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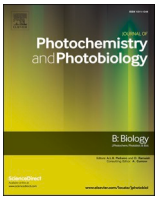

Impact of daytime spectral tuning on cognitive function

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ABSTRACT

Light at night can improve alertness and cognition. Exposure to daytime light, however, has yielded less conclusive results. In addition to direct effects, daytime light may also mitigate the impact of nocturnal light exposure on alertness. To examine the impact of daytime lighting on daytime cognitive performance, and evening alertness, we studied nine healthy individuals using a within subject crossover design. On four visits, participants were exposed to one of four lighting conditions for 10 h (dim fluorescent, room fluorescent, broad-spectrum LED, standard white LED; the latter three conditions were matched for 100 lx) followed by an exposure to bright evening light. Cognitive performance, subjective and objective measures of alertness were regularly obtained. While daytime alertness was not impacted by light exposure, the broad-spectrum LED light improved several aspects of daytime cognition. The impact of evening light on alertness was not mitigated by the pre-exposure to different daytime lighting conditions. Results suggest that daytime exposure to white light with high melanopic efficacy has the potential to improve daytime cognitive function and that such improvements are likely to be direct rather than a consequence of light-induced changes in alertness.

1. Introduction

Light has a greater impact on humans than just allowing us to perceive the world around us. There are a variety of non-image forming (NIF) impacts of light including its influence on circadian timing, hormone production, and cognition, among other aspects of physiology. Light activation of rods and cones, with projections to the visual cortex, directly influences vision [1]. There are three different subsets of cones, with heightened sensitivity to short (S-cones, $\lambda_{max} = 420$ nm), medium (M-cone, $\lambda_{max} = 530$ nm), and long (L-cone, $\lambda_{max} = 560$ nm) wavelengths of light [2]. The more newly discovered class of photoreceptors, the intrinsically photosensitive retinal ganglion cells (ipRGCs) are critical for NIF responses, such as entrainment of the biological clock to a 24-h cycle to the external light cycle [3–5], light-induced suppression of the hormone melatonin [6–8], and acute alerting effects of light [8–16]. In addition to their intrinsic light sensitivity being conveyed through expression of melanopsin ($\lambda_{max} = 479$ nm at retinal level, $\lambda_{max} = 490$ at corneal level) [2], ipRGCs also integrate light information through input from rods and cones [17], though the exact nature of this integration is not well understood.

While the ipRGC are responsible for conveying light information for a variety of NIF responses, the ipRGC themselves are a heterogeneous group of neurons with varied patterns of dendritic arborization that could differentiate integration of rod/cone signals with intrinsic melanopsin [17,18]. The implication of this heterogeneity is that responses from one NIF effect cannot be used to necessarily predict another NIF response [19]. As such, it is important to study the NIF response of interest. One well-studied NIF responses is alertness, which is a construct associated with high levels of environmental awareness and is defined as achieving and maintaining a state of high sensitivity to incoming stimuli [1]. It is usually assessed through a multi-measure approach, consisting of both subjective sleepiness questionnaires as well as objective performance measures [20]. Other NIF responses, such as cognitive function, cover a very wide range of most forms of mental abilities and can be parsed into more basic components using specific testing.

Multiple studies have investigated the effects of light intensity on alertness [8,21–25], indicating that while there is a robust increase in alertness in response to nighttime light exposure [8], daytime light exposure evokes little or no increase in alertness [20–22]. Fewer studies have examined the impact of light on cognitive functions. Improvements in specific aspects of cognition have been reported after nocturnal light exposure [26–28] and, as with alertness, minimal or no changes have

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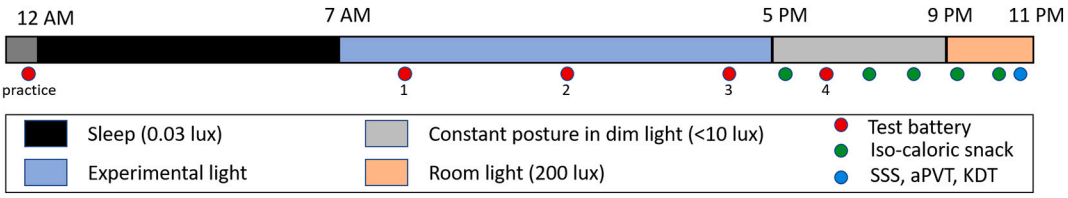

Fig. 1. In-laboratory experimental design. Example clock times are given for an individual with HSon (habitual sleep onset) of midnight; all experimental times were operationalized relative to an individual's HSon. The number below the red circles indicate test number. The final test battery consisted of the Stanford Sleepiness Scale (SSS), auditory Psychomotor Vigilance Task (aPVT), and Karolinska Drowsiness Test (KDT). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

been observed after daytime exposure [26,29]. Many of these studies, however, have not considered the very high interindividual variability in cognitive task responses and the covariance of this with time of day.

NIF responses have an unusual property in that the intensity responses tend to not be sensitive to absolute light intensity but to the intensity of light relative to that which was received during the prior hours. This relative response to light intensity has been observed in a variety of NIF responses, including alertness [30] and circadian phase shifting [31]. The time course and neural locus (e.g., retina vs. hypothalamus) of this relative response is unknown. Similarly, the contributions of the different photoreceptive systems in the adaptation of the responses to prior light exposure are not understood.

The purpose of this study was, therefore, two-fold. The first was to examine the direct responses of various cognitive functions to daytime artificial light exposure that differed in spectral composition, which could differentially impact melanopsin and cones, and intensity. We hypothesized that broad-spectrum light, encompassing a relatively greater stimulation of melanopsin, would lead to the largest improvements in daytime cognitive function. The second aim was to examine the indirect consequences of this daytime light exposure on the response to an evening light exposure. We hypothesized that exposure to broad-spectrum light during the daytime would mitigate effects of evening light exposure on alertness and cognition.

2. Materials and Methods

2.1. Ethics Statement

This study and all related procedures were reviewed and approved by the Stanford University Institutional Review Board and conform to the principles expressed in the Declaration of Helsinki. Participants provided informed consent prior to any procedures.

