




Effect of intensity of short-wavelength light on electroencephalogram and subjective alertness

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Short-wavelength light is known to have an effect on human alertness in the night-time. However, there are very few studies that focus on the effect of intensity of light on alertness. This study evaluates the acute alerting ability of short-wavelength light of three different intensities (40 lux, 80 lux and 160 lux). Eight subjects participated in a 60-minute exposure protocol for four evenings, during which electroencephalogram (EEG) as well as subjective sleepiness data were collected. EEG power in the beta range was significantly higher after subjects were exposed to 160 lux light than after they were exposed to 40 lux, 80 lux light or remained in darkness. Also, the alpha theta power was significantly lower under 160 lux light than in darkness. These results show that the effect of intensity on alertness is not linear and further work should be done to investigate the threshold intensity that is required to produce an alerting effect.

1. Introduction

Light has been shown to exert strong non-visual effects on a range of biological functions such as the regulation of human circadian system. Exposure to light in the evening and night-time, especially of short-wavelength (but not necessarily limited to short-wavelengths), has been shown to lead to an increase in alertness in humans. This effect is suggested to be related to circadian disruption. Circadian disruption is associated with reduced levels of the hormone melatonin and is primarily (though note that rods and cones may also participate in this process¹) mediated by activation of the intrinsically photosensitive retinal ganglion cells which respond to short-wavelength light most strongly. Exposure to light in the evening can inhibit the production of melatonin which

otherwise would naturally build-up in the body during the late-evening hours.

Studies to date have linked the alerting effects of light to its ability to suppress melatonin.² However, hormonal changes might not be the only pathway mediating the non-visual effects of light. More recent studies have suggested that acute melatonin suppression is not needed for light to evoke alertness responses in humans. For example, it has been shown that both short-wavelength (blue) and long-wavelength (red) lights increased alertness at night, as measured by EEG, but only blue light suppressed melatonin significantly.³ Light exposure during the day has no impact on modulating melatonin,^{4,5} though it has been shown to affect objective and subjective alertness in the afternoon – as measured by EEG and the Karolinska Sleepiness Scale (KSS).⁶ These studies have clearly demonstrated that light can increase alertness independent of light-induced melatonin suppression.

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Studies on the non-visual effects of light have suggested that the alerting effect of light exposure during the daytime is more modest than its effect during night-time.⁵ Bright light exposure at night has been shown to reliably increase alertness.⁷ These findings suggest that the impact of light on alertness is a complex physical, physiological and psychological activity that can result from different pathways. Although melatonin level is associated with circadian rhythm, EEG power fluctuations reflect the immediate neuroendocrine responses.⁸

EEG has been one of the measures often used to evaluate acute alertness change, since light can have an impact on EEG measures without affecting melatonin levels.⁶ One study investigated how 48-minute exposures to three lighting conditions (red, blue and dark) affected subjects and found that EEG alpha and alpha theta power were both lower after the exposure to red and blue lights compared to the darkness condition.⁹ Similarly, another study compared short-wavelength light, long-wavelength light and darkness, and found that alpha power was significantly lower after 30 minutes under both the short- and long-wavelength light than remaining in darkness.¹⁰ Red and blue lights have been found to increase beta signals and reduce sleepiness relative to preceding dim light exposure.¹¹ By looking into individual EEG frequencies, it was also suggested that short-wavelength light in particular enhances high alpha activity.¹² With these findings, it is generally agreed that a decrease in low EEG frequencies (theta alpha) power and an increase in high EEG frequencies (beta) power are associated with an increase in alertness.

Short-wavelength light is becoming a critical safety concern. For example, there have been concerns about home lighting in the evening, where tungsten filament lamps of low correlated colour temperature (CCT) have been replaced by solid-state lighting of

higher CCT; the use of emissive electronic displays may also be responsible for the increasing sleep problem.¹³ Differences in the properties of lighting were shown to affect individuals in various ways. Past studies have tried to define and quantify the timing, illuminance levels, exposure duration and wavelength distribution of the light required to evoke alerting responses.¹⁴

A study has looked at how three different illuminances ranging from 3 lux to 9100 lux affect EEG activity over 6.5 hours of exposure, and a dose-response relationship was found in subjective alertness and EEG power.¹⁵ Other studies have also demonstrated a non-linear relationship between light intensity and circadian shifts.^{16,17} It is generally agreed that brighter light has a stronger alerting ability than dimmer light. However, there is no consensus yet about the threshold of light intensity needed to produce these effects.

