **46**, zsad096 (2023).

52. Phipps-Nelson, J., Redman, J. R., Dijk, D.-J. & Rajaratnam, S. M. W. Daytime Exposure to Bright Light, as Compared to Dim Light, Decreases Sleepiness and Improves Psychomotor Vigilance Performance. *Sleep* **26**, 695–700 (2003).

53. Meyer, C. *et al.* Seasonality in human cognitive brain responses. *Proceedings of the National Academy of Sciences* **113**, 3066–3071 (2016).

54. Schöllhorn, I., Stefani, O., Blume, C. & Cajochen, C. Seasonal Variation in the Responsiveness of the Melanopsin System to Evening Light: Why We Should Report Season When Collecting Data in Human Sleep and Circadian Studies. *Clocks & Sleep* **5**, 651–666 (2023).

55. Spitschan, M., Mead, J. & Veitch, J. A. luox: Platform for calculating quantities related to light and lighting. (2022).

56. Loh, S., Lamond, N., Dorrian, J., Roach, G. & Dawson, D. The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behavior Research Methods, Instruments, & Computers* **36**, 339–346 (2004).

57. Psychology Software Tools, I. E-Prime 3.0. (2016).

58. Adan, A. & Almirall, H. Horne & Östberg morningness-eveningness questionnaire: A reduced scale. *Personality and Individual Differences* **12**, 241–253 (1991).

59. Adamsson, M., Laike, T. & Morita, T. Annual variation in daily light exposure and circadian change of melatonin and cortisol concentrations at a northern latitude with large seasonal differences in photoperiod length. *Journal of Physiological Anthropology* **36**, 6 (2016).

60. Buuren, S. van & Groothuis-Oudshoorn, K. mice: Multivariate Imputation by Chained Equations in R. *Journal of Statistical Software* **45**, 1–67 (2011).

R Core Team. 2024. "R: A Language and Environment for Statistical Computing." [Software]. Available from https://www.R-project.org/

62. Wickham, H. *et al.* Welcome to the Tidyverse. *Journal of Open Source Software* **4**, 1686 (2019).

63. Brooks, M., E. *et al.* glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal* **9**, 378 (2017).

64. Bates, D., Mächler, M., Bolker, B. & Walker, S. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* **67**, 1–48 (2015).

65. Kuznetsova, A., Brockhoff, P. B. & Christensen, R. H. B. lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software* **82**, 1–26 (2017).

66. Hartig, F. DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. (2022).

67. Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P. & Makowski, D. performance: An R Package for Assessment, Comparison and Testing of Statistical Models. *Journal of Open Source Software* **6**, 3139 (2021).

Lenth, Russell. 2023. "Emmeans: Estimated Marginal Means, Aka Least-Squares Means." [Software] Available from https://CRAN.R-project.org/package=emmeans.

69. Lüdecke, D. ggeffects: Tidy Data Frames of Marginal Effects from Regression Models. *Journal of Open Source Software* **3**, 772 (2018).

70. Ben-Shachar, M. S., Lüdecke, D. & Makowski, D. effectsize: Estimation of Effect Size Indices and Standardized Parameters. *Journal of Open Source Software* **5**, 2815 (2020).

71. Wagenmakers, E.-J. & Brown, S. On the linear relation between the mean and the standard deviation of a response time distribution. *Psychological Review* **114**, 830–841 (2007).

72. Hayes, A. *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach*. (The Guilford Press, New York, 2022).

73. Chellappa, S. L., Steiner, R., Oelhafen, P. & Cajochen, C. Sex differences in light sensitivity impact on brightness perception, vigilant attention and sleep in humans. *Sci Rep* **7**, 14215 (2017).

74. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*. (Routledge, New York, 1988). doi:10.4324/9780203771587.

75. Lorah, J. Effect size measures for multilevel models: definition, interpretation, and TIMSS example. *Large-scale Assessments in Education* **6**, 8 (2018).

76. Kroes, A. D. A. & Finley, J. R. Demystifying omega squared: Practical guidance for effect size in common analysis of variance designs. *Psychological Methods* (2023) doi:10.1037/met0000581.

77. Field, A. *Discovering Statistics Using IBM SPSS Statistics*. (Sage Publications Ltd (UK), London, 2013).

78. Nakagawa, S. & Schielzeth, H. A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution* **4**, 133–142 (2013).

79. Sahin, L., Wood, B. M., Plitnick, B. & Figueiro, M. G. Daytime light exposure: effects on biomarkers, measures of alertness, and performance. *Behav. Brain Res.* **274**, 176–185 (2014).

80. Leth-Steensen, C., King Elbaz, Z. & Douglas, V. I. Mean response times, variability, and skew in the responding of ADHD children: a response time distributional approach. *Acta Psychologica* **104**, 167–190 (2000).

81. MacDonald, S. W. S., Nyberg, L. & Bäckman, L. Intra-individual variability in behavior: links to brain structure, neurotransmission and neuronal activity. *Trends in Neurosciences* **29**, 474–480 (2006).

82. Whelan, R. Effective Analysis of Reaction Time Data. *The Psychological Record* **58**, 475–482 (2008).

83. Basner, M. *et al.* Repeated Administration Effects on Psychomotor Vigilance Test Performance. *Sleep* **41**, zsx187 (2018).

84. Yang, J. *et al.* The effects of ambient light on task switching depend on the chronotype. *Lighting Research & Technology* **51**, 544–556 (2019).

85. Jewett, M. E. *et al.* Time course of sleep inertia dissipation in human performance and alertness. *Journal of Sleep Research* **8**, 1–8 (1999).

86. Tassi, P. & Muzet, A. Sleep inertia. *Sleep Med Rev* **4**, 341–353 (2000).

87. Thorne, H. C., Jones, K. H., Peters, S. P., Archer, S. N. & Dijk, D.-J. Daily and Seasonal Variation in the Spectral Composition of Light Exposure in Humans. *Chronobiology International* **26**, 854–866 (2009).

88. Phillips, A. J. K. *et al.* High sensitivity and interindividual variability in the response of the human circadian system to evening light. *Proceedings of the National Academy of Sciences* **116**, 12019–12024 (2019).

89. Rushton, W. A. H. Pigments and signals in colour vision. *The Journal of Physiology* **220**, 1–31 (1972).

90. Allen, A. E., Hazelhoff, E. M., Martial, F. P., Cajochen, C. & Lucas, R. J. Exploiting metamerism to regulate the impact of a visual display on alertness and melatonin suppression independent of visual appearance. *Sleep* **41**, zsy100 (2018).

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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.

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Competing Interests

The authors declare no competing interests.