2.2. Participants

Nine healthy individuals (aged 18–36 years, 27.8 ± 5.06 years; 4 females) participated in a within subject experimental design, consisting of four in-laboratory sessions that were separated by at least two weeks. Participants had no active disease processes, were non-smokers, and had hearing sufficient to interact with study staff and perform auditory-based testing (see below). Participants did not have evidence of a sleep disorder (Pittsburgh Sleep Quality Index score < 5 [32], 3.00 ± 1.58) nor did they routinely take medication that could impact their sleep, including daily use of antihistamines or antidepressants. Participants did not have evidence of depression (Center for Epidemiological Studies Depression scale 24 3.00 ± 2.55 [33]) and were of intermediate chronotype (reduced Horne-Östberg questionnaire 325 19.6 ± 4.53 [34]).

2.3. Protocol

A regular at-home sleep schedule was maintained for three days prior to coming into the laboratory. Regularity was defined as keeping into and out of bed times that were 7–9 h apart and within 1 h of target into and out of bed times, selected by the participant. During this three-day at-home portion of the protocol, participants were equipped with a wrist actigraph (Actiwatch2, Philips-Respironics, Bend OR or Motionlogger, Ambulatory Monitoring, Ardsley NY) and completed daily sleep logs. The actigraph and log data were used to confirm sleep timing upon lab entrance. Participants who did not maintain the required at-home sleep schedule were rescheduled. On the day of entry, participants were asked not to take any non-steroidal anti-inflammatory medications [35] to ingest caffeine [36] to drink alcohol (Alco-Screen 02, Chematics, North Webster IN), or use any non-approved medications (IDTC-II 6 Panel, Cliawaived, Carlsbad CA).

During the 26-h in-laboratory part of the study, participants were in a time isolation suite at the VA Palo Alto Health Care System. Lighting was controlled by a technician located outside of the room. The room had an *en suite* bathroom. To minimize variance in illumination intensity, the walls of the room were coated with a highly reflective white, titanium dioxide-based paint. There were no time cues within the suite (e.g., windows, clocks, radio, internet, television). Room temperature was maintained within a normal ambient range (~ 17 °C).

Participants arrived 3 h before habitual sleep onset (HSOn), after which actigraphy was checked for regularity. Participants who's into and out of bed times deviated by more than one hour across the prior three days were not empaneled in the study. Participants performed a practice test session (see below) that was not analyzed (Fig. 1). Participants went to sleep at HSOn and after 7 h of sleep were awoken under one of four experimental light conditions: Dim, Fluorescent, Broad-Spectrum LED or Standard LED (further defined below). Sleep duration was curtailed by 1 h to induce a slight amount of homeostatic sleep pressure. For breakfast (30 min after habitual sleep offset) and lunch (4 h after habitual offset), participants could choose one out of three pre-selected items. All meals were free of alcohol, caffeine, chocolate, bananas and all three items were equicaloric. Test batteries were performed 2, 5, 8, 11, and 15.5 h after sleep offset. Between test sessions, participants could read, work or watch movies on a dimly lit (illuminance <10 lx at eye level in downward angle of gaze towards the screen) laptop screen. Exercise or napping was not allowed. Ten hours after habitual sleep offset, a constant posture protocol commenced. Participants remained in bed with the head of the bed slightly elevated (30° ± 10° per participant comfort, but constant throughout once set within the first hours of the constant posture) and in dim light (<10 lx maximal illumination in the horizontal plane). If the participant needed to urinate or defecate, they remained in bed and a urinal or bed pan was provided as appropriate. Participants received hourly isocaloric snacks and isovolumetric water rations that were calculated as replacements for the evening meal [37].After four hours of the dim light constant posture, participants remained in the constant posture protocol for an additional two hours during which the light was increased to 200 lx (defined below). Participants were discharged from the laboratory at the end of this light stimulus.

