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Original Article

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Supplementation of ambient lighting with a task lamp improves daytime alertness and cognitive performance in sleep-restricted individuals

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Abstract

Study Objectives: We examined the impact of adding a single-high-melanopic-illuminance task lamp in an otherwise low-melanopic-illuminance environment on alertness, neurobehavioral performance, learning, and mood during an 8-h simulated workday.

Methods: Sixteen healthy young adults [mean(±SD) age = 24.2 ± 2.9, 8F] participated in a 3-day inpatient study with two 8-h simulated workdays and were randomized to either ambient fluorescent room light (~30 melanopic EDI lux, 50 lux), or room light supplemented with a light emitting diode task lamp (~250 melanopic EDI lux, 210 lux) in a cross-over design. Alertness, mood, and cognitive performance were assessed throughout the light exposure and compared between conditions using linear mixed models.

Results: The primary outcome measure of percentage correct responses on the addition task was significantly improved relative to baseline in the supplemented condition (3.15% ± 1.18%), compared to the ambient conditions (0.93% ± 1.1%; FDR-adj $q = 0.005$). Additionally, reaction time and attentional failures on the psychomotor vigilance tasks were significantly improved with exposure to supplemented compared to ambient lighting (all, FDR-adj $q \leq 0.030$). Furthermore, subjective measures of sleepiness, alertness, happiness, health, mood, and motivation were also significantly better in the supplemented, compared to ambient conditions (all, FDR-adj $q \leq 0.036$). There was no difference in mood disturbance, affect, declarative memory, or motor learning between the conditions (all, FDR-adj $q \geq 0.308$).

Conclusions: Our results show that supplementing ambient lighting with a high-melanopic-illuminance task lamp can improve daytime alertness and cognition. Therefore, high-melanopic-illuminance task lighting may be effective when incorporated into existing suboptimal lighting environments.

Clinical trials: NCT04745312. Effect of Lighting Supplementation on Daytime Cognition. https://clinicaltrials.gov/ct2/show/NCT04745312

Key words: light; melanopsin; cognition; melanopic illuminance; blue light

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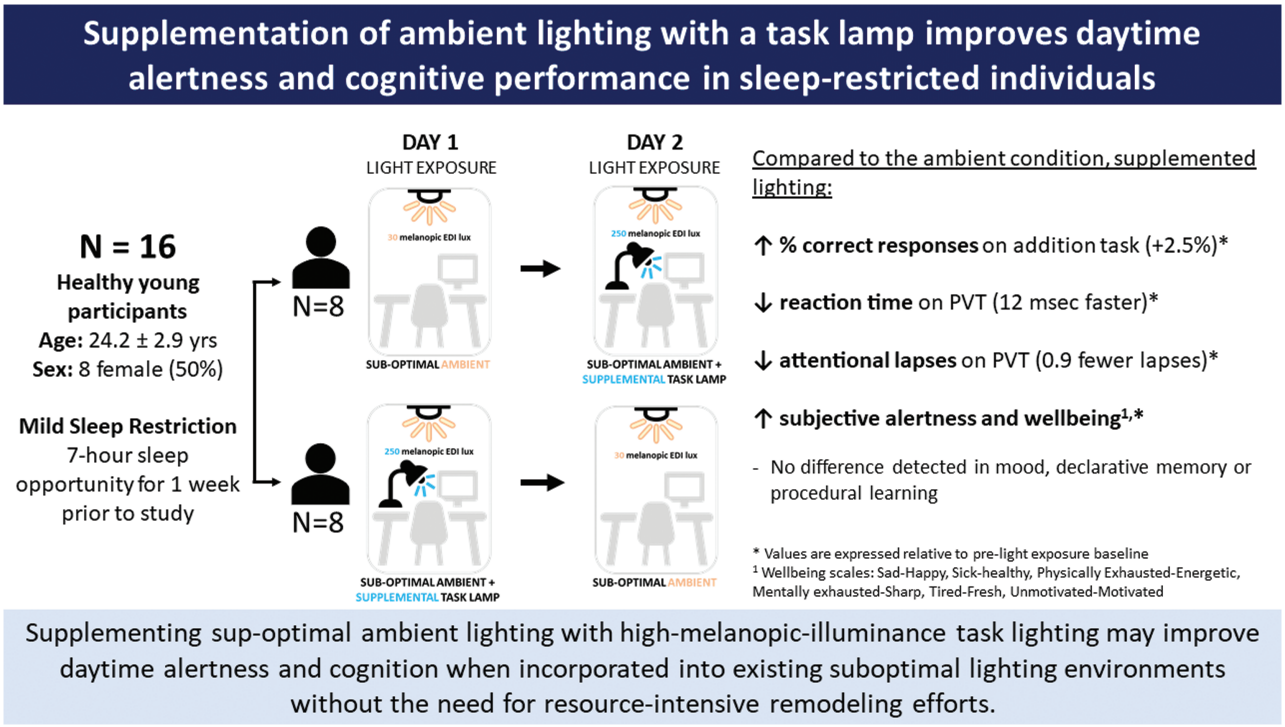
Graphical Abstract



Statement of Significance

Task lighting has the potential to supplement suboptimal ambient lighting to improve alertness and performance. We found that the addition of a high-melanopic-illuminance task lamp on the work surface significantly improved daytime alertness and multiple domains of cognition during a simulated 8-h workday. As both light spectrum and illuminance were changed, the relative contribution of these factors to the improvements observed requires further investigation. Our results show that a single-task lamp may be effective in supplementing suboptimal ambient lighting to improve alertness and cognitive performance during the day.

