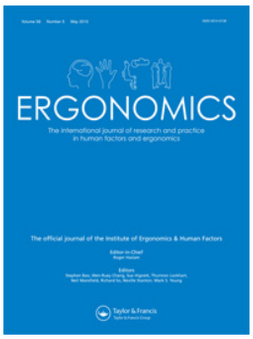

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Blue light aids in coping with the post-lunch dip: an EEG study

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The 'post-lunch dip' is a commonly experienced period of drowsiness in the afternoon hours. If this inevitable period can be disrupted by an environmental cue, the result will be enhanced workplace performance. Because blue light is known to be a critical cue for entraining biological rhythms, we investigated whether blue light illumination can be a practical strategy for coping with the post-lunch dip. Twenty healthy participants underwent a continuous performance test, during which the electroencephalogram (EEG) was recorded under four different illumination conditions: dark (< 0.3 lx), 33% blue-enriched light, 66% blue-enriched light and white polychromatic light. As a result, exposure to blue-enriched light during the post-lunch dip period significantly reduced the EEG alpha activity, and increased task performance. Since desynchronisation of alpha activity reflects enhancement of vigilance, our findings imply that blue light might disrupt the post-lunch dip. Subsequent exploration of illumination parameters will be beneficial for possible chronobiological and ergonomic applications.

Practitioner Summary: As blue light is a crucial cue to entrain human circadian rhythms, we investigated whether blue light can cope with the post-lunch dip. As a result, blue light significantly improved cognitive performance, and reduced the EEG alpha activity, reflecting enhancement of vigilance. Therefore, blue light helps in avoiding the post-lunch dip.

Keywords: blue light; EEG alpha activity; illumination; post-lunch dip; work efficacy

1. Introduction

The 'post-lunch dip' is a period of drowsiness experienced by most people after lunch, which causes a temporary drop in alertness (Monk 2005). The circadian drive for daytime vigilance is not sufficiently robust to counteract the homeostatic sleep urge during this period (Edgar, Dement, and Fuller 1993; Cajochen, Blatter, and Wallach 2004). As a result, performance is severely hampered, and poor judgement due to tiredness and loss of alertness is a large contributor to workspace accidents, especially in the mid-afternoon (Mitler et al. 1988). Therefore, if this dip in alertness can be disrupted by an environmental cue, it will certainly promote better workplace performance. Light affects brain function through modulation of alertness and performance, and by influencing the timing of circadian rhythms (Blatter and Cajochen 2007). Indeed, there is growing evidence that blue light is a crucial cue to entrain human circadian rhythms (Warman et al. 2003; Revell et al. 2005). Although Sahin and Figueiro (2013) recently reported that monochromatic red light is a stronger arousal stimulus in the afternoon than monochromatic blue light, it still remains unclear whether blue light has a counteracting impact upon the post-lunch dip. Although the colour red may attract more attention (Humphrey 1976), unpleasant associations of red with fire, danger or blood (Gerard 1958) may make it impractical for workplace illumination. In contrast, colours in the blue range of the spectrum produce quiet feelings (Yoto et al. 2007), and are associated with positive thoughts (Gerard 1958). In addition, monochromatic blue light is not practical for use in everyday life, due to its colour-salience. Thus, it is necessary to determine the level of blue-light enrichment in polychromatic light that is sufficient to boost alertness. It has also been proposed that the circadian timing system can be strengthened by increasing the blue content of artificial light during the daytime (Holzman 2010). Therefore, two levels of blue-enriched polychromatic light (33% and 66%, based on the 1931 CIE chromaticity coordinates) were tested in order to determine whether a small or large proportional increase in blue light exposure can effectively counteract the post-lunch dip, and enhance mid-afternoon performance. Because routine daily tasks usually require sustained vigilance, a workplace-like environment was designed to impose a sustained attentional task on participants, with minimal mental effort required to remain alert. This experimental design differs from that of Sahin and Figueiro (2013), in which participants were not given a task to perform. Since ongoing electroencephalogram (EEG) alpha activity is associated with sustained attention (Orekhova, Stroganova, and Posikera 2001), our analysis was focused on EEG alpha activity recorded under different illumination conditions. It was hypothesised that if blue-enriched polychromatic light enhances vigilance during the expected post-lunch dip, subsequent

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cognitive performance will be improved, and EEG alpha power will decrease, given that alpha power negatively correlates with arousal level (Klimesch 1999, 2012).

2. Materials and methods

2.1 Participants

Twenty healthy volunteers (11 female; mean age 24.5 years, range 22–28 years) participated in the study. All participants met the following criteria: (1) neither 'extreme late' nor 'extreme early' type, according to their responses on the Munich Chronotype Questionnaire (Roenneberg, Wirz-Justice, and Merrow 2003), (2) no report of any physical or mental health problems, (3) a body mass index no higher than 30, (4) no experience of shift-work or travel to a different time zone in the 3 months prior to the experiment and (5) no colour-blindness, as determined by the Ishihara test. Participants were asked to go to sleep between 22:00 and 23:00 the night before the experiment, and to wake up no later than 07:30 on the day of the experiment. Participants were also told to refrain from napping on the day of the experiment. Participants were asked to avoid alcohol and caffeine intake for a full day before the experimental session. All participants reported having eaten between 60 and 90 min prior to arriving at the laboratory. This study was conducted in accordance with the ethics guidelines established by the Institutional Review Board of Korea University. Participants provided informed consent prior to the experiment.