2. Method

The alerting effect of intensity of light in humans has so far received little attention. This work is concerned with exploring the threshold intensity of light needed to evoke acute alertness responses in humans at night-time. Based on the notion that melatonin suppression is not the only mechanism contributing to light-induced alertness, this study has measured both subjective and objective alertness using KSS and EEG, respectively. The objective, specifically, is to investigate the effect of three intensities (40 lux, 80 lux and 160 lux) of a short-wavelength light ($\lambda_{\max} = 475$ nm), compared to remain in darkness (<1 lux), on human alertness during the evening.

2.1. Test participants

Nine participants (aged 28 ± 3.4 years; five females) were recruited for the within-subject,

four-session study. All participants went through a pre-screening procedure where individual sleep/rise time was collected and the daily consumption of nicotine, caffeine and alcohol was reported. Smokers and those who were rated as extreme late chronotypes (e.g. those who went to bed after 1am) were excluded. The study was approved by the University of Leeds Ethics Committee and all participants signed informed consent forms prior to the study. An information sheet was given and participants were asked to refrain from caffeine and alcohol intake three hours prior to the experiment, and to try to maintain a regular, constant sleep schedule during the entire experimental period. As a result, there is no report of any major health problems or currently taking any medications. One participant did not finish all of the experimental sessions, and their data was excluded from further analysis. In total, the results produced from eight participants (aged 28 ± 3.6 years; five females) are reported here.

2.2. Lighting conditions

Light was delivered through 12 luminaires (LEDs, provided by Thouslite Lighting System) mounted in the ceiling of a room with white walls and grey carpets. The lighting system provides spectral tunable lighting based on multi-channel LED technology. Participants were asked to sit under the light whilst reading, with a white table in front of them (Figure 1). The lighting measures were taken within the flat reading area on the table.

Four light settings were used: a dim (CCT 2000 K, <1 lux) and three short-wavelength lighting conditions. The short-wavelength condition had a peak at about 480 nm and was approximately Gaussian with a half-width half-height of 35 nm. Three intensities were 40 lux, 80 lux and 160 lux (± 1 lux). The spectra of the three test lighting conditions were measured with an X-Rite i1Pro spectrophotometer (Figure 2). The α -opic irradiance



Figure 1 Lighting room showing the position of the participant and the luminaires

for each lighting was calculated according to the new CIE S 026 /E:2018¹⁸ (Table 1).

2.3. Experiment protocol

Each participant completed four sessions over four nights, all starting at the same time (8 p.m.). Participants were fitted with EEG electrodes prior to the start of the exposure. The order of the conditions (Dim, Blue 40 lux, 80 lux and 160 lux) was selected randomly for each participant to avoid potential sequence effects. Sessions were separated by at least 72 hours for the same participant to avoid potential carry-over effects.

During each evening study EEG was continuously recorded over 60 minutes. EEG data was collected using B-Alert Live Software with wireless advanced brain monitoring (ABM) EEG device (X10 headset with standard sensor strips). Recordings consisted of EEG with nine electrode positions (Fz, Cz,