Introduction

One of the characteristic non-visual responses to light is the direct alerting effect observable both during the daytime and at night [1, 2]. Several key properties of the light stimulus determine the magnitude of the physiologic responses, including the timing and duration of exposure, illuminance level, and spectral characteristics. Typically, higher illuminance and short-wavelength (blue) enriched light elicits greater physiological responses than dimmer and blue-depleted light [1–9].

The preferential sensitivity of non-visual responses to short-wavelength light [10] is due to intrinsically photosensitive retinal ganglion cells (ipRGCs), which are most sensitive to the short-wavelength portion of the visible spectrum (~480 nm peak sensitivity [11]). Although rods and cones can contribute to non-visual responses to light, the ipRGCs are the principal photoreceptors mediating non-visual responses over long-duration exposures (>3 h) [12–20], such as the course of a workday. Specifically, the strength of a given light stimulus to promote ipRGC activation modeled as melanopic illuminance, correlates well with the magnitude of non-visual response [12, 17–19]. Therefore, enhancement of lighting sub-optimal for non-visual responses could be achieved by increasing its melanopic illuminance.

While several studies have now reported that short-wavelength enriched ambient lighting (i.e. high-melanopic-illuminance) improves alertness and neurobehavioral performance [3, 5, 21–25], there is limited evidence that supplementing sub-optimal (i.e. low-melanopic illuminance) ambient room lighting with task lighting can improve neurobehavioral performance. If effective, however, improvement of non-visual alerting effects using supplemental high-melanopic-illuminance task lighting may facilitate incorporating such an intervention readily into existing lighting environments without the need for resource-intensive remodeling efforts. Therefore, in the current study, we examined whether the addition of a single high-melanopic-illuminance task light as a point source on the work surface can improve alertness, neurobehavioral performance, learning, and mood during an 8-h simulated workday.

Method

Participants

Sixteen participants (mean ± SD age = 24.2 ± 2.9 years; range 18–30 years; 8 females) were studied in the Intensive Physiological Monitoring (IPM) Unit in the Center for Clinical Investigation at Brigham and Women's Hospital. Of the eight women, one was

studied in the luteal phase of the menstrual cycle, and seven were studied while using a form of contraception (two hormonal IUD, one non-hormonal IUD, two oral contraception, one vaginal ring, and one implant). The study was approved by the Mass General Brigham Human Research Committee, and participants provided written informed consent prior to study.

Based on screening questionnaires, all participants were free from medical and psychological conditions and had a negative Ishihara color blindness test. For 1 week prior to entering the unit, participants maintained a self-selected, constant 7-h sleep/dark schedule which was confirmed with (1) calls to a time- and date-stamped voicemail at bedtime and wake time, and (2) wrist-worn actigraphy (Actiwatch, MiniMitter Company, Inc., Sunriver, OR). Participants were asked to refrain from the use of any prescription or nonprescription medications, supplements, recreational drugs, caffeine, alcohol, or nicotine. Compliance was verified by urine toxicology upon entry to the unit.

Protocol

The participants were studied in a 3-day inpatient protocol with 8-h daytime experimental light-exposures on days 2 and 3 of the study (Figure 1). The light exposure order was counter-balanced and block randomized by sex. The studies were conducted in an environment free of time cues (no access to windows, clocks, watches, live TV, radio, internet, computers, telephones, and newspapers) and continually supervised by staff trained not to reveal information about the time of day.

Participants were admitted to the IPM Unit approximately 6 h prior to their self-selected habitual bedtime. A 7-h sleep episode was scheduled according to the centered average of daily sleep reported in the week prior to admission. Participants began a constant posture starting 25 min after waking on day 2, which was maintained until the end of the experimental light exposure. The 8-h experimental light exposure began 2 h after wake. Participants received 10-min bathroom breaks every ~2 h. After the first experimental light exposure, participants were ambulatory until their 7-h scheduled sleep opportunity. Day 3 was identical to day 2: participants underwent a second 8-h experimental light exposure in constant posture. After this second experimental light exposure, participants were discharged from the unit.