2.2 Stimuli and procedure

A 60×60-cm^2 plate with a 14×14 array of light-emitting diodes (LEDs) was used as the illumination source. Since the action-spectrum for human melatonin suppression peaks between 420–480 nm (Brainard et al. 2001; Wright, Lack, and Kennaway 2004), 451 nm was chosen as the wavelength for blue-light enrichment. Participants experienced two experimental sessions, separated by 1 week, with two lighting conditions assigned to each session. Consequently, there were four illumination conditions, each lasting for 60 min: dark (<0.3 lx at the cornea), white light and two different types of short-wavelength polychromatic light (33% and 66% blue-enriched, peak wavelength = 451 nm). The colour schemes used for the illuminating light, defined according to the 1931 CIE chromaticity coordinates, were as follows: 33% blue (x: 0.2364, y: 0.1765, 40.1 lx), 66% blue (x: 0.1787, y: 0.0828, 40.6 lx), white (x: 0.3303, y: 0.331, 40.2 lx) and dark (<0.3 lx at the cornea). In order to rule out any illuminance effect, all light was maintained as close as possible to 40 lx (Chellappa et al. 2011). The order of illumination conditions was counterbalanced across participants. The experiment was performed within a light booth (Figure 1(A)). The walls of the booth were surrounded by light-reflecting white screens, and covered with light-blocking curtains to prevent contamination from outside light. The experiment began at 14:00 each day. By imposing a mental task (e.g. attention, perception or memory) between every EEG recording session, the mental state of the participants was deemed similar to when they were at their actual workplace under each of the four illumination conditions.

In order to assess possible effects of lighting condition on sustained attention during work, a continuous performance test (CPT; Riccio, Reynolds, and Lowe 2001) was employed, which featured a rapid presentation of continuously changing stimuli with an infrequently occurring target stimulus. Sustained attention is defined as the ability to focus attention over time (Mirsky et al. 1991). It was expected that a stationary illumination condition might affect a sustained mental state, such as sustained attention. Randomly drawn single-digit numbers (0–9) were presented, one at a time, on a display monitor (Full HD LED 27-in., S27B550, Samsung, Seoul, Korea) for 1500 ms, with a 2000-ms interstimulus interval. Participants were instructed to respond by pressing a button with one hand whenever the digit '0' appeared, and to press a button with the opposite hand if one of the remaining single digits (1–9) was presented. Participants were required to press the button as quickly as possible. The target stimulus ('0') was presented in 30% of stimuli; the remaining 70% of stimuli consisted of digits 1–9. The stimulus-digit was presented in grey (47.0 lx) subtended at 4° (visual angle) on a black background (1.6 lx). Under the white and blue-enriched light conditions, the LEDs were energised for 48 min, preceded by a 12-min dark period (Figure 1(B)).

2.3 EEG acquisition and analysis

After the initial dark adaptation and the acquisition of an EEG baseline (E0) consisting of the last 3 min of the dark-adaptation period, the participants completed a sequence which consisted of the CPT task ($\sim$5 min) followed by an EEG acquisition (3 min); the sequence was repeated six times (Figure 1(B)). EEG was measured using a BrainAmp DC amplifier, with Ag/AgCl electrodes (Brain Products, Gilching, Germany). The electrodes were placed at Fz, Cz, Pz and Oz, in accordance with the international 10–10 system. A reference electrode was placed on the tip of the nose, and a ground

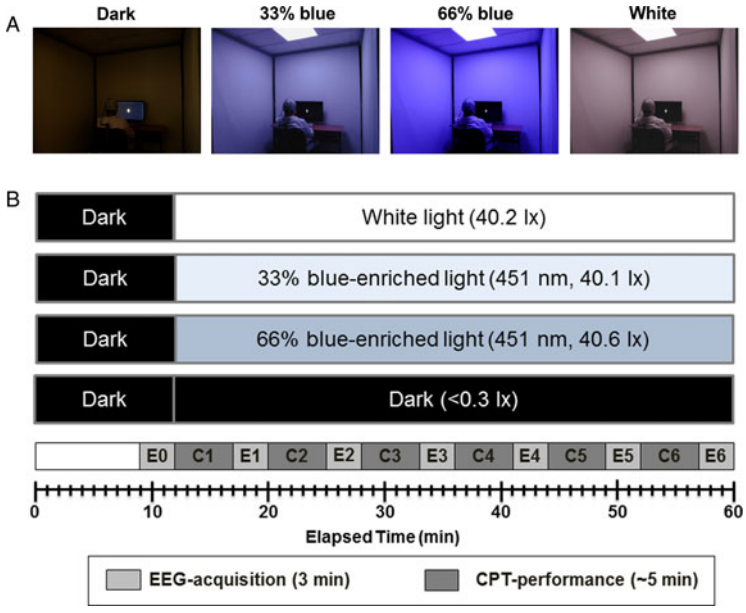

Figure 1. Experimental setup and design. (A) Four different illumination conditions during the post-lunch dip (dark, 33% blue enriched, 66% blue enriched, and white). A randomly drawn, single-digit number (0–9) was presented on a computer monitor for 1500 ms, with a 2000-ms interstimulus interval, and participants were instructed to perform a CPT under each different illumination condition. (B) The elapsed time from the start of the experiment is shown at the bottom of the figure. The CPT was performed at 12 (C1), 20 (C2), 28 (C3), 36 (C4), 44 (C5) and 52 (C6) min after the onset of the experiment, and each instance lasted for approximately 5 min. EEG was measured for 3 min immediately following each CPT (E1, E2, E3, E4, E5 and E6). E0 marks an EEG recording during the last 3 min of the initial dark adaptation trial, and was used as a baseline for normalisation.