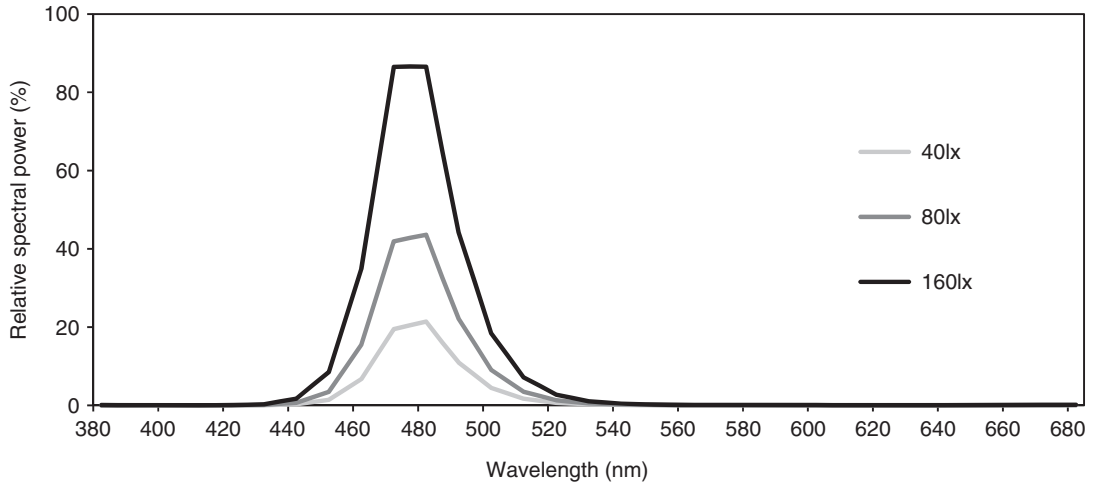


Figure 2 Spectral power distributions of three test lighting conditions

Table 1 α -Opic irradiance (mW/m^2) for three lighting conditions and 1 lux daylight (for reference)

α -opic irradiance for	S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
40 lux	157.98	131.44	80.48	277.64	324.25
80 lux	340.38	273.25	167.00	580.18	678.81
160 lux	716.54	557.33	340.56	1187.21	1389.97
1 lux D65	0.82	1.46	1.63	1.45	1.33

Poz, F3, F4, C3, C4, P3 and P4) and two reference mastoid electrodes. The electrode impedance test was performed each time before experiment to ensure the good conductivity between the scalp and electrodes, thus the good quality of the signal. The EEG signal was band-passed to 1 to 40 Hz and decontaminated using ABM's validated artefact identification and decontamination algorithms which identify and remove five artefact types: electromyogram, electrooculogram, excursions, saturations and spikes. Power spectral density (PSD) was computed by performing Fast Fourier Transform with application of a Kaiser window. PSD of selected 1-Hz bins was averaged after application of a 50% overlapping window across three one-second overlays.

Under the Dim condition, participants were kept in the dim light for 60 minutes. Under the Blue condition, test lights were energized for 40 minutes, preceded by a 20-minute dim (<1 lux) period.

Subjective sleepiness was evaluated using the KSS, a self-reporting scale that ranges from 1 ('extremely alert') to 9 ('very sleepy, fighting sleep').¹⁹ This scale has previously been shown to be sensitive to changes in sleepiness and the alerting effects of lights.^{12,20} The KSS was rated three times (every 20 minutes – at the 20th, 40th and 60th minutes) during each session. Participants were asked to rate themselves from 1 to 9, according to their sleepiness. For the duration of the 60 minutes the participants were free to read a book. They were also asked to keep their eyes open and reduce head movement

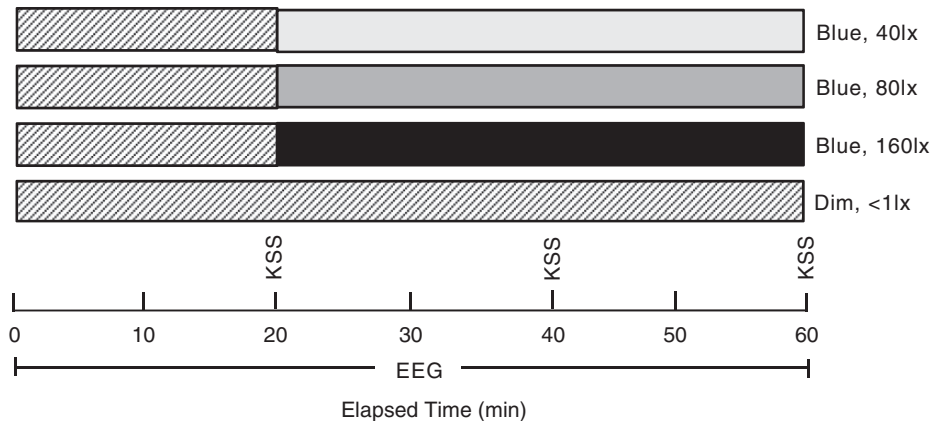


Figure 3 Experimental design

throughout the experiment. No other activities (e.g. using electronic devices, eating or talking) were allowed (Figure 3).