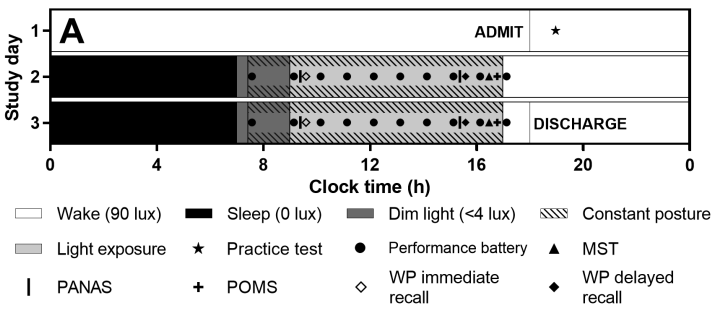
Baseline lighting

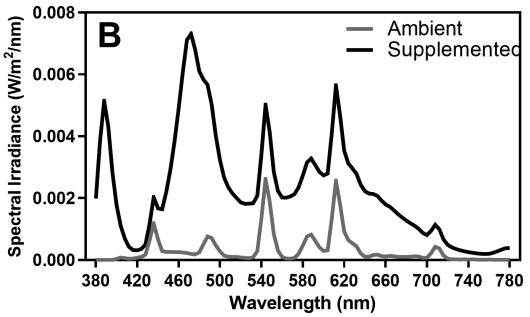
On day 1 (admission) the light intensity was approximately 23 μW/cm^2 (~55 melEDI lux, ~89 lux) at 137 cm from the floor in the vertical plane and had a maximum of 48 μW/cm^2 (~93 melEDI lux, ~150 lux) at 187 cm from the floor in the horizontal plane anywhere in the room.

Immediately at waking on day 2, the light intensity was approximately 0.87 μW/cm^2 (~2.2 melEDI lux, ~3.3 lux) at 137 cm from the floor in the vertical plane and had a maximum of 4.8 μW/cm^2 (~9.9 melEDI lux, ~15 lux) at 187 cm from the floor in the horizontal plane anywhere in the room. Following the experimental light exposure (see below), the maximum light level was returned to 23 μW/cm^2 (~55 melEDI lux, ~89 lux) at 137 cm from the floor in the vertical plane and had a maximum of 48 μW/cm^2 (~93 melEDI lux, ~150 lux) at 187 cm from the floor in the horizontal plane anywhere in the room until scheduled sleep. The ambient lighting was identical for day 3.

Experimental light exposure conditions

During the experimental light exposure, participants were exposed to either ambient fluorescent room lighting ("Ambient"), or ambient fluorescent room lighting supplemented with a high-melanopic illuminance light emitting diode (LED) task lamp ("Supplemented"). The illuminance in the ambient conditions was set to achieve an exposure of ~30 melanopic EDI lux (~50 photopic lux; measured mean [± SD] illuminance during the start and end of the light exposure were 47.29 ± 3.33 and 46.5 ± 2.9 lux, respectively) at the eye in the vertical plane 112 cm from the ground, whereas in the supplemented condition, the ambient room lighting was supplemented with the task lamp to achieve an exposure of ~250 melanopic EDI lux (~210 photopic lux [26]; measured mean [± SD] illuminance during the start and end of the light exposure were 217.38 ± 21.95 and 207.85 ± 12.48 lux, respectively) at the eye in the vertical plane 112 cm from the ground. The lighting levels for the ambient and supplemented





C

Lighting condition	Radiometric and photometric values (380-780 inclusive)		Retinal photopigment weighted Illuminances (α-opic EDI lux)					DER
	Irradiance μW/cm²	Photopic Illuminance lux	S Cone	Melanopsin	Rod	M Cone	L Cone	Melanopsin
Ambient	16.18	52.47	29.78	30.40	34.08	44.76	52.81	0.58
Supplemented	92.50	211.61	211.68	250.80	233.81	213.26	218.34	1.19

Figure 1. Study protocol and the spectral characteristics of the lighting sources. Three-day inpatient protocol and testing schedule (A). Spectrum of the ambient (grey) and supplemented (black) lighting conditions (B). Table reporting CIE values (CIE S 026 α-opic toolbox—v1.049a—2020/11) for both light sources (C). Spectral measurements were taken in the vertical plane at a height of 112cm.DER = daylight (D65) efficacy ratio; EDI = equivalent daylight (D65) illuminance; MST = motor sequence task; PANAS = positive and negative affect schedule; POMS = profile of mood states; WP = word pairs.

conditions were chosen to be consistent with minimum recommendations for vertical illuminance in office and classroom spaces [27] and daytime lighting to support physiology, sleep, and wakefulness in healthy adults [26]. The position of the task lamp in the supplemented condition (i.e. left or right side of the desk) was randomized and the lamp remained on the desk during both the ambient (switched off) and supplemented (switched on) conditions. Constant posture throughout the experimental lighting was maintained to ensure a constant level of light exposure at the eye throughout the 8 h.

The light for the ambient condition and for the non-experimental lighting described above was generated using ceiling-mounted 4100K fluorescent lamps (F96T12/41U/HO/EW, 95W; F32T8/ADV841/A, 32W; F25T8/TL841, 25W; Philips Lighting, The Netherlands) with digital ballasts (Hi-Lume 1% and Eco-10 ballasts, Lutron Electronics Co., Inc., Coopersburg, PA) transmitted through a UV-stable filter (Lexan 9030 with prismatic lens, GE Plastics, Pittsfield, MA). The task lamp used in the supplemented condition was provided by Biological Innovation and Optimization Systems, LLC (Carlsbad, CA). The spectral profiles, CIE α-opic equivalent daylight (D65) illuminance (EDI), and melanopic daylight (D65) efficacy ratio (DER) (CIE, 2020) for the two lighting conditions are shown in Figure 1. Spectral measurements were conducted using a PR-650 SpectraScan Colorimeter with CR-650 cosine receptor (Photo Research Inc., Chatsworth, CA).