electrode was placed at AFz. Electrode impedances were maintained below 5 kΩ prior to data acquisition. EEG was recorded at 500 Hz (analogue band-pass filter, 0.5–50 Hz). The electrooculogram was corrected offline using an independent component analysis method (Jung et al. 1997).

EEG data were grouped into 2-s epochs, with a 1-s overlap between each epoch, and a fast Fourier transformation (FFT) was applied to each epoch, using a Hanning window with a 10% taper. The power spectra from each epoch were then averaged to yield average power spectra for each trial. Spectra from each of the four electrode sites were grouped into two alpha frequency bins: 8–10 Hz (lower alpha band) and 10–13 Hz (upper alpha band). These frequency bands were chosen because desynchronised EEG activity in both lower and upper alpha bands is involved in attentional processing and semantic memory performance, respectively (Klimesch 1999). In order to make FFT results compatible with each other, irrespective of their initial-state variations, EEG power at each interval and each frequency range was normalised to the power obtained during E0. To compare an illumination effect between the first and second halves of the experimental period for each condition, the first three EEG recordings for each condition were collapsed to yield the EEG measured in the first half, while the remaining three EEG recordings were averaged to represent those in the second half. All data were analysed by two-way repeated-measures ANOVA, with 'illumination' (dark, 33% blue, 66% blue and white) and 'period' (first and second half) as within-subjects factors. When necessary, the Greenhouse–Geisser correction was used. A false discovery rate (FDR) of $q < 0.2$ (Benjamini and Hochberg 1995) was used to correct for multiple comparisons, since q-values between 0.1 and 0.2 after FDR correction are known to be acceptable for this purpose (Genovese, Lazar, and Nichols 2002). All analyses were performed using the software package MATLAB (ver. R2011b, MathWorks, Natick, MA, USA) or SPSS Statistics (ver. 20, IBM, Armonk, NY, USA). In this study, the P value of 0.05 was taken to indicate a significant difference.

3. Results

3.1 Behavioural data

Reaction times became systematically shorter as the percentage of blue-light enrichment increased ($F(3, 57) = 5.104$, $P < 0.005$; dark = 418.529 ± 71.124 (SD) ms; 33% blue = 396.625 ± 50.305 ms; 66% blue = 394.895 ± 54.773 ms; white = 381.088 ± 48.649 ms). Post-hoc comparisons revealed that, as compared to the dark condition, the 33% blue ($F(1, 19) = 4.577$, $P < 0.05$, FDR-corrected) and white conditions ($F(1, 19) = 12.196$, $P < 0.005$, FDR-corrected) significantly reduced reaction times (Figure 2(A)). The 66% blue condition showed a marginally significant reduction of reaction times