3. Results

3.1. EEG

EEG measures collected from nine electrode sites were averaged to produce overall EEG PSD, and then grouped into the following frequency bins: 5–9 Hz (theta alpha), 8–9 Hz (lower alpha), 11–13 Hz (higher alpha), and 13–30 Hz (beta). In each frequency range, EEG power averaged over the 40 minutes under test lighting was normalized to the initial 20 minutes of dim light period. One-way analysis of variance (ANOVA) was performed using the normalized power in each of the frequency ranges studied. *Post-hoc t* tests (with Bonferroni corrections) were used to further compare the significance between lighting conditions. Analyses were performed using IBM SPSS Statistics 25 and the results for beta ranges are listed in Table 2.

One-way ANOVA revealed a close to significant main effect of lighting condition in the normalized theta alpha ($F_{3,28} = 2.785$; $p = 0.059$) and a significant main effect of

Table 2 Pairwise comparisons for EEG beta power

Pairs	Significance*
Dim–40 lux	1.000
Dim–80 lux	1.000
Dim–160 lux	0.001*
40–80 lux	1.000
40–160 lux	0.005*
80–160 lux	0.025*

*Statistically significant ($p \leq 0.05$).

lighting condition in beta ($F_{3,28} = 7.571$; $p = 0.001$). No significant difference was observed in lower alpha ($F_{3,28} = 0.477$; $p = 0.701$) or higher alpha ($F_{3,28} = 0.385$; $p = 0.765$) ranges. *Post-hoc* pairwise comparisons found significant differences between Dim and 160 lux, 40 lux and 160 lux, 80 lux and 160 lux in beta range (Table 2). Figure 4 shows the results of normalized power for four lighting conditions in four frequency ranges studied (where * indicates statistical significance). Power in theta alpha was lower after exposure to 40 lux and 160 lux blue lights than after remaining in the Dim condition. Power in beta range was significantly higher after exposure to 160 lux blue lights than after exposure to the other three lighting

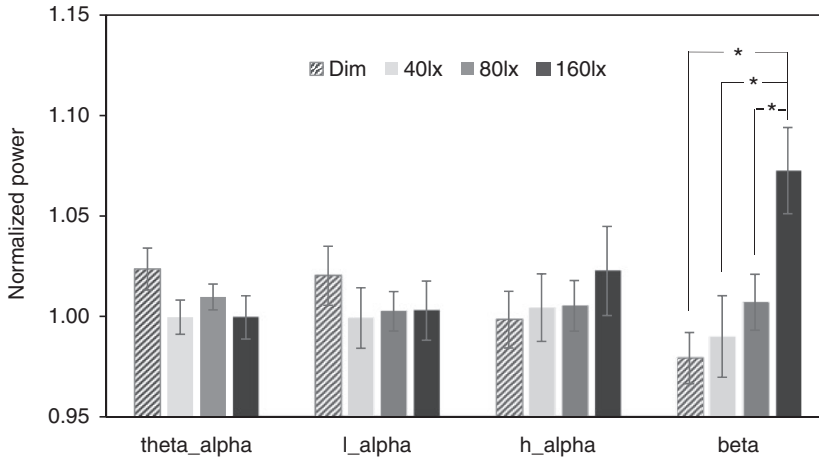


Figure 4 Mean ± standard error of the mean normalized EEG power for four frequency ranges

conditions. Compared to Dim, exposure to 160 lux blue light has also reduced lower alpha power and increased high alpha power, although these differences did not reach statistical significance ($p > 0.05$). Figure 5 shows the individual EEG beta power values.