Sleepiness, Performance, and Learning Assessments

The Performance Battery (black symbols; Figure 1A), which included the 10-min Psychomotor Vigilance Task (PVT [28]), 2-min Addition Task [29], Karolinska Sleepiness Scale (KSS [30]), and Visual Analog Scales (VAS [29]), was administered once under dim light conditions (baseline) and then hourly throughout the light exposure. The battery assessed sustained attention (PVT), working memory and processing speed (addition task), subjective sleepiness (KSS), and alertness, health and well-being (VAS), including scales for sleep-alert, calm-stressed, sad-happy, healthy-sick, energetic-physically exhausted, mentally exhausted-sharp, tired-fresh and motivated-unmotivated. A brief practice session to familiarize participants with the battery was administered at admit (Figure 1A). The performance battery has been described in detail elsewhere [22].

The learning and memory tasks (green symbols, Figure 1A) included the motor sequence task (MST [31]) and word pairs (WP [32]) tasks to assess procedural learning and declarative memory, respectively. There were two versions of each task which participants were randomly assigned on each study day. For the MST, the main outcome measures were improvements in performance speed, which was calculated as the percentage change in the number of correct sequences between the first trial and the average of the last three trials (trials 10, 11, and 12). For the WP task, the main outcome measures were the percentage of words recalled correctly during the immediate and delayed recall sessions relative to the total number of correct word pairs in the final learning round. Descriptions of the MST and WP tasks have been reported previously [22].

Mood, affect, and mood disturbance

Mood was measured using a VAS administered as part of the performance battery described above. Affect (purple symbols, Figure 1A) was assessed using the positive and negative affect schedule (PANAS [33]) and the mood disturbance was assessed using the profile of mood states (POMS [34]). The PANAS is a 20-item questionnaire that consists of 10-word scales to measure positive and negative affect. Each word, which describes a feeling or emotion (e.g. excited, nervous, interested, afraid) was rated on a 5-point scale from 1—"Very slightly/Not at all" to 5—"Extremely." The score for the positive and negative scales were calculated by summing the 10 items including the positive and negative scales, respectively. The POMS is a 65-item questionnaire that asks participants to rate items to best describe how they currently feel. The items, which are words that describe emotions and feelings, are rated on a 5-point scale from 0—"Not at all" to 4—"Extremely." The outcome measure for the POMS was the total mood disturbance score.

Headache and Eye Strain Scale

The headache and eye strain scale [35] is an 8-item questionnaire assessing irritability, headache, eye strain, eye discomfort, eye fatigue, difficulty focusing, difficulty concentrating, and blurred vision. Each of the items is rated from 0—"absent" to 3—"severe."

Data analysis

Time-series data from the hourly performance battery (i.e. ADD, KSS, PVT, and VAS) were expressed relative to the pre-LE baseline test performed on each study day prior to statistical testing. PVT data from one individual (4140V) during their supplemented condition was not included in the analysis due to missing baseline PVT data on that day caused by equipment malfunction. For the MST analysis, outliers, defined as data points that were located more than ±1.5 times the interquartile range [36] were removed from the analysis [22], resulting in a final sample size of 14 (removed 4163V, 4101V) for the Ambient condition and 13 for the supplemented (removed 4144V, 4145V, 4168V) condition. For analysis of the word pairs task, two female participants who did not meet criterion (e.g. 18 of 36 words learned) by the end of the five trials were removed from the analysis (4132V1T2; 4134V).

The effect of lighting conditions on the performance, mood, and learning/memory outcomes was examined using linear mixed models with participant-level random effects. Normal distribution of residuals was verified by visual inspection of Q–Q plots. For tests repeated longitudinally during the light exposure (i.e. ADD, KSS, PVT, VAS, PANAS), the effect of time on light exposure and the interaction between lighting condition and time was also examined. Similarly, for the MST, secondary analyses were conducted to examine the effect of trial number, and the interaction between lighting conditions and trial within each MST session. Covariates that were adjusted for in all models included order of condition and study day. *P*-values for the main effect of lighting conditions were subjected to false discovery rate adjustment. Effect size was estimated using Cohen's *D* calculated from arithmetic means and pooled standard deviations.

The number of participants reporting moderate or severe symptoms on the Headache and Eye Strain Scale were compared between the lighting conditions using a binomial test. The results of this analysis are reported in Supplemental Material.

Results

Working Memory and Neurobehavioral Performance

Indicators of working memory were better under supplemented compared to ambient lighting conditions. Relative to baseline in

