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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 nighttime. 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 (40lx, 80lx and 160lx). 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 160lx light than after they were exposed to 40lx, 80lx light or remained in darkness. Also, the alpha theta was significantly lower under 160lx light then 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.

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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 nighttime, 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 process [1]) 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.

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 nighttime.[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.[9] 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.[10] 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.[11] Red and blue lights have been found to increase beta signals and reduce sleepiness relative to preceding dim light exposure.[12] By looking into individual EEG frequencies, it was also suggested that short-wavelength light in particular enhances high alpha activity.[13] With these findings, it is generally agreed that decrease in low EEG frequencies (theta alpha) power and 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.[14] 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.[15]

A study has looked at how three different illuminances ranging from 3 lx to 9100 lx affect EEG activity over 6.5 hours of exposure, and a dose-response relationship was found in subjective alertness and EEG power.[16] Other studies have also demonstrated a non-linear relationship between light intensity and circadian shifts.[17,18] 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 nighttime. 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 Karolinska Sleepiness Scale (KSS) and EEG respectively. The objective, specifically, is to investigate the effect of three intensities (40lx, 80lx and 160lx) of a short-wavelength light (λmax = 475nm), compared to remain in darkness (<1lx), 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 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.

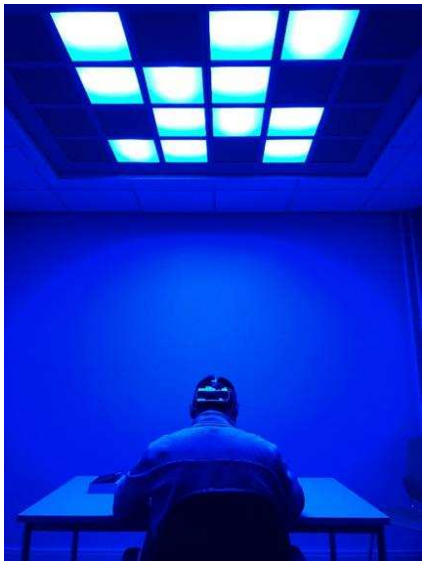

Figure 1 – Lighting Room showing the position of the participant and the luminaires

Four light settings were used: a dim (CCT 2000 K, <1 lx) 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 lx, 80 lx and l60 lx (±1 lx). The spectra of the three test lighting conditions were measured with an X-Rite i1Pro spectrophotometer (Figure 2). The α-

opic irradiance for each lighting was calculated according to the new CIE S 026 /E:2018[19] (Table 1).

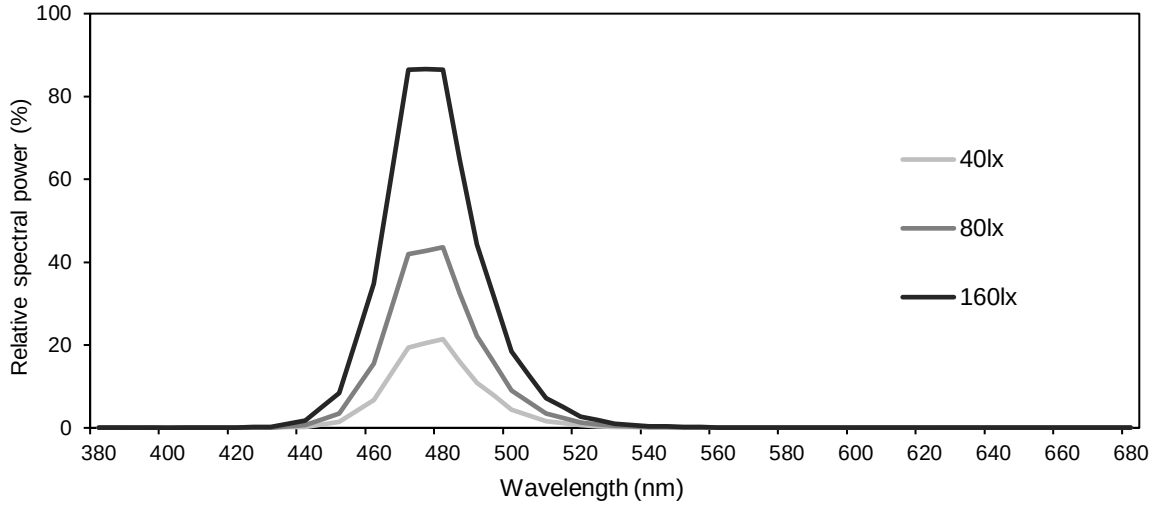

Figure 2 – Spectral power distribution of three test lighting conditions

Table1 - α-opic irradiance (mW/m^2) for three lightings and 1lx Daylight (for reference)