3.2. Subjective sleepiness (KSS)

Mean scores over the experimental condition were normalized to the initial Dim session. One-way ANOVA was performed and *post-hoc t* tests (with Bonferroni corrections) were used to further compare the significance between lighting conditions. The results are listed in Table 3.

ANOVA revealed a significant difference between Dim and 160 lux conditions. Figure 6 shows the results for the normalized KSS scores under four lighting conditions (where * indicates statistical significance). Mean score in 160 lx condition was significantly lower than score in Dim condition (a lower KSS score means more alertness). Mean scores under 40 lux and 80 lux conditions were lower than score under the Dim, and higher than score under the 160 lux condition, although these differences did not reach statistical significance ($p > 0.05$). Figure 7 shows the individual KSS scores.

Table 3 Pairwise comparisons for KSS scores

Pairs	Significance*
Dim–40 lux	0.240
Dim–80 lux	0.252
Dim–160 lux	0.024*
40–80 lux	0.973
40–160 lux	0.209
80–160 lux	0.198

KSS: Karolinska Sleepiness Scale.

*Statistically significant ($p \leq 0.05$).

4. Discussion

This study investigated how exposures to short-wavelength lights of three different intensities (40 lux, 80 lux and 160 lux) affect objective and subjective alertness during the night-time. Results showed the effect of intensity on EEG theta alpha (5–9 Hz) and beta (13–30 Hz) powers. Exposure to 40 lux and 160 lux lights reduced theta alpha power compared to remaining in the Dim condition. Exposure to 160 lux light significantly increased beta power compared to the Dim, 40 lux and 80 lux light conditions. It has been observed and agreed in many studies that the decrease in theta alpha power and the

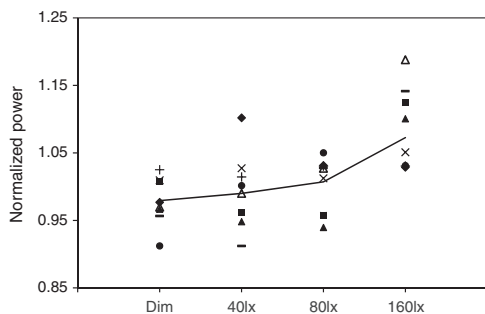


Figure 5 Individual EEG power values in beta range (the same symbol indicates the values obtained from the same participant)

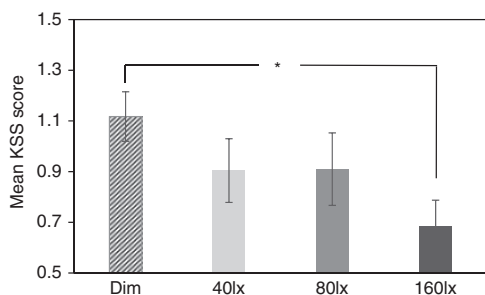


Figure 6 Mean \pm standard error of the mean normalized KSS scores (lower scores indicate greater alertness)

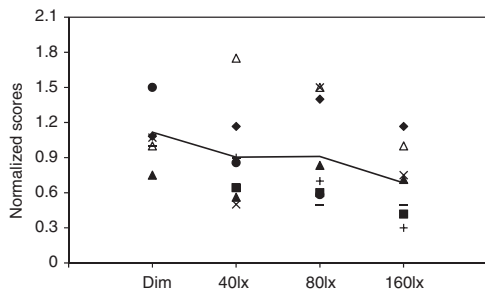


Figure 7 Individual KSS scores (the same symbol indicates the values obtained from the same participant)

increase in beta power indicate greater alertness. It has also been suggested that reduction in EEG alpha power (8–12 Hz) is related to alertness increase, and the increase in high-frequency alpha activity especially is

associated with the circadian regulation of arousal.²¹ We did not find a significant effect on lower or higher alpha power, which might be due to the limited sample size. Considering the practical difficulties in conducting the study, we included eight participants, which is relatively small (but nevertheless sufficient to show some statistically significant results in theta alpha and beta ranges). The results of lower and higher alpha actually showed the consistent trend with other results, although these are not statistically significant. To combine the findings in EEG together, this study showed that exposure to 160 lux blue light significantly increases alertness compared to Dim, 40 lux and 80 lux conditions; exposure to 40 lux and 80 lux also increase alertness compared to Dim light, although not as significant as 160 lux light. Furthermore, 40 lux and 80 lux exposure did not show a large difference between each other.