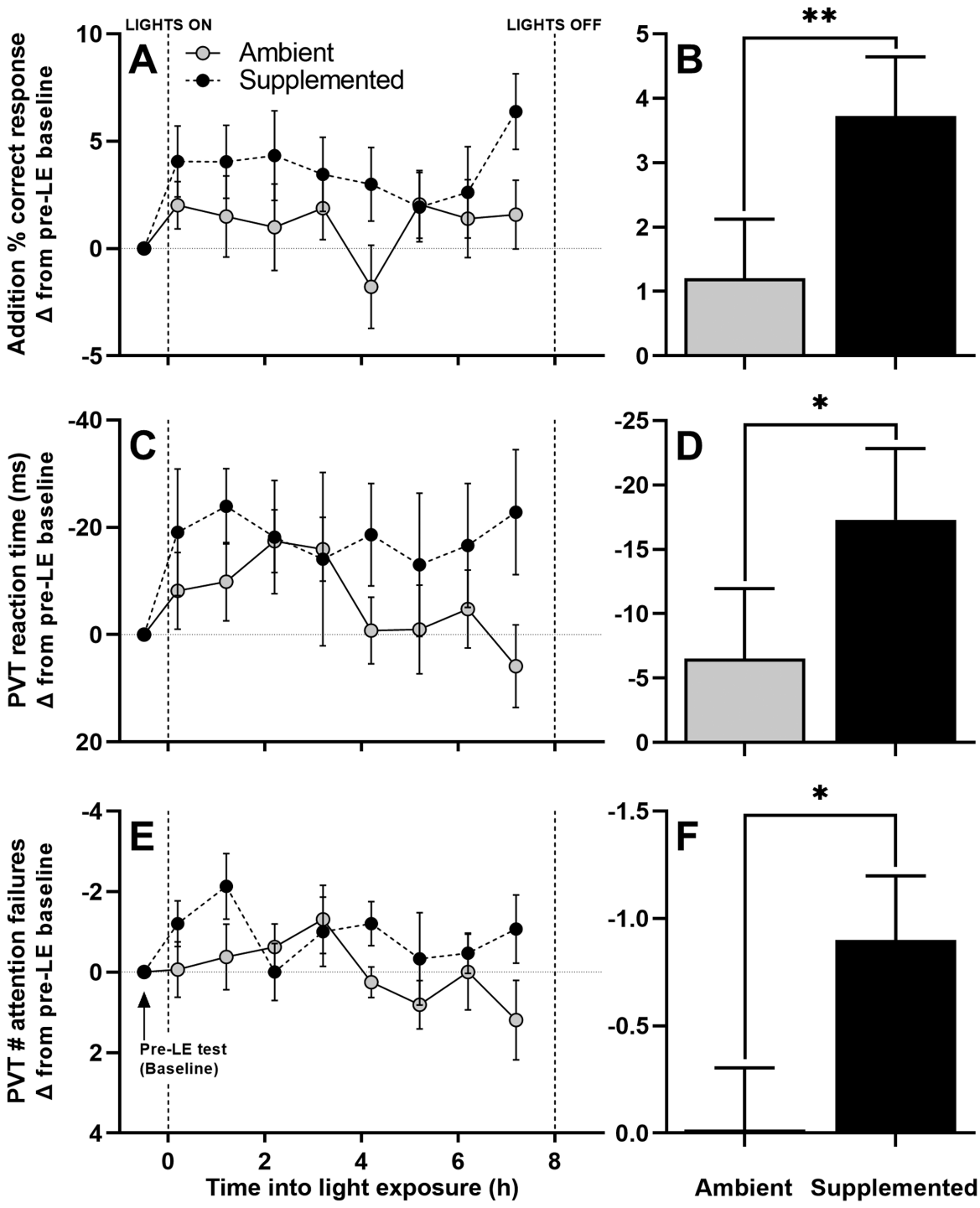


Figure 2. Effect of light condition on working memory and neurobehavioral performance. Time course of the change in percent correct responses on the addition task (A), and PVT reaction time (C) and attentional failures (E) relative to the pre-light exposure baseline. The main effect of lighting condition for percent correct responses (B), reaction time (D), and attentional failures (F). Time course data are plotted as mean ± SEM and main effect results are plotted as least square means ± SE. * denotes $p < 0.05$, ** denotes $p < 0.01$.

dim lighting, percent correct responses on the addition task were on average 2.2% higher throughout the 8-h exposure in the supplemented condition, compared to the ambient condition ($F_{1,224}$ = 11.12, FDR-adj q = 0.005, d = 0.48) (Figure 2A and B, Table 1), representing a small to medium effect. The number of attempted additions did not differ between the conditions (Table 1). Neither of these outcomes changed across the course of the light exposure nor did the differential impact of lighting condition change with exposure duration (Table 1).

Neurobehavioral performance was better under the supplemented compared to ambient condition as measured by reaction time and attentional lapses on the PVT (Table 1). Compared to the ambient condition, baseline-adjusted PVT reaction time was 11 ms faster ($F_{1,219}$ = 6.86, FDR-adj q = 0.03, d = 0.84) and there were

Table 1. Mean ± SEM and results from statistical tests[†]