2.4. Experimental Light Specifications

All individuals were exposed to one of the four daytime lighting

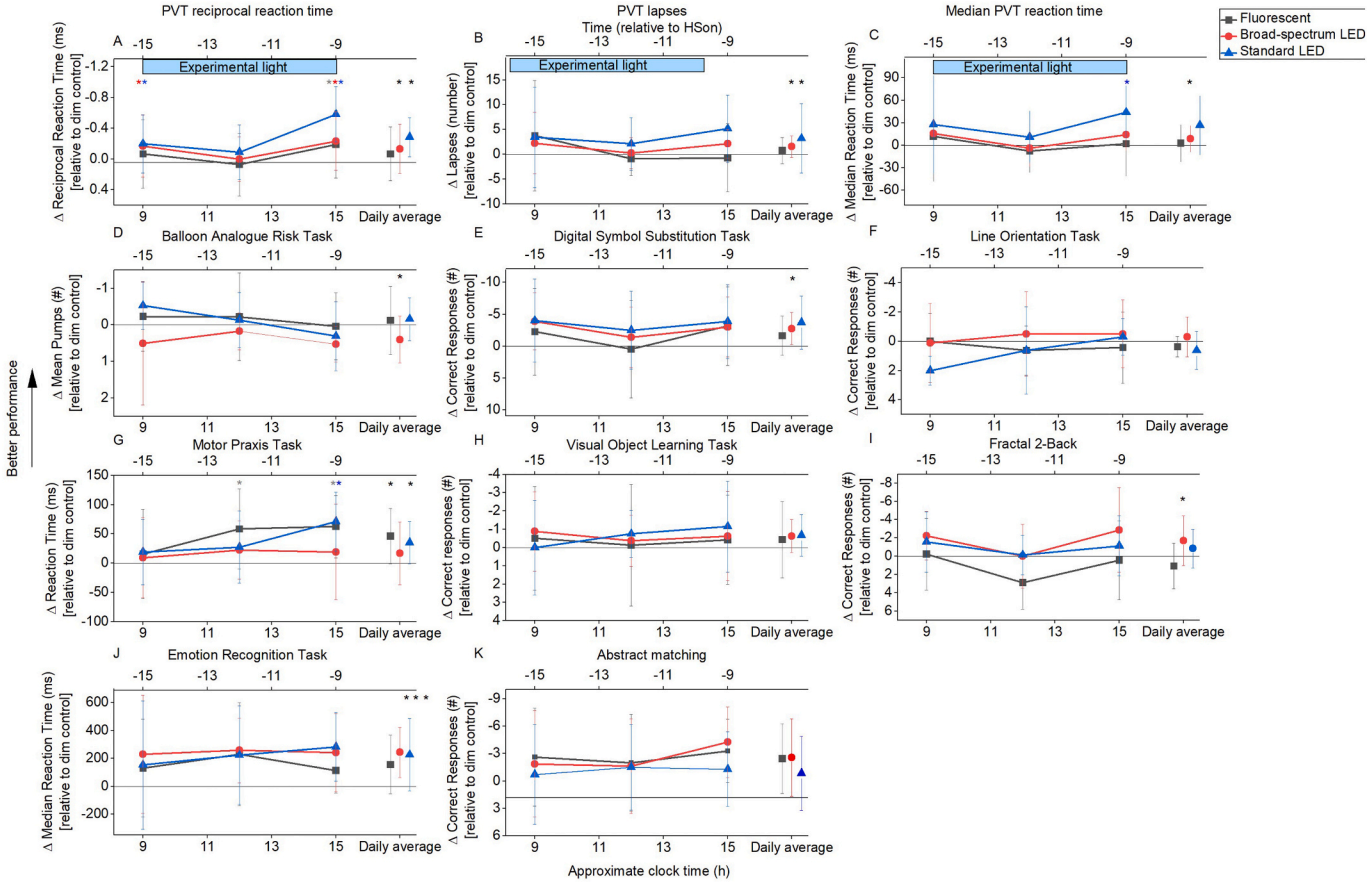

Fig. 2. Effects of light conditions on cognitive performance. Visual PVT reciprocal reaction time (A), lapses (B), and median reaction time (C) are depicted, as well as performance on the Balloon Analogue Risk Task (D), Digital Symbol Substitution Task (E), Line Orientation Task (F), Motor Praxis Task (G), Visual Object Learning Task (H), Fractal 2-Back (I), Emotion Recognition Task (J), and Abstract Matching task (K). Better performance is depicted as above y = 0 on the y-axis. All values are presented relative to dim light control; asterisks indicate $p < 0.05$ in comparison to the control condition.

conditions on each of four separate visits, the order of which was randomized prior to the onset of the experiment in a single block. Randomization was based on atmospheric noise and produced by Random.org on July 12, 2019. Daytime lighting conditions lasted for 10 h, starting at habitual wake time. The four conditions were: Dim, Fluorescent, Broad-Spectrum LED, and Standard LED. The three active conditions were each of the same photopic illuminance (100 lx, half of the fitted maximal alerting effect of light at night) and similar correlated color temperature (~4000 K) but differed in the spectral composition (Fig. S1). Dim (control) exposure was produced by overhead fluorescent lighting filtered with neutral density filters (Roscolux neutral gray, #398; Rosco, Stamford CT). The maximum illuminance in the horizontal angle of gaze in Dim was 10 lx. Fluorescent exposure was produced by an array of ceiling-mounted fluorescent lamps (Cool White, 4100 K, F32T8; Philips, Eindhoven, Netherlands) that provided uniform illuminance across the room of approximately 100 lx. Broad-spectrum LED exposure was produced by an array of ceiling-mounted white light LED strips (Seoul SunLike LED, 4000 K, BK3402; Knema, Shreveport LA) that provided uniform illuminance across the room of approximately 100 lx. Standard LED exposure was produced by a white light LED produced by a parallel array of ceiling-mounted LED strips (Nichia LED, 4000 K, BK3202; Knema, Shreveport LA) that provided uniform illuminance across the room of approximately 100 lx. Illuminance levels were checked during each change in light setting and measured in the horizontal plane at the level of the eye. The strength of the melanopic drive relative to the photopic illuminance level (efficacy of luminous radiation, ELR) as well as the Melanopic Equivalent Daylight Illuminance (m-EDI) was determined (Luox [38]) for each of the lighting conditions: Dim (ELR = 0.770, m-EDI = 2.25 lx), Fluorescent (ELR = 0.770, m-EDI = 56.2 lx), Broad-Spectrum LED (ELR = 1.06 ELR, m-EDI = 80.6 lx), and Standard LED (ELR = 0.993 ELR, m-EDI = 73.2 lx). Other photometric values and complete spectral data can be obtained at: https://doi.org/10.5287/bodleian:0ogQP5bb5.

2.5. Testing Sleepiness and Cognitive Performance

Four different tests were administered: Stanford Sleepiness Scale (SSS), a cognitive test battery, auditory sustained attention testing, and the Karolinska Drowsiness Test (KDT). The SSS assesses sleepiness using a seven-point Likert-like scale [39] with higher scores indicating greater subjective sleepiness. Cognitive testing was performed on a tablet (iPad air, model no. A2152, illuminance <10 lx at eye level in downward angle of gaze towards the screen) using a series of computer tablet-based tests [40] including the Balloon Analogue Risk Task (BART, risk taking [41]), Digital Symbol Substitution Task (DSST, visual scanning and tracking [42]), Line Orientation Task (LOT, spatial orientation [43,44]), Motor Praxis Task (MPT, sensory motor speed [45]), Visual Object Learning Task (VOLT, spatial working memory [46]), Fractal 2-Back (F2B, working memory [47]), Abstract Matching (AM, executive function flexibility [48]), Emotion Recognition Task (ERT, emotion identification [49]), and 3-min version of the Psychomotor Vigilance Test (PVT, sustained attention [50]). These tests are fully described elsewhere [40]. Data were automatically analyzed (Joggle Research, Seattle WA) and specific metrics sensitive to sleep loss were a priori selected for further analysis [41]: BART (mean number of pumps), DSST (number of correct responses), LOT (number of correct responses), MPT (median