In the result alpha power was split into two parts. The full alpha range was initially examined and there were no significant results. However, in some studies, high alpha power alone was examined (as high alpha is also suggested to be a specific marker for alertness). Therefore in this study, alpha power was then split into higher alpha and lower alpha for further analysis. As shown in Figure 4, the two parts seem to have opposite patterns. In lower alpha, Dim light condition has the greatest power, whereas in higher alpha, 160 lux light condition has the greatest power. One possible explanation might be that the lower part of alpha is close to the theta range (where alertness is negatively related to the power), and the higher part of alpha is closer to beta (where alertness is positively related to the power). However, these results would need further study to assess this possibility.

The subjective alertness (KSS) reported is consistent with the above EEG results. Participants rated themselves as sleepier in

the Dim condition, and more alert under the blue lights. With the Dim condition having the highest score and 160 lux having the lowest, this again shows a significant alerting effect of 160 lux compared to Dim light. Both 40 lux and 80 lux exposure were rated in between the Dim and 160 lux conditions, at about the same level. In addition, participants were asked to report changes on their bed time and any other unusual feelings (including a sleep problem) after experiments. As a result, there is no report on unusual bed time shifts after exposure; however, one participant reported suffering from headache at night after being kept in blue light.

Very few studies have so far looked into the effect of intensity of short-wavelength light on alertness. In some studies, blue light of 40 lux has been suggested to have an alerting effect.^{9,10} Some other studies, for example, have compared light of 40 lux at 2500 K, 3000 K and 6500 K,²² and light of 295 lux at 2700 K and 209 lux at 5600 K.²³ These studies, however, have focussed on spectral composition or exposure duration, rather than light intensity.

This study extends the research on the effect of intensity on light-induced alertness. The findings suggested that, firstly, a certain level of intensity is needed to induce alertness (to produce a significant effect a higher level of intensity might be needed). Secondly, the relations between intensity and alertness change is not linear, which certain parameters, e.g. the intensity that could maximally increase alertness might be identified. Lastly, these threshold intensities could be difficult to measure. Assuming that the relations between intensity and alertness are not linear, the closer to the threshold, the smaller the difference would be. Study of higher precision is required in order to detect smaller effect, e.g. a bigger sample size. The practical difficulties in conducting such experiment limit the sample size that is normally included, whereas the small sample size further limits the statistical power to detect the subtle effect. The other limitation

is that reading a book during the experiment might have affected participants' brain activity, although this is difficult to avoid. In similar studies, participants will normally be allowed to conduct light tasks such as crossword puzzles¹¹ over the relatively long exposure hours. However, they were asked to read continuously and try to maintain their mood and attention throughout the session, so to control the potential effect as much as possible.

5. Conclusions

This study provides some evidence that short-wavelength light exposure in the evening can increase human alertness and that this can occur relatively quickly (even though some other studies have suggestion that melatonin inhibition, for example, may have a longer time course). Both objective and subjective results also suggest that for the lighting conditions tested in the present study, light of higher intensity has a stronger alerting effect than light of lower intensity. These findings, in themselves, do not enable a threshold effect to be identified. However, the methodology described in this study may provide a basis for future on-going work to address this question explicitly.