	Ambient (M ± SEM)	Supplemented (M ± SEM)	Condition *P*-value	Time *P*-value	Cond × Time *P*-value
Additions % correct Change from baseline	1.20 ± 1.27	3.72 ± 1.34	**0.001**	0.56	0.71
Additions # attempted Change from baseline	1.62 ± 0.78	1.22 ± 1.12	0.38	0.95	0.94
Additions # correct Change from baseline	1.95 ± 0.71	1.88 ± 1.16	0.88	0.96	0.94
PVT reaction time (ms) Change from baseline	−6.51 ± 5.16	−18.29 ± 0.93	**0.009**	0.84	0.68
PVT attentional failures Change from baseline	−0.02 ± 0.54	−0.93 ± 0.51	**0.015**	0.36	0.45
WP immediate recall % improvement from learning trials	131.44 ± 4.25	138.99 ± 5.37	0.20	—	—
WP delayed recall % improvement from learning trials	127.01 ± 3.92	128.33 ± 4.86	0.79	—	—
MST performance speed % change from Trial 1	48.68 ± 9.45	51.05 ± 9.12	0.42	—	—
MST motor speed # sequences per trial	21.05 ± 1.29	20.81 ± 1.09	**0.027**	**0.0001**[a]	0.27
PANAS positive score	24.69 ± 2.56	24.91 ± 2.19	0.79	**0.0004**	0.13
PANAS negative score	10.88 ± 0.24	10.84 ± 0.18	0.90	**0.035**	0.70
POMS total mood disturbance	2.00 ± 3.26	4.19 ± 2.22	0.27	**—**	—
KSS Change from baseline	0.22 ± 0.42	−0.25 ± 0.43	**0.010**	0.11	0.85
Sleepy—alert Change from baseline	−3.96 ± 3.63	2.13 ± 5.42	**0.004**	0.24	0.81
Calm—stressed Change from baseline	4.31 ± 2.92	3.20 ± 1.71	0.45	0.22	0.52
Sad—happy Change from baseline	−3.33 ± 1.87	−0.61 ± 1.30	**0.0003**	**0.0002**	0.51
Healthy—sick Change from baseline	0.69 ± 1.78	−1.79 ± 1.74	**0.001**	0.74	0.71
Energetic—physically exhausted Change from baseline	7.27 ± 3.40	0.92 ± 3.10	**0.0002**	**0.017**	0.92
Mentally exhausted—sharp Change from baseline	−4.46 ± 3.10	−0.12 ± 3.70	**0.013**	**0.0002**	0.76
Tired—fresh Change from baseline	−4.15 ± 2.49	−0.78 ± 3.46	**0.02**	**0.0004**	0.79
Motivated—unmotivated Change from baseline	6.36 ± 2.64	1.36 ± 3.04	**0.003**	**0.005**	0.76

[†]Arithmetic means are shown. Outcomes without an effect of time or a time by condition interaction were measured only once on each study day.
[a]For the analysis of MST motor speed, the time variable refers to trial number.

0.9 fewer lapses ($F_{1,223}$ = 6.03, FDR-adj q = 0.03, d = 0.44) throughout the 8-h exposure to supplemented lighting (Figure 2B and C), representing medium to large effects. Neither reaction time nor attentional lapses changed across the course of the light exposure nor did the differential impact of lighting condition change with exposure duration (Table 1).

Subjective sleepiness, mood, health, and well-being

Throughout the 8-h exposure to supplemented lighting, KSS-rated subjective sleepiness relative to dim-light baseline was 0.5 points lower, on average, indicating less sleepiness compared to the ambient condition ($F_{1,224}$ = 6.74, FDR-adj q = 0.045, d = 0.28), representing a small effect. There was no effect of exposure duration or an interaction-effect between lighting conditions and exposure duration (Table 1).

Compared to the ambient light condition, when exposed to supplemented lighting participants reported being more alert (+6 mm, $F_{1,224}$ = 8.64, FDR-adj q = 0.01, d = 0.10), happy (+3 mm, $F_{1,224}$ = 13.46, FDR-adj q = 0.003, d = 0.12), mentally sharp (+4 mm, $F_{1,224}$ = 6.34, FDR-adj q = 0.03, d = 0.32) and fresh (+3.4 mm, $F_{1,224}$ = 5.3, FDR-adj q = 0.04, d = 0.28), and less sick (−2.5 mm, $F_{1,224}$ = 6.84, FDR-adj q = 0.005, d = 0.35), physically exhausted (−6.3mm, $F_{1,224}$ = 14.85, FDR-adj q = 0.003, d = 0.49) and unmotivated (−5 mm,