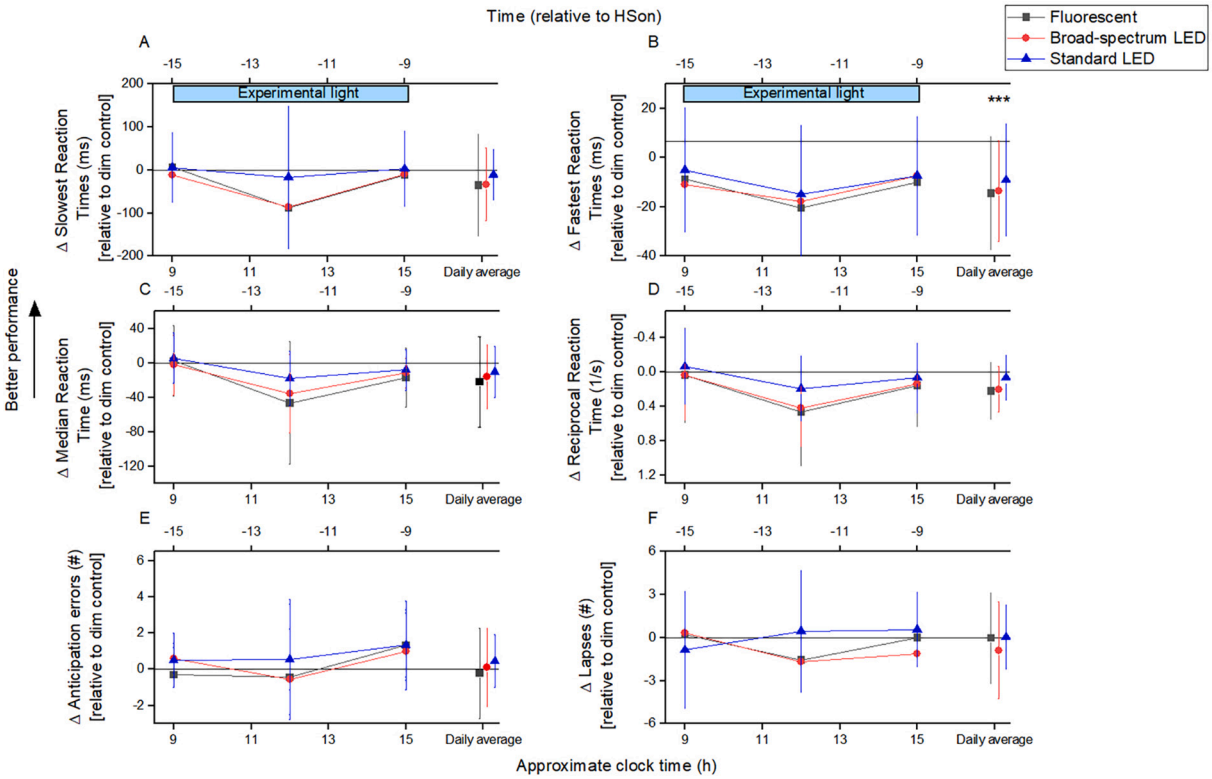

Fig. 3. Effects of light conditions on auditory Psychomotor Vigilance Task performance. Depicted are the 10% slowest (A) and fastest (B) aPVT reaction times, median reaction times (C), reciprocal reaction time (D), number of anticipation errors (E) and number of lapses (F). All values are presented relative to dim light control; asterisks indicate $p < 0.05$ in comparison to the control condition.

reaction time), VOLT (number of correct responses), F2B (number of correct responses), AM (number of correct responses), ERT (median reaction time), PVT (number of lapses, mean reciprocal reaction time, median reaction time).

Given the potential impact of light on performance of a visual-based task independent of the impact of light on attention, we administered a separate sustained attention test, a 10-min auditory version of the PVT (aPVT) [51]. In the aPVT, participants are instructed to press a button as soon as they hear a tone via a set of headphones. Tones are separated by a random interval of 1–6 s. Output metrics include median reaction time, average reaction time, 10% fastest reaction times, 10% slowest reaction times, reciprocal reaction time and number of lapses (within participant threshold set at the median reaction time + two standard deviations [52]).

The KDT is an objective measure of sleepiness. In the KDT, participants are asked to fix their attention for 5 min at a dot placed 1 m away, and then to keep their eyes closed for 2 min. Electroencephalographic (EEG) data collected from central derivations (C3 and C4; Siesta, Compumedics, Charlotte NC) were analyzed to derive spectral power. EEG data were transformed using a fast Fourier transform (FFT) with a window length of 2 s, overlap of 0%, using a Hanning window type with a maximum frequency of 50 Hz, followed by Welch averaging with a mean averaging type on 30 s for a threshold of 50%, and feature extraction on both power (absolute IU^2) and frequency (mean Hz and peak Hz). Using this method for each 30 s bin, the absolute power in the theta (4–7.5 Hz) and alpha (8–12.5 Hz) frequency bands were calculated. Only data from artifact-free periods during the 7 min of KDT were examined.

2.6. Statistics

Data were analyzed using a linear mixed model (package "lme4") [53] in R (R Core Team, 2015; version 4.0.4) using the "summary" function, with visit and test session included as factors. Tukey post-hoc analysis (with "holm" adjustment) was conducted ("glht" function in the "multcomp" R-library). Two-tailed tests with a critical *p*-value of 0.05 was maintained for all analyses. All data were analyzed at the level of the individual per test session and condition. Cohen's d was calculated by dividing the mean difference between the experimental and dim light condition by the standard deviation of that difference. Data are expressed relative to the dim light control, except for the KDT, due to incomplete EEG data. Data are presented as mean ± SD unless otherwise specified.

3. Results

3.1. Daytime Cognitive Testing

In response to the four different 10-h exposures to different daytime lighting, there were differential effects based on both the cognitive domain being tested and the type of lighting. Lighting condition had significant impacts on multiple domains of the PVT ($F_{(3,108)} > 3.03$, $p's < 0.05$), BART ($F_{(3,108)} = 4.21$, $p = 0.008$), DSST ($F_{(3,108)} = 2.44$, $p = 0.05$), MPT ($F_{(3,108)} = 4.79$, $p = 0.0037$), ERT ($F_{(3,108)} = 4.97$, $p = 0.0031$) and F2B ($F_{(3,108)} = 4.055$, $p = 0.0094$) (Fig. 2). Lighting condition did not impact performance on the LOT ($F_{(3,108)} = 0.18$, $p = 0.67$), AM ($F_{(3,108)} = 1.82$, $p = 0.15$), or VOLT ($F_{(3,108)} = 0.015$, $p = 0.97$) (Fig. 2).