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References

- 1 Hattar S, Lucas RJ, Mrosovsky N, Thompson S, Douglas RH, Hankins MW, Lem J, Biel M, Hofmann F, Foster RG, Yau KW. Melanopsin and rod-cone photoreceptive systems account for all major accessory visual functions in mice. *Nature* 2003; 424: 75.
- 2 Figueiro MG, Bullough JD, Bierman A, Fay CR, Rea MS. On light as an alerting stimulus at night. *Acta Neurobiologiae Experimentalis* 2007; 67: 171.
- 3 Figueiro MG, Bierman A, Plitnick B, Rea MS. Preliminary evidence that both blue and red light can induce alertness at night. *BMC Neuroscience* 2009; 10: 105.
- 4 Figueiro MG, Rea MS. The effects of red and blue lights on circadian variations in cortisol, alpha amylase, and melatonin. *International Journal of Endocrinology*. DOI: 10.1155/2010/829351.
- 5 Figueiro MG, Rea MS. Sleep opportunities and periodic light exposures: impact on biomarkers, performance and sleepiness. *Lighting Research and Technology* 2011; 43: 349–369.
- 6 Sahin L, Figueiro MG. Alerting effects of short-wavelength (blue) and long-wavelength (red) lights in the afternoon. *Physiology and Behavior* 2013; 116: 1–7.
- 7 Badia P, Myers B, Boecker M, Culpepper J, Harsh JR. Bright light effects on body temperature, alertness, EEG and behavior. *Physiology and Behavior* 1991; 50: 583–588.
- 8 Jung TP, Makeig S, Stensmo M, Sejnowski TJ. Estimating alertness from the EEG power spectrum. *IEEE Transactions on Biomedical Engineering* 1997; 44: 60–69.
- 9 Figueiro MG, Sahin L, Wood B, Plitnick B. Light at night and measures of alertness and performance: implications for shift workers. *Biological Research for Nursing* 2016; 18: 90–100.
- 10 Okamoto Y, Rea MS, Figueiro MG. Temporal dynamics of EEG activity during short-and long-wavelength light exposures in the early morning. *BMC Research Notes* 2014; 7: 113.
- 11 Plitnick B, Figueiro MG, Wood B, Rea MS. The effects of red and blue light on alertness and mood at night. *Lighting Research and Technology* 2010; 42: 449–458.
- 12 Lockley SW, Evans EE, Scheer FA, Brainard GC, Czeisler CA, Aeschbach D. Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep* 2006; 29: 161–168.
- 13 Chang AM, Aeschbach D, Duffy JF, Czeisler CA. Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness. *Proceedings of the National Academy of Sciences* 2015; 112: 1232–1237.
- 14 Cajochen C. Alerting effects of light. *Sleep Medicine Reviews* 2007; 11: 453–464.
- 15 Cajochen C, Zeitzer JM, Czeisler CA, Dijk DJ. Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness. *Behavioural Brain Research* 2000; 115: 75–83.
- 16 Boivin DB, Duffy JF, Kronauer RE, Czeisler CA. Dose-response relationships for resetting of human circadian clock by light. *Nature* 1996; 379: 540.
- 17 Zeitzer JM, Dijk DJ, Kronauer RE, Brown EN, Czeisler CA. Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression. *The Journal of Physiology* 2000; 526: 695–702.
- 18 Commission Internationale de l'Éclairage. *CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*. CIE S 026/E:2018. Vienna: CIE, 2018.
- 19 Shahid A, Wilkinson K, Marcu S, Shapiro CM. Karolinska sleepiness scale (KSS). In: *STOP, THAT and One Hundred Other Sleep Scales*. New York: Springer, 2011.
- 20 Cajochen C, Brunner DP, Kräuchi K, Graw P, Wirz-Justice A. EEG and subjective sleepiness during extended wakefulness in seasonal affective disorder: circadian and homeostatic influences. *Biological Psychiatry* 2000; 47: 610–617.
- 21 Aeschbach D, Matthews JR, Postolache TT, Jackson MA, Giesen HA, Wehr TA. Two circadian rhythms in the human electroencephalogram during wakefulness. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* 1999; 277: R1771–1779.

- 22 Chellappa SL, Steiner R, Blattner P, Oelhafen P, Götz T, Cajochen C. Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? *PLoS One* 2011; 6: e16429.
- 23 Nagare R, Plitnick B, Figueiro MG. Effect of exposure duration and light spectra on nighttime melatonin suppression in adolescents and adults. *Lighting Research and Technology* 2019; 51: 530–543.