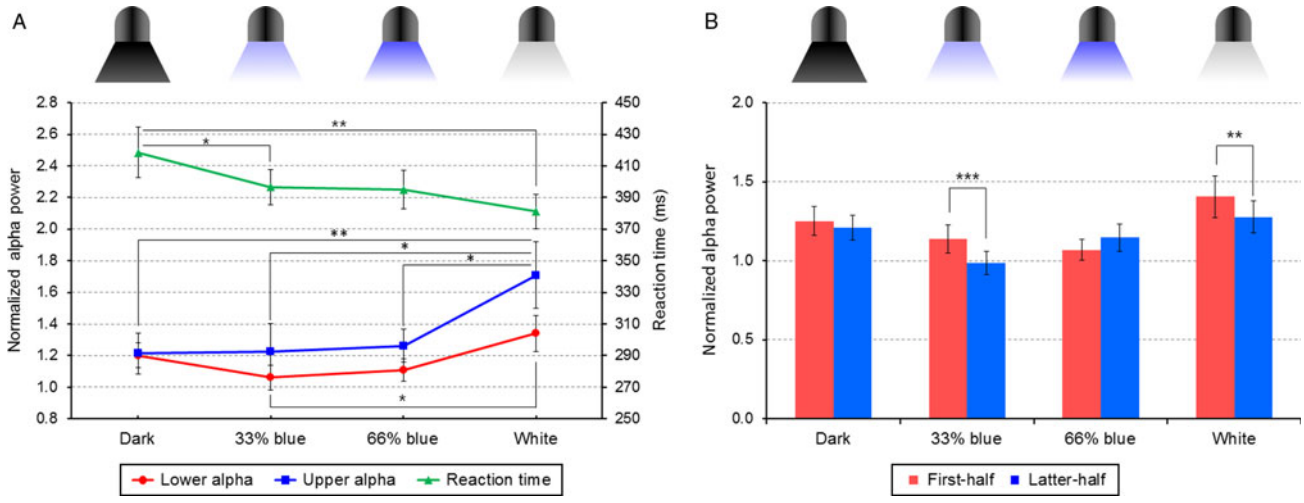

Figure 2. Effects of blue light on EEG alpha activity and behavioural responses during the post-lunch dip. (A) Note the significant reduction of lower and upper alpha-band activity under both 33% and 66% blue-enriched light conditions, and shorter reaction times. The left *y*-axis indicates normalised EEG power, while the right *y*-axis represents the scale for reaction times in milliseconds (red line: lower alpha-band activity, blue line: upper alpha-band activity, green line: reaction times). (B) The normalised EEG activity in the lower alpha band is compared between the first-half (0–30 min) and second-half (30–60 min) periods. The red bar indicates the first-half period while the blue bar represents the second-half period. Error bars indicate ± 1 standard error of the mean. One asterisk denotes $P < 0.05$, and two asterisks indicate $P < 0.005$. *P* values are corrected for FDR.

as compared to the dark condition ($F(1, 19) = 4.151$, $P = 0.06$, FDR-corrected). The remaining comparisons yielded no significant differences in reaction times. Neither a main effect of period ($F(1, 19) = 3.391$, n.s.) nor an interaction between illumination and period ($F(3, 57) = 2.001$, n.s.) had a significant effect on the reaction times. Neither illumination ($F(3, 57) = 1.610$, n.s.) nor period ($F(1, 19) = 0.254$, n.s.) significantly affected the accuracy of task performance. No interaction was found to significantly affect the accuracy of task performance ($F(3, 57) = 0.603$, n.s.).

3.2 *Lower alpha-band activity*

The EEG activity in the lower alpha band was significantly affected by illumination conditions ($F(3, 57) = 3.414$, $P < 0.05$; dark = 1.202; 33% blue = 1.062; 66% blue = 1.108; white = 1.340). Subsequent tests indicated that lower alpha-band activity was significantly reduced by 33% blue light as compared to that by white light ($F(1, 19) = 5.566$, $P < 0.05$, FDR-corrected). The 66% blue light exhibited a marginally significant reduction in lower alpha-band activity as compared to the white condition ($F(1, 19) = 4.352$, $P = 0.05$, FDR-corrected). No other comparisons yielded significant differences in lower alpha-band activity. In addition, lower alpha-band activity was further reduced during the second half (30–60 min) of the experiment as compared to that during the first half (0–30 min; $F(1, 19) = 5.928$, $P < 0.05$; first half, 1.216; second half, 1.155). A significant interaction between illumination and period (first or second half) was also observed in the lower alpha band ($F(3, 57) = 5.104$, $P < 0.005$). Post-hoc tests revealed that the 33% blue-enriched light reduced lower alpha-band activity during the second half of the experiment more than during the first half ($F(1, 19) = 12.059$, $P < 0.005$, FDR-corrected; first half, 1.138; second half, 0.986). Under white light, lower alpha-band activity was also reduced more during the second half of the experiment than during the first half ($F(1, 19) = 4.672$, $P < 0.05$, FDR-corrected; first half, 1.405; second half, 1.276). However, there were no significant differences between the first and second halves in terms of lower alpha-band activity, under the dark ($F(1, 19) = 0.338$, n.s., FDR-corrected) or 66% blue light ($F(1, 19) = 2.292$, n.s., FDR-corrected) conditions.

3.3 *Upper alpha-band activity*

As shown in Figure 2(A), upper alpha-band activity was also significantly suppressed by blue-enriched light during the post-lunch dip ($F(3, 57) = 5.598$, $P < 0.01$; dark, 1.213; 33% blue, 1.227; 66% blue, 1.263; white, 1.709). Subsequent tests revealed that the dark ($F(1, 19) = 10.518$, $P < 0.005$, FDR-corrected), 33% blue ($F(1, 19) = 7.234$, $P < 0.05$, FDR-corrected) and 66% blue ($F(1, 19) = 5.781$, $P < 0.05$, FDR-corrected) conditions significantly suppressed upper alpha-band activity as compared to the white condition. The remaining comparisons yielded no significant differences in upper

alpha-band activity. Neither a significant main effect of period ($F(1, 19) = 0.873$, n.s.) nor a significant interaction effect ($F(3, 57) = 1.991$, n.s.) was detected in the upper alpha band.

4. Discussion

In this study, blue-enriched polychromatic light during the post-lunch dip significantly reduced lower and upper alpha-band activity, and improved reaction times during a sustained attention task. Our observations provide neurophysiological evidence in line with Viola et al. (2008), who reported that exposure to blue-enriched light during daytime work-hours improves subjective alertness and performance. Because blue-enriched light produced substantial reductions of lower and upper alpha-band power, reflecting better attentional and semantic memory processing (Klimesch 1999), blue-enriched polychromatic light may be used to enhance cognitive performance during afternoon drowsiness. It is noteworthy that alpha activity is considered to reflect an 'attentional buffer' that maintains target information (Klimesch 2012), and the ability to activate this buffer might selectively lead to a pronounced event-related reduction of alpha activity. It has been shown that blue light is able to significantly enhance brain activity in a number of higher order cortical areas, which are all known to be involved in working memory and executive control (Cabeza and Nyberg 2000). Vandewalle et al. (2011) also observed that blue-light-mediated enhancement of brain activity occurred in the vicinity of deactivations observed in darkness, and they interpreted their findings to mean that blue light facilitates restoration of diminished attentional resources. Thus, blue-enriched light may facilitate an attentional buffer, which could explain the reduced alpha power in this study. Furthermore, it has been reported that exposure to blue light enhances cognitive performance, and suppresses melatonin release (Brainard et al. 2001; Lockley, Brainard, and Czeisler 2003; Chellappa et al. 2011). Overall, blue light seems to counteract drowsiness, and enhance cognitive performance.