Specifically, as compared to the dim light control condition, exposure to Broad-Spectrum LED lead to faster reciprocal response speeds on the PVT ($t(90.75) = 4.32$, $p < 0.0001$; Fig. 2A) and fewer PVT lapses ($t(92.15) = -2.75$, $p = 0.0072$; Fig. 2B), fewer pumps (less risk taking) on the BART ($t(91.11) = -3.31$, $p < 0.001$; Fig. 2D), more correct responses on the DSST ($t(90.19) = 2.41$, $p = 0.02$; Fig. 2E), more correct responses on the F2B ($t(87.91) = 2.15$, $p = 0.034$; Fig. 2I), and faster reaction times on the ERT (($t(91.79) = -2.84$, $p = 0.0055$; Fig. 2J). The impact of the Broad-Spectrum LED exposure on DSST (d = 1.17) and ERT (d = 1.21)

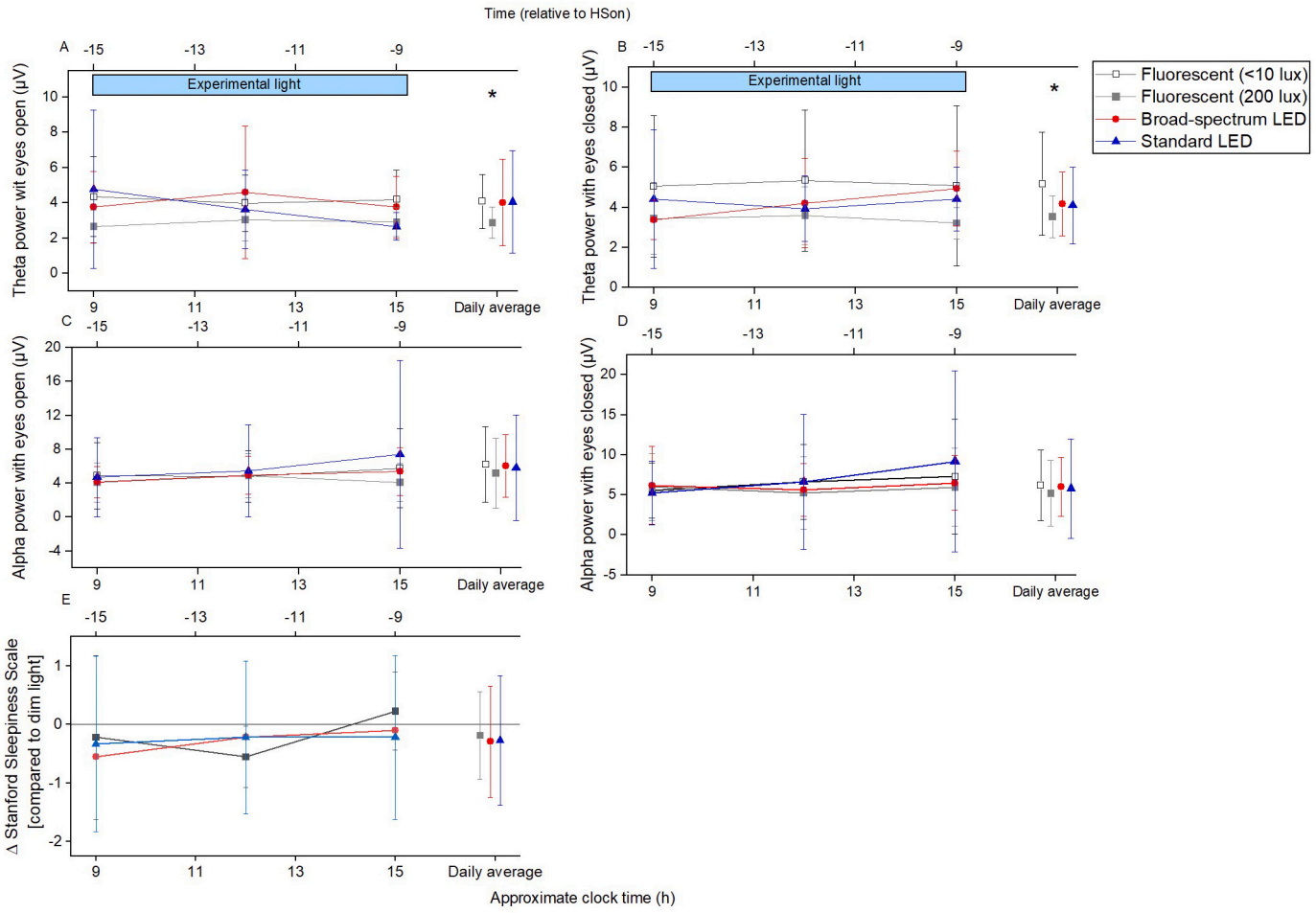

Fig. 4. Effects of light conditions on daytime sleepiness. Depicted are theta power with eyes open (A) and closed (B), alpha power with eyes open (C) and closed (D) as well as subjective sleepiness rated in the Stanford Sleepiness Scale (E). Due to incomplete EEG data, $n = 6$ at 15:00 (approximate clock time), Subjective sleepiness values are presented relative to dim light control. Asterisks indicate $p < 0.05$ in comparison to the control condition.

was both consistent and of large effect size, while it was consistent and of medium effect size on the F2B (d = 0.54) and BART (d = 0.49) (Fig. S2). The impact of the Broad-Spectrum LED exposure on the PVT reciprocal response speeds (d = 0.18) and lapses (d = 0.34) were both of small effect size and inconsistent among participants (Fig. S2).

As compared to the dim light control, exposure to Standard LED was associated with faster response speeds on the PVT ($t(91.88) = 4.67$, $p < 0.0001$, Fig. 2A), fewer PVT lapses ($t(94.41) = -2.57$, $p = 0.011$, Fig. 2B), faster median PVT reaction time ($t(92.60) = -3.65$, $p < 0.00043$, Fig. 2C), faster response speed on the MPT ($t(95.39) = -1.98$, $p = 0.0037$; Fig. 2G), and faster response speed on the ERT ($t(94.79) = -3.69$, $p < 0.00039$; Fig. 2J). The impact of the Standard LED exposure on the MPT (d = 0.81) and ERT (d = 0.72) were both consistent and of large effect size (Fig. S3). The impact of the Standard LED exposure on PVT (d's < 0.41) and BART (d = 0.30) were both of small effect size and inconsistent among participants (Fig. S3).

As compared to the dim light control, exposure to Fluorescent was associated with faster response speed on the MPT ($t(93.77) = -3.37$, $p = 0.0011$; Fig. 2G) and ERT (t(92.90) = −2.89, $p = 0.0048$; Fig. 2J). The impact of Fluorescent exposure on MPT (d = 0.78) and ERT (d = 0.59) were of medium effect size and mixed consistency (Fig. S4).