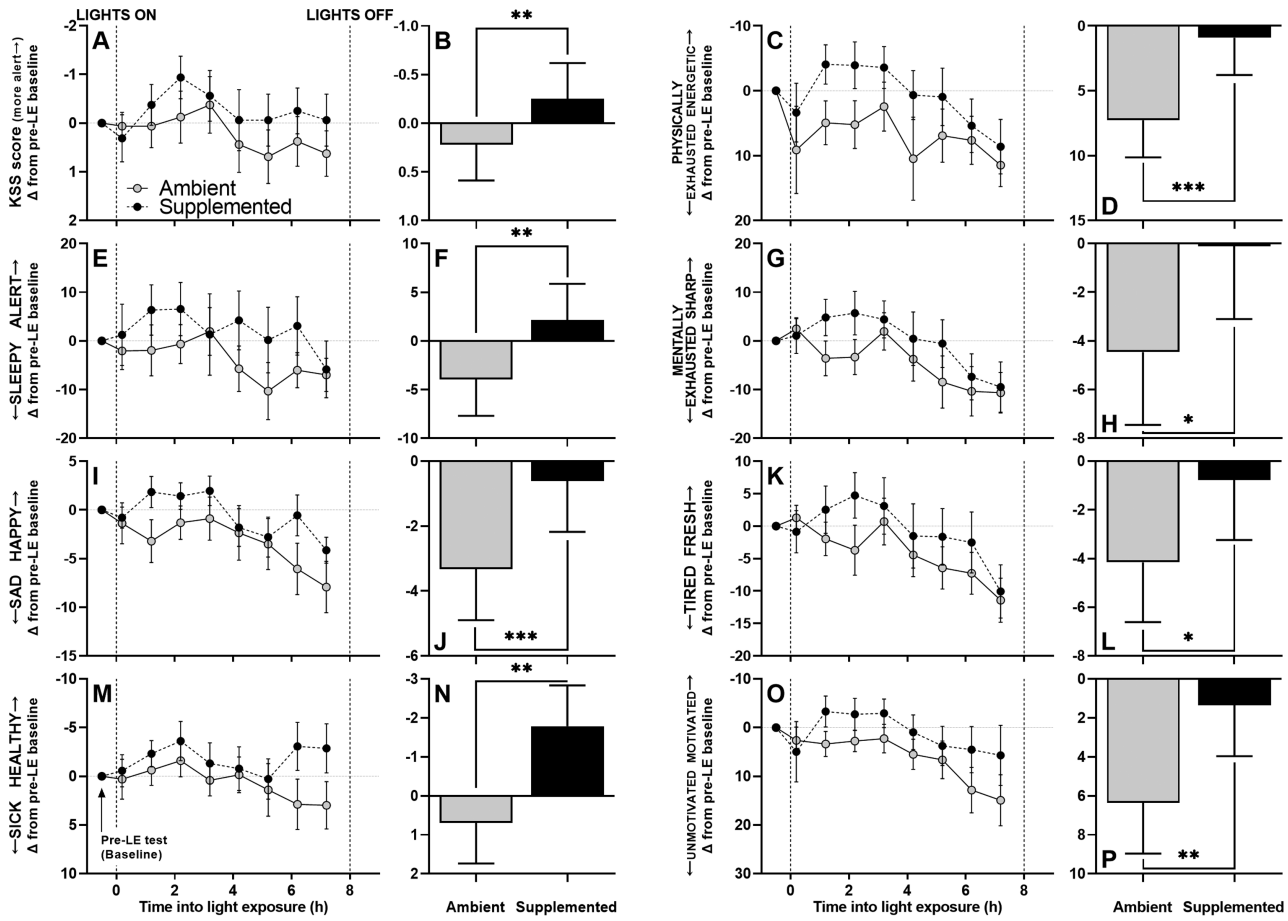


Figure 3. Effect of light condition on subjective sleepiness, alertness, health, and wellbeing. Time course of the change in KSS scores (A), and VAS scales for energetic—physically exhausted (C), sleepy—alert (E), mentally exhausted—physically sharp (G), sad—happy (I), tired—fresh (K), healthy–sick (M), motivated—unmotivated (O). The main effect of lighting condition for KSS scores (B), energetic—physically exhausted (D), sleepy—alert (F), mentally exhausted—physically sharp (H), sad—happy (J), tired—fresh (L), healthy—sick (N), motivated—unmotivated (P). Time course data are plotted as mean ± SEM and main effect results are plotted as least square means ± SE. *Denotes $p < 0.05$, **denotes $p < 0.01$; ***denotes $p < 0.001$.

$F_{1,224}$ = 9.23, FDR-adj q = 0.01, d = 0.44) on the VAS compared to the pre-light exposure baseline (Figure 3), representing small to medium effect sizes. Subjective reports of feeling stressed were not statistically different between conditions and several of these measures changed with exposure duration (Figure 3, Table 1).

Positive and negative affect measured by the PANAS were not different between lighting conditions but during the course of the 8-h exposure, positive affect decreased significantly ($F_{1,44}$ = 14.67, $p < 0.001$) and negative affect increased significantly ($F_{1,44}$ = 4.74, $p < 0.05$) (Table 1). The impact of lighting conditions on positive or negative affect did not change based on exposure duration (both, $p \geq 0.13$, Table 1). Additionally, mood disturbance measured by the POMS was not different between lighting conditions (Table 1).

The supplemented lighting condition was not associated with adverse visual experience or discomfort as compared to the dimmer and low melanopic strength ambient condition (Supplementary Table S1).

Procedural learning and declarative memory

There was no effect of lighting condition, study day, or condition order on performance speed on the MST (Supplementary Figure S1A), nor percent improvement of the immediate or delayed recall on the word pairs task (Table 1). In secondary analyses of the MST data by trial, the number of sequences completed during each 30-s trial increased across the learning trials (Supplementary Figure S1B) for all participants, in both lighting conditions ($F_{11,284}$ = 12.96 $p < 0.001$; Table 1), as expected. Furthermore, there was also a significant main effect of lighting condition such that participants typed on average an additional 0.8 more sequences per trial in the supplemented, compared to the ambient, condition ($F_{1,289}$ = 4.92, FDR-adj q = 0.045, d = 0.06, Supplementary Figure S1C), representing a very small effect.

Discussion

Our results show that ambient lighting supplemented with a high-melanopic-illuminance task lamp improved working memory, neurobehavioral performance and subjective sleepiness, alertness and well-being outcomes during the daytime. In this study, we found improvement in daytime cognition and alertness outcomes through supplementation of sub-optimal ambient room lighting with high-melanopic-illuminance task lighting. Consistent with previous studies, we found that exposure to higher melanopic illuminance improved subjective sleepiness, alertness and wellbeing, and objective measures of neurobehavioral performance and working memory [1–6, 21–25, 37–43]. For example, a recent study from Lok et al. showed improved working memory and PVT performance compared to a dim light control during a 10-h daytime exposure to broad-spectrum LED (~80 melanopic lux) but not fluorescent

(~56 melanopic EDI lux) lighting [25], confirming our previous report of a robust effect of melanopic illuminance on working memory using the same light source albeit at a lower illuminance (~45 melEDI) [22]. Moreover, when the results of our prior and current studies are compared qualitatively, a dose–response between melanopic illuminance and lower KSS score is apparent, consistent with other reports [17].