Since both 33% and 66% blue light significantly reduced the EEG activity in both lower and upper alpha bands, as well as reaction times, during the first 30 min (Figure 2(A)), illumination for this period of time seems to be sufficient to induce arousal during the post-lunch dip. Therefore, dynamic illumination may provide an economically feasible means of regulating circadian rhythms in everyday situations. Moreover, as compared to 66% blue-enriched light, 33% blue-enriched light reduced lower alpha-band activity more during the second half of the experiment than during the first half (Figure 2(B)). This result can be interpreted as a conditional modulation of alpha activity with illumination time, depending on the level of blue enrichment. Consistent with this hypothesis, a recent study showed that the lowest tested level of blue-enriched light had robust effects on both melatonin secretion and subjective alertness (Wahnschaffe et al. 2013). Therefore, the spectral composition of polychromatic blue light can determine its capacity to improve human alertness during the post-lunch dip. Because such a significant interaction between illumination and time period was observed for lower alpha-band activity, which reflects attentional processing (Klimesch 1996), the duration of illumination appears to be critical for modulating attention. On the other hand, modulation of upper alpha-band activity did not depend on illumination time. That is, as compared to lower alpha-band activity, upper alpha-band activity is not easily modulated by the amount of external light. In line with this observation, it has been reported that upper alpha-band activity (9.25–12 Hz) does not show a powerful sleep–wake (i.e. homeostatic) dependence (Aeschbach et al. 1999). Rather, upper alpha-band activity is proposed as a neurophysiological correlate of the endogenous circadian drive for sleep (Aeschbach et al. 1999).

There is neurobiological evidence consistent with our present observations. Intrinsic photosensitive retinal ganglion cells (ipRGCs) represent a new class of retinal photoreceptors (compared to classical image-forming photoreceptors: rods and cones), which are maximally sensitive to short-wavelength blue light (approximately 480 nm; Benarroch 2011), and project extensively throughout the brain (Sernagor 2005; Hanifin and Brainard 2007). The ipRGCs express the photopigment, melanopsin and mediate non-image-forming photoreception (Provencio et al. 2000; Berson, Dunn, and Takao 2002). The light-induced regulation of circadian, neuroendocrine and neurobehavioural functions is sometimes termed non-image-forming (or non-visual) responses, via outputs from ipRGCs (Hatori and Panda 2010; Schmidt, Chen, and Hattar 2011). It is also noteworthy that blue light has been considered a crucial cue in the entrainment of human circadian rhythms (Lockley, Brainard, and Czeisler 2003; Warman et al. 2003; Revell et al. 2005; Holzman 2010; Vetter et al. 2011). Taken together, the ipRGC non-visual pathway (sensitive particularly to blue light) seems to serve as a crucial role in the entrainment of the circadian rhythm (Legates, Fernandez, and Hattar 2014). This concept dates back to Hollwich's original postulation about the existence of a non-visual pathway involved in the synchronisation of the circadian rhythm (Hollwich and Dieckhues 1971).

In our study, post-hoc comparisons revealed that the reduction of reaction times by 33%-enriched blue light was not significantly different from the reduction by white light. Furthermore, as shown in Figure 2(A), 33%-enriched blue light yielded similar levels of reduced alpha power and reaction times as 66%-enriched blue light. All of these observations imply that the 33%-enriched blue illumination is sufficient to disrupt the post-lunch dip. Fortunately, such mild blue light is significantly less intense and more comfortable as an illuminating light than deep (66%-enriched) blue light. Furthermore, a

positive effect was found with *polychromatic* blue light, but not with *monochromatic* blue light, which is more artificial and too intense for comfort. This further supports the practicality of applying our results to the workplace.

The light–dark cycle can have significant influences on human health and well-being. One example of this is light exposure given to night and shift workers. Shift workers face fatigue due to continuous sleep deprivation and constant vigilance during work. As a consequence, these individuals are at greater risk of cardiovascular disease and emotional/social issues (Boyce 2006). It has been suggested that these problems are due to a mismatch between the demands of sleep and the state of the worker's circadian rhythm. The use of light is effective in alleviating this problem because it can shift an individual's circadian rhythm, thus resulting in a better match of functional requirements (Eastman et al. 1994). After exposure to light during night shift work, improvements in both alertness and cognitive performance have been observed. These improvements are also accompanied by physiological changes that indicate the state of the circadian rhythm (French, Hannon, and Brainard 1990; Boyce et al. 1997). Therefore, light therapy helps shift workers adjust to irregular schedules. A variety of light therapies (e.g. goggles, lamps or light boxes) have been substantially developed to reduce the misalignment of daytime sleep and night work (Eastman et al. 1994; Crowley et al. 2003). In this respect, our observations with blue light may provide progressive evidence for light-mediated therapeutic technology for night and shift workers.