To examine whether changes in daytime cognitive performance were associated with change in (visual) sustained attention, we examined the correlation between the change in median reaction time on the PVT (as compared with the dim light control) to the change in the various measures of cognition. Linear mixed models indicated, however, that there were no significant correlations under any of the three lighting conditions (Table S1).

In contrast to the findings of the visual response elicited PVT, the auditory response elicited PVT exhibited fewer differences in response to the lighting conditions. Experimental light exposure only impacted the 10% fastest reaction times ($F_{(1,\ 108)} = 4.71$, $p = 0.0041$), with worse performance under Fluorescent ($t(94.00) = -3.27$, $p < 0.01$), Broad-Spectrum LED ($t(94.00) = -3.01$, $p < 0.01$), and Standard LED ($t(94.00) = -2.24$, $p < 0.01$) (Fig. 3B). Lighting condition did not impact the 10% slowest aPVT reaction times ($F_{(1,\ 108)} = 1.54$, $p = 0.21$, Fig. 3A), median reaction time ($F_{(1,\ 108)} = 1.54$, $p = 0.088$, Fig. 3C), reciprocal reaction time ($F_{(1,\ 108)} = 1.08$, $p = 0.32$, Fig. 3D), number of anticipation errors ($F_{(1,\ 108)} = 0.77$, $p = 0.51$, Fig. 3E), or number of lapses ($F_{(1,\ 108)} = 0.82$, $p = 0.47$, Fig. 3F).

3.2. Daytime Sleepiness

In response to the four different 10-h exposures to different daytime lighting, there was a limited impact on objective measures of alertness. Power in the theta band with both eyes open ($F_{(3,112)} = 2.73$, $p = 0.05$) and eyes closed ($F_{(3,112)} = 3.50$, $p = 0.02$) was impacted by light exposure, with lower theta power being observed during exposure to Fluorescent (eyes open: $t(88.03) = -2.80$, $p = 0.0062$; eyes closed: $t(96.77) = -2.005$, $p = 0.00215$; Fig. 4A/B). There was no impact of daytime light exposure on alpha power with eyes open ($F_{(3,112)} = 2.71$, $p = 0.06$) nor with eyes closed ($F_{(3,112)} = 0.76$, $p = 0.51$) (Fig. 4C/D).

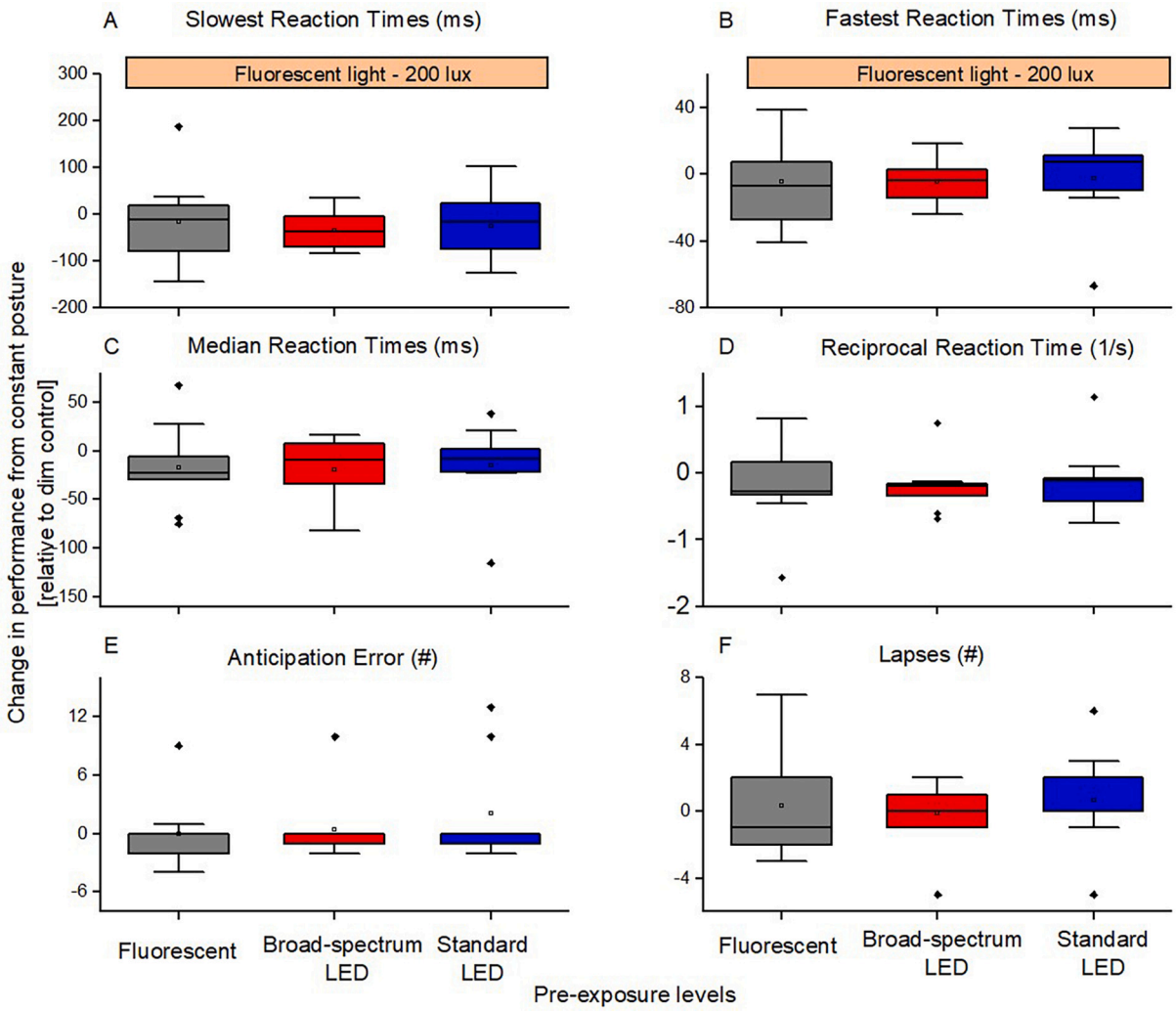

Fig. 5. Effects of evening light exposure on performance. Overview of 10% slowest (A) and fastest (B) PVT reaction times, median reaction time (C), reciprocal reaction time (D), number of anticipation errors (E) and number of lapses (F). Values are expressed as change from to constant posture (test session 4) and expressed relative to the dim light control.