There are some apparent inconsistencies, however, when comparing the results of our own, and others', studies. In the previous report that used a similar design to the current study [22], we did not, for example, see a light-induced improvement in PVT reaction time and attentional lapses, in contrast to the current study. The results of the MST, which measures procedural learning, are also varied. In the current study, daytime learning did not improve with a large increase in light illuminance (as indicated by MST speed) but did across the more modest lighting change in the prior study [22]. Declarative memory, as assessed by delayed recall of the word pairs was not improved by light in either of our studies but has been reported following exposure to narrow bandwidth blue (λ_{max} 469 nm) compared to amber (λ_{max} 578 nm) light using the California Verbal Learning Test [44].

There are a number of potential reasons for these differences that make direct comparison of results difficult including study design (between versus within-participant, which would in turn change prior light history); the relative magnitude of the lighting difference between conditions in each study (the current study compared the effect of ~30 with 250 melEDI lux whereas our prior study examined performance changes over a more modest range of 24–45 melEDI lux [22]); difference in light geometry; and differences in duration between initial learning and subsequent recall in the declarative memory tests, plus differences between laboratories in their screening, pre-admission instructions, procedures, test delivery, light measurement and devices, and many others. While in the current study, the difference in lighting levels between ambient and supplemented conditions was maximized to detect the impact on a broad range of neurobehavioral outcomes, future studies are needed to characterize potential dose–response relationships between these outcomes and lighting supplementation.

There is also a potential disconnect between laboratory and field-based studies, and studies in healthy controls compared to patient populations, which may lead to apparent inconsistencies. For example, contrary to our hypothesis, we did not observe an effect of lighting conditions on affect regulation and mood disturbance, measured by the PANAS and POMS, respectively. Although lighting interventions have been shown to have beneficial effects for individuals with mood disorders such as depression and seasonal affective disorder [45], including blue-enriched light [46, 47], less is known about the effects of different light spectra in individuals without a history of mood disorders. While we did not observe differences between lighting conditions on the POMS and PANAS, mood and related outcomes assessed with visual analog scales (e.g. sad/happy, motivated/unmotivated) showed that mood was more positive in the supplemented lighting condition, which is consistent with other studies using similar scales to assess mood [2, 37]. A larger sample size, clinical populations, and/or longer exposure intervals (i.e. days or weeks) may be required for differences in affect and mood disturbance to be detected. For example, a 4-week office blue-enriched lighting intervention (17 000K, ~370 melEDI lux) significantly improved positive affect on the PANAS in ~100 office workers as compared to typical white light (4000K, ~230 melEDI lux) [35].

While we did not see a difference between the lighting conditions in procedural and declarative learning or mood, importantly, these outcomes were not worse by the addition of the high-melanopic-illuminance task lamp lighting. Additionally, the supplemented lighting condition was not associated with adverse visual experience or discomfort as compared to the dimmer and low-melanopic-strength ambient condition (Supplementary Table S1) and there was, for some items on the Headache and Eye Strain Scale, a trend toward the supplemented lighting condition being rated as more favorable.

Although our results show a benefit of supplementing sub-optimal ambient lighting in some cognitive domains, further investigation of the benefits of task lamps at the work surface is necessary. For example, the current study cannot determine relative photoreceptor contribution in the responses because of the increased α-opic illuminance across photoreceptor types and concurrent increase in photopic and melanopic illuminance. Identifying the photoreceptor mechanism is harder when using white light but is necessary for any practical translation. Future work is also needed to examine whether lighting supplementation using a task lamp is efficacious to improve performance and mood over longer durations (e.g. multiple days, weeks) and across varying levels of sleep restriction. Furthermore, the current analysis of data relative to the dim light baseline on each study day was necessary to adjust for baseline differences and order effects; however, this analytic approach may have impacted the degree of improvement in task performance during the subsequent light exposure. Future studies with a longer washout period between light exposures are required to determine the magnitude of the improvement with greater precision.

Taken together, the results of the current study, showing benefits of supplementing ambient lighting with a high-melanopic content task lamp, support lighting supplementation to improve sub-optimal lighting environments to improve alertness and cognition.

Supplementary Material

Supplementary material is available at *SLEEP* online.

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Author Contributions

All authors have contributed to and approved this manuscript. LKG, SWL and SAR contributed to the initial concept and design of the study. LKG, PCC, MDM, MSH and SAR contributed to, or oversaw, participant recruitment and data collection. LKG, RS, and SAR contributed to the analysis of the data. All authors contributed to the interpretation of the data and drafting of the manuscript.

Data Availability

The datasets and code supporting the current study have not been deposited in a public repository to preserve patient confidentiality but are available from the corresponding author on reasonable request. Execution of a Materials Transfer Agreement is required if the data will be used in research supported by a for-profit company, per Mass General Brigham Institutional Review Board policy.

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