Although our observations suggest that blue light can be used as a promising method to cope with drowsiness, any possible concerns associated with potential harmful effects of blue light should be carefully considered. For example, excessive or cumulative exposure to blue light could induce irreversible damage to the retina (Ham, Mueller, and Sliney 1976; Ham and Mueller 1989; Sparrow and Cai 2001). As photon energy is inversely correlated with wavelength, high-energy visible (i.e. short-wavelength: blue) light exposure induces oxidative damage, to which retinal cells are particularly vulnerable (Wu, Seregard, and Algvere 2006). Indeed, this is a matter of actual debate in occupational medicine. Therefore, further technical studies on this safety issue must be performed prior to the general use of blue light in daily life.

5. Conclusions

The present findings may lead to interventions that will lead to better cognitive performance in the mid-afternoon, when the most significant drowsiness occurs. Our results could be used to improve the productivity of employees working indoors, the learning ability of school children, the vigilance of human security officers and one's alertness during prolonged driving. Subsequent exploration of illumination parameters is needed to further the understanding of possible chronobiological and ergonomic applications. In addition, architects and lighting engineers will need to be adequately prepared to reduce possible undesirable side effects caused by exposure to artificial blue light.

Disclosure statement

The authors declare that they have no competing interests.

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Note

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References

Aeschbach, D., J. R. Matthews, T. T. Postolache, M. A. Jackson, H. A. Giesen, and T. A. Wehr. 1999. "Two Circadian Rhythms in the Human Electroencephalogram During Wakefulness." *The American Journal of Physiology* 277 (6 Pt 2), R1771–R1779. http://www.ncbi.nlm.nih.gov/pubmed/10600925

Benarroch, E. E. 2011. "The Melanopsin System: Phototransduction, Projections, Functions, and Clinical Implications." *Neurology* 76 (16): 1422–1427. http://www.ncbi.nlm.nih.gov/pubmed/21502603

Benjamini, Y., and Y. Hochberg. 1995. "Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing." *Journal of the Royal Statistical Society: Series B* 57 (1): 289–300.

Berson, D. M., F. A. Dunn, and M. Takao. 2002. "Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock." *Science* 295 (5557): 1070–1073. http://www.ncbi.nlm.nih.gov/pubmed/11834835

Blatter, K., and C. Cajochen. 2007. "Circadian Rhythms in Cognitive Performance: Methodological Constraints, Protocols, Theoretical Underpinnings." *Physiology & Behavior* 90 (2–3): 196–208. http://www.ncbi.nlm.nih.gov/pubmed/17055007

Boyce, P. R. 2006. "Illumination." In *Handbook of Human Factors and Ergonomics*, edited by G. Salvendy. 3rd ed., 643–669. Hoboken, NJ: John Wiley & Sons.

Boyce, P. R., J. W. Beckstead, N. H. Eklund, R. W. Strobel, and M. S. Rea. 1997. "Lighting the Graveyard Shift: The Influence of a Daylight-Simulating Skylight on the Task Performance and Mood of Night Shift Workers." *Lighting Research and Technology* 29: 105–142.

Brainard, G. C., J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, and M. D. Rollag. 2001. "Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor." *Journal of Neuroscience* 21 (16): 6405–6412. http://www.ncbi.nlm.nih.gov/pubmed/11487664

Cabeza, R., and L. Nyberg. 2000. "Imaging Cognition II: An Empirical Review of 275 PET and fMRI Studies." *Journal of Cognitive Neuroscience* 12 (1): 1–47. http://www.ncbi.nlm.nih.gov/pubmed/10769304

Cajochen, C., K. Blatter, and D. Wallach. 2004. "Circadian and Sleep-Wake Dependent Impact on Neurobehavioral Function." *Psychologica Belgica* 44 (1–2): 59–80. <Go to ISI>://WOS:000224075700004.

Chellappa, S. L., R. Steiner, P. Blattner, P. Oelhafen, T. Gotz, and C. Cajochen. 2011. "Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert?" *PLoS One* 6 (1): e16429. http://www.ncbi.nlm.nih.gov/pubmed/21298068

Crowley, S. J., C. Lee, C. Y. Tseng, L. F. Fogg, and C. I. Eastman. 2003. "Combinations of Bright Light, Scheduled Dark, Sunglasses, and Melatonin to Facilitate Circadian Entrainment to Night Shift Work." *Journal of Biological Rhythms* 18 (6): 513–523. http://www.ncbi.nlm.nih.gov/pubmed/14667152

Eastman, C. I., K. T. Stewart, M. P. Mahoney, L. Liu, and L. F. Fogg. 1994. "Dark Goggles and Bright Light Improve Circadian Rhythm Adaptation to Night-Shift Work." *Sleep* 17 (6): 535–543. http://www.ncbi.nlm.nih.gov/pubmed/7809567

Edgar, D. M., W. C. Dement, and C. A. Fuller. 1993. "Effect of SCN Lesions on Sleep in Squirrel-Monkeys – Evidence for Opponent Processes in Sleep Wake Regulation." *Journal of Neuroscience* 13 (3): 1065–1079. <Go to ISI>://WOS:A1993KP71100017.