In response to the four different 12-h exposures to different daytime lighting, there were no differential responses in subjective sleepiness (SSS) during the daytime ($F_{(1,\ 108)} = 0.78$, $p = 0.83$, Fig. 4E).

3.3. Response to Evening Light Exposure

Changes in objective auditory PVT performance in response to evening light exposure did not differentiate based on pre-exposure to the four different daytime lighting conditions (Fig. 4): 10% slowest reaction time ($F_{(3,36)} = 0.54$, $p = 0.67$; Fig. 5A), 10% fastest reaction times ($F_{(3,36)} = 0.14$, $p = 0.93$; Fig. 5B), median reaction times ($F_{(3,36)} = 0.88$, $p = 0.47$; Fig. 5C), reciprocal reaction time ($F_{(3,36)} = 0.46$, $p = 0.71$; Fig. 5D), number of anticipation errors ($F_{(3,36)} = 1.15$, $p = 0.36$; Fig. 5E) and lapses ($F_{(3,36)} = 0.27$, $p = 0.85$; Fig. 5F).

Similarly, in response to evening light exposure, the pattern of EEG activity did not systematically vary based on daytime light exposure, as measured in the theta band during eyes open ($F_{(3,28)} = 1.14$, $p = 0.35$, Fig. 6A) and eyes closed ($F_{(3,28)} = 0.33$, $p = 0.79$, Fig. 6B), alpha band with eyes open ($F_{(3,28)} = 1.06$, $p = 0.39$, Fig. 6C) and closed ($F_{(3,28)} = 0.67$, $p = 0.58$, Fig. 6D). Subjective sleepiness scores in response to the evening light also did not vary in response according to daytime light exposure patterns ($F_{(3,36)} = 1.49$, $p = 0.24$, Fig. 6E).

4. Discussion

Exposure to four different lighting regimens – dim fluorescent lighting (control), standard fluorescent lighting, standard LED lighting, and broad-spectrum LED lighting – during the daytime leads to differential impacts on daytime cognitive function but does not differentially mitigate the impact of room light in the evening on sustained attention, subjective alertness, or EEG correlates of alertness. More specifically, exposure to a broad-spectrum LED light during the daytime lead to a reduction in risk taking behavior (BART), improvement in working memory (F2B), improvement in visual scanning and tracking (DSST), faster emotion recognition (ERT) and an improvement in vigilant attention (PVT). Exposure to an equiluminant narrower spectrum LED led to improvements only in vigilant attention (PVT), emotion recognition speed (ERT) and sensory motor speed (MPT), while exposure to an equiluminant fluorescent light led to improvements only in emotion recognition (ERT) and sensory motor speed (MPT). Under none of the lighting conditions did spatial orientation (LOT), executive function flexibility (AM), or spatial working memory (VOLT) improve. Therefore, light of the same consciously perceivable intensity (identical lux) and color temperature, but with different spectral compositions and melanopic drive, can differentially impact daytime cognitive performance, without significantly mitigating light effects on nighttime sustained attention or alertness. It should be noted that the impact of the high

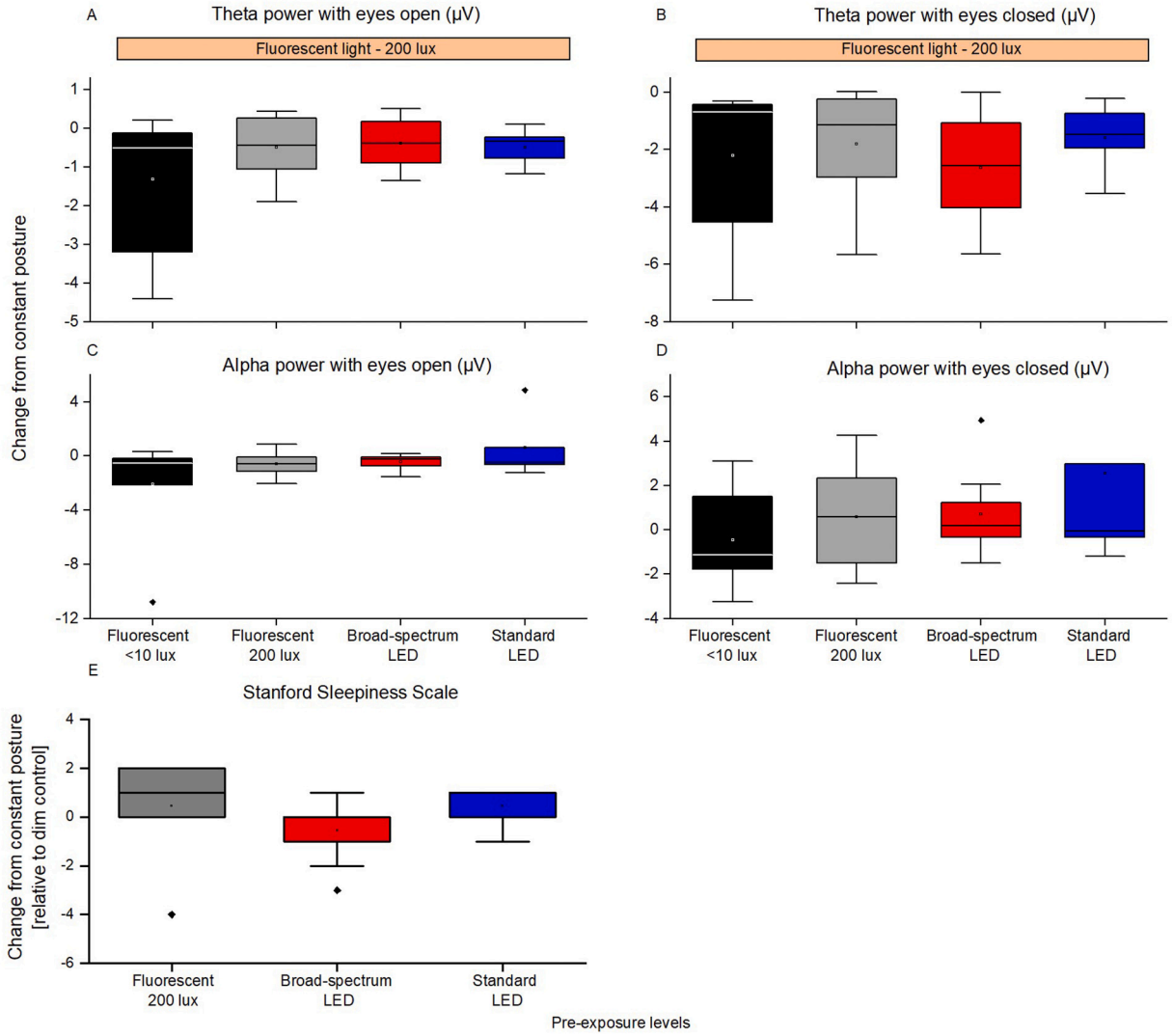

Fig. 6. Effects of evening light exposure on sleepiness. Overview of theta power with eyes open (A) and closed (B), alpha power with eyes open (A) and closed (B) as well as subjective sleepiness scores (E). Values are expressed as change from constant posture (test session 4). Subjective sleepiness scores are expressed relative to the dim light control.