French, J., P. Hannon, and G. C. Brainard. 1990. "Effects of Bright Illuminance on Body Temperature and Human Performance." *Annual Review of Chronopharmacology* 7: 37–40.

Genovese, C. R., N. A. Lazar, and T. Nichols. 2002. "Thresholding of Statistical Maps in Functional Neuroimaging Using the False Discovery Rate." *Neuroimage* 15 (4): 870–878. http://www.ncbi.nlm.nih.gov/pubmed/11906227

Gerard, R. M. 1958. *Differential Effects of Coloured Lights on Psycho-Physiological Functions*. Los Angeles: University of California.

Ham, W. T. Jr., and H. A. Mueller. 1989. "The Photopathology and Nature of the Blue Light and Near-UV Retinal Lesions Produced by Lasers and Other Optical Sources." *Laser Applications in Medicine and Biology* 4: 191–246.

Ham, W. T. Jr., H. A. Mueller, and D. H. Sliney. 1976. "Retinal Sensitivity to Damage from Short Wavelength Light." *Nature* 260 (5547): 153–155. http://www.ncbi.nlm.nih.gov/pubmed/815821

Hanifin, J. P., and G. C. Brainard. 2007. "Photoreception for Circadian, Neuroendocrine, and Neurobehavioral Regulation." *Journal of Physiological Anthropology* 26 (2): 87–94. http://www.ncbi.nlm.nih.gov/pubmed/17435349

Hatori, M., and S. Panda. 2010. "The Emerging Roles of Melanopsin in Behavioral Adaptation to Light." *Trends in Molecular Medicine* 16 (10): 435–446. http://www.ncbi.nlm.nih.gov/pubmed/20810319

Hollwich, F., and B. Dieckhues. 1971. "Circadian Rhythm in the Blind." *Journal of Interdisciplinary Cycle Research* 2 (2–3): 291–301.

Holzman, D. C. 2010. "What's in a Color? The Unique Human Health Effect of Blue Light." *Environmental Health Perspectives* 118 (1): A22–A27. http://www.ncbi.nlm.nih.gov/pubmed/20061218

Humphrey, N. 1976. "The Colour Currency of Nature." In *Colour for Architecture*, edited by T. Porter and B. Mikellides, 95–98. London: Studio Vista.

Jung, T. P., S. Makeig, M. Stensmo, and T. J. Sejnowski. 1997. "Estimating Alertness from the EEG Power Spectrum." *IEEE Transactions on Biomedical Engineering* 44 (1): 60–69. <Go to ISI>://WOS:A1997VZ94100006.

Klimesch, W. 1996. "Memory Processes, Brain Oscillations and EEG Synchronization." *The International Journal of Psychophysiology* 24 (1–2): 61–100. http://www.ncbi.nlm.nih.gov/pubmed/8978436

Klimesch, W. 1999. "EEG Alpha and Theta Oscillations Reflect Cognitive and Memory Performance: A Review and Analysis." *Brain Research Brain Research Reviews* 29 (2–3): 169–195. http://www.ncbi.nlm.nih.gov/pubmed/10209231

Klimesch, W. 2012. "Alpha-Band Oscillations, Attention, and Controlled Access to Stored Information." *Trends in Cognitive Sciences* 16 (12): 606–617. http://www.ncbi.nlm.nih.gov/pubmed/23141428

Legates, T. A., D. C. Fernandez, and S. Hattar. 2014. "Light as a Central Modulator of Circadian Rhythms, Sleep and Affect." *Nature Reviews Neuroscience* 15 (7): 443–454. http://www.ncbi.nlm.nih.gov/pubmed/24917305

Lockley, S. W., G. C. Brainard, and C. A. Czeisler. 2003. "High Sensitivity of the Human Circadian Melatonin Rhythm to Resetting by Short Wavelength Light." *The Journal of Clinical Endocrinology & Metabolism* 88 (9): 4502–4505. http://press.endocrine.org/doi/abs/10.1210/jc.2003-030570

Mirsky, A. F., B. J. Anthony, C. C. Duncan, M. B. Ahearn, and S. G. Kellam. 1991. "Analysis of the Elements of Attention: A Neuropsychological Approach." *Neuropsychology Review* 2 (2): 109–145. http://www.ncbi.nlm.nih.gov/pubmed/1844706

Mitler, M. M., M. A. Carskadon, C. A. Czeisler, W. C. Dement, D. F. Dinges, and R. C. Graeber. 1988. "Catastrophes, Sleep, and Public-Policy – Consensus Report." *Sleep* 11 (1): 100–109. <Go to ISI>://WOS:A1988M299700011.