melanopic (broad spectrum) LED on visual scanning and tracking, working memory, emotion recognition, and risk taking was both consistent among the participants and from medium to very large effect sizes, indicating that, unlike the observed changes in daytime alertness, these evoked changes can be considered robust.

While the direct impact of light on the conduct of some of these specific cognitive tasks have not been previously assessed, the impact of light intensity on working memory tasks (2-Back) has been assessed before with results showing either no effects [29,54,55] or positive effects during blue light exposure [54,56–58]. Performance on other working memory tasks (addition task) have been positively influenced by daytime exposure to high melanopic lighting as well [59]. Positive effects of blue-shifted white light during nighttime (independent of subjective sleepiness performance) on visual scanning and tracking (DSST) have been reported as well [27,28]. While we are not aware of other studies investigating light effects on emotion recognition (ERT), some studies have reported negative [60,61] or an absence of light effects [61,62] on other emotion recognition tasks. In prior studies, neither increased light intensity [63] nor blue light exposure [64] significantly altered risk taking (BART) behavior. One of the critical elements in our study design that may have allowed us to detect a robust impact of light on specific aspects of cognition [65] is that we controlled for the covariation of interindividual [66] and diurnal variations [67] in alertness and performance by comparing each test with a similarly timed test under conditions of dim light.

Though each of the three room lighting conditions was matched for photopic illuminance (100 lx), they varied significantly on melanopic ELR, with the standard LED (+29%) and the broad-spectrum LED (+37%) having greater drive on the melanopic system as compared to the equiluminant fluorescent lighting condition. Activation of melanopsin has been directly implicated in many non-imaging forming functions, including increasing alertness [10] Our data are, therefore, consistent with the prior literature indicating the potential involvement of the melanopsin system in driving our observed improvements in daytime cognitive performance. We did not, however, have the statistical power to directly test whether the broad-spectrum LED was superior to the standard LED or fluorescent light and, therefore, whether variation in melanopsin stimulation was the driver of the observed effects.

It should be noted, however, that we did not observe improvements in vigilant attention when it was tested using an auditory version of the PVT. As the three active lighting conditions were all matched for photopic illuminance, which measures the impact of light on image-forming visual functions within the central retina, they should have

had similar impacts on a participant's ability to see the screen (e.g., contrast, glare) in the standard PVT. Thus, if there were a non-specific impact due to visualizing the screen, this should be similar in the three active lighting conditions, which was not the case. While matched for photopic efficiency, there were differences in the spectral power distribution that could have led to differences in perception of the visual stimulus in the two LED conditions (e.g., the S-cone efficacy of luminous radiation was twice as high in the two LED conditions as compared to the Fluorescent condition), though this was not directly tested. It is possible that the visual PVT was able to detect more subtle effects on vigilant attention than the auditory PVT [68], SSS, or KDT, none of which indicated a consistent improvement in daytime alertness. Nevertheless, the impact of daytime light exposure on cognitive performance might be independent of its impact on alertness. Indeed, we found no association between PVT-measured changes in alertness and any of the improvements in cognitive function. Other studies, investigating effects of light of similar spectral distributions and intensities, also did not report any effects on auditory sustained attention, or subjective alertness [29,55]. Given the current data, the most parsimonious explanation is that daytime light exposure can improve specific domains of cognitive function not by increasing alertness, which is the proposed mechanism by which light improves nighttime cognitive performance, but by directly increasing performance through its impact on non-hypothalamic targets of the ipRGC that may either be involved in the visual processing of the task (e.g., ventral and dorsal lateral geniculate nucleus) or in the response to the task itself (e.g., lateral and *peri* habenular nuclei for the BART and ERT). We cannot, however, exclude the possibility that performance on different tests was not due to a direct impact of light on specific cognitive circuits, but was due secondarily to differential effects of the light sources on color perception, visual acuity, or other aspects of image perception.

Contrary to our a priori hypothesis, the different daytime lighting conditions did not change the impact of evening light exposure on sustained attention, brain activity and subjective alertness. These results are somewhat surprising, as previous studies have reported effects of daytime light exposure on nighttime subjective alertness scores [69]. It is possible however, that the illuminance of our test light (200 lx) was sufficiently bright to override desensitization effects of daytime light exposure. Other studies have shown that light 10-fold dimmer than what was used in our experiment can increase nighttime alertness under dimly light conditions [69]. It is possible, therefore, that differential sensitization with daytime light patterns could have been realized under dimmer lighting condition, including those common during the evening in many Western households (~80 lx) [70].

5. Conclusion

While fluorescent lighting during the daytime had a minimal impact on cognitive function, broad-spectrum LED lighting with an elevated melanopic efficacy can improve functioning in specific cognitive domains, likely independent of its impact on alertness. This daytime light exposure, however, was unable to mitigate the alerting impacts of a relatively bright (200 lx) evening light exposure. Further research is necessary to determine whether such daytime lighting could impact less bright evening light exposure that is more ecologically relevant and to determine the specific aspects of daytime cognitive function that are directly impacted by activation of melanopsin. The data are, however, consistent with the use of high melanopic efficacy LED lighting for the purpose of improving daytime cognitive function in individuals who are not particularly sleep deprived.

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Data availability

All original data, r-codes and origin files are available upon request. Light data are available at: https://doi.org/10.5287/bodleian:0ogQP5bb5.

Declaration of Competing Interest

The author(s) declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jphotobiol.2022.112439.

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