Monk, T. H. 2005. "The Post-Lunch Dip in Performance." *Clinics in Sports Medicine* 24 (2): e15–e23, xi–xii. http://www.ncbi.nlm.nih.gov/pubmed/15892914

Orekhova, E. V., T. A. Stroganova, and I. N. Posikera. 2001. "Alpha Activity as an Index of Cortical Inhibition During Sustained Internally Controlled Attention in Infants." *Clinical Neurophysiology* 112 (5): 740–749. http://www.ncbi.nlm.nih.gov/pubmed/11336888

Provencio, I., I. R. Rodriguez, G. Jiang, W. P. Hayes, E. F. Moreira, and M. D. Rollag. 2000. "A Novel Human Opsin in the Inner Retina." *The Journal of Neuroscience* 20 (2): 600–605. http://www.ncbi.nlm.nih.gov/pubmed/10632589

Revell, V. L., J. Arendt, M. Terman, and D. J. Skene. 2005. "Short-Wavelength Sensitivity of the Human Circadian System to Phase-Advancing Light." *Journal of Biological Rhythms* 20 (3): 270–272. http://www.ncbi.nlm.nih.gov/pubmed/15851533

Riccio, C. A., C. R. Reynolds, and P. A. Lowe. 2001. *Clinical Applications of Continuous Performance Tests: Measuring Attention and Impulsive Responding in Children and Adults*. New York: John Wiley & Sons.

Roenneberg, T., A. Wirz-Justice, and M. Merrow. 2003. "Life Between Clocks: Daily Temporal Patterns of Human Chronotypes." *Journal of Biological Rhythms* 18 (1): 80–90. http://www.ncbi.nlm.nih.gov/pubmed/12568247

Sahin, L., and M. G. Figueiro. 2013. "Alerting Effects of Short-Wavelength (Blue) and Long-Wavelength (Red) Lights in the Afternoon." *Physiology & Behavior* 116: 1–7. <Go to ISI>://WOS:000320074900001.

Schmidt, T. M., S. K. Chen, and S. Hattar. 2011. "Intrinsically Photosensitive Retinal Ganglion Cells: Many Subtypes, Diverse Functions." *Trends in Neurosciences* 34 (11): 572–580. http://www.ncbi.nlm.nih.gov/pubmed/21816493

Sernagor, E. 2005. "Retinal Development: Second Sight Comes First." *Current Biology* 15 (14): R556–R559. http://www.ncbi.nlm.nih.gov/pubmed/16051165

Sparrow, J. R., and B. Cai. 2001. "Blue Light-Induced Apoptosis of A2E-Containing RPE: Involvement of Caspase-3 and Protection by Bcl-2." *Investigative Ophthalmology & Visual Science* 42 (6): 1356–1362. http://www.ncbi.nlm.nih.gov/pubmed/11328751

Vandewalle, G., S. N. Archer, C. Wuillaume, E. Balteau, C. Degueldre, A. Luxen, D. J. Dijk, and P. Maquet. 2011. "Effects of Light on Cognitive Brain Responses Depend on Circadian Phase and Sleep Homeostasis." *Journal of Biological Rhythms* 26 (3): 249–259. http://www.ncbi.nlm.nih.gov/pubmed/21628552

Vetter, C., M. Juda, D. Lang, A. Wojtysiak, and T. Roenneberg. 2011. "Blue-Enriched Office Light Competes with Natural Light as a Zeitgeber." *Scandinavian Journal of Work, Environment & Health* 37 (5): 437–445. http://www.ncbi.nlm.nih.gov/pubmed/21246176

Viola, A. U., L. M. James, L. J. Schlangen, and D. J. Dijk. 2008. "Blue-Enriched White Light in the Workplace Improves Self-Reported Alertness, Performance and Sleep Quality." *Scandinavian Journal of Work, Environment & Health* 34 (4): 297–306. http://www.ncbi.nlm.nih.gov/pubmed/18815716

Wahnschaffe, A., S. Haedel, A. Rodenbeck, C. Stoll, H. Rudolph, R. Kozakov, H. Schoepp, and D. Kunz. 2013. "Out of the Lab and into the Bathroom: Evening Short-Term Exposure to Conventional Light Suppresses Melatonin and Increases Alertness Perception." *International Journal of Molecular Sciences* 14 (2): 2573–2589. http://www.ncbi.nlm.nih.gov/pubmed/23358248

Warman, V. L., D. J. Dijk, G. R. Warman, J. Arendt, and D. J. Skene. 2003. "Phase Advancing Human Circadian Rhythms with Short Wavelength Light." *Neuroscience Letters* 342 (1–2): 37–40. http://www.ncbi.nlm.nih.gov/pubmed/12727312

Wright, H. R., L. C. Lack, and D. J. Kennaway. 2004. "Differential Effects of Light Wavelength in Phase Advancing the Melatonin Rhythm." *Journal of Pineal Research* 36 (2): 140–144. http://www.ncbi.nlm.nih.gov/pubmed/14962066

Wu, J., S. Seregard, and P. V. Algvere. 2006. "Photochemical Damage of the Retina." *Survey of Ophthalmology* 51 (5): 461–481. http://www.ncbi.nlm.nih.gov/pubmed/16950247

Yoto, A., T. Katsuura, K. Iwanaga, and Y. Shimomura. 2007. "Effects of Object Color Stimuli on Human Brain Activities in Perception and Attention Referred to EEG Alpha Band Response." *Journal of Physiological Anthropology* 26 (3): 373–379. http://www.ncbi.nlm.nih.gov/pubmed/17641457