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

2.3 Experiment protocol

Each participant completed four sessions over four nights, all starting at the same time (8pm). Participants were fitted with EEG electrodes prior to the start of the exposure. The order of the conditions (Dim, Blue 40 lx, 80 lx and 160 lx) 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 (BLS) with wireless Advanced Brain Monitoring (ABM) EEG device (X10 headset with standard sensor strips). Recordings consisted of EEG with 9 electrode positions (Fz, Cz, 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 5 artefact types: electromyogram (EMG), electrooculogram (EOG), excursions, saturations, and spikes. Power spectral density (PSD) was computed by performing Fast Fourier Transform (FFT) 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-min dim (<1lx) period.

Subjective sleepiness was evaluated using the Karolinska Sleepiness Scale (KSS), a self-reporting scale that ranges from 1 (‘extremely alert’) to 9 (‘very sleepy, fighting sleep’).[20] This scale has previously been shown to be sensitive to changes in sleepiness and the alerting effects of lights.[21,22] 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 throughout the experiment. No other activities (e.g. using electronic devices, eating or talking) were allowed (Figure 3).

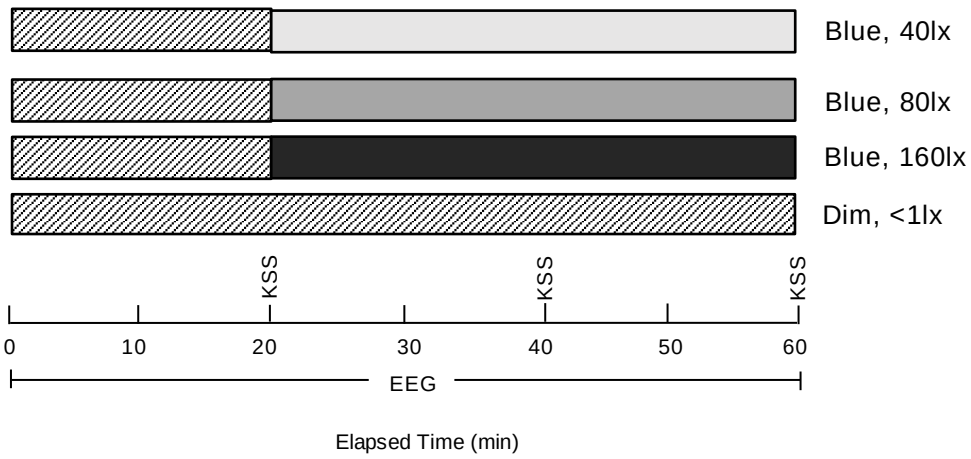

Figure 3 – Experimental design

3 Results

3.1 EEG

EEG measures collected from 9 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.

Table 2 – Pairwise comparisons for EEG beta power

Pairs	Sig.*
Dim-40lx	1.000
Dim-80lx	1.000
Dim-160lx	0.001*
40lx-80lx	1.000
40lx-160lx	0.005*
80lx-160lx	0.025*

* Statistically significant (p≤0.05).

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 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 lx, 40 lx and 160 lx, 8 0lx and 160 lx in beta range (Table 2). Figure 4 shows the results of normalized power for four lighting conditions in four frequency ranges studied (where *indicates significance). Power in theta alpha was lower after exposure to 40 lx and 160 lx blue lights than after remaining in the Dim condition. Power in beta range was significantly higher after exposure to 160 lx blue lights than after exposure to the other three lighting conditions. Compared to Dim, exposure to 160 lx blue light has also reduced lower alpha power and increased high alpha power, although these differences did not reach statistical significance ($p>0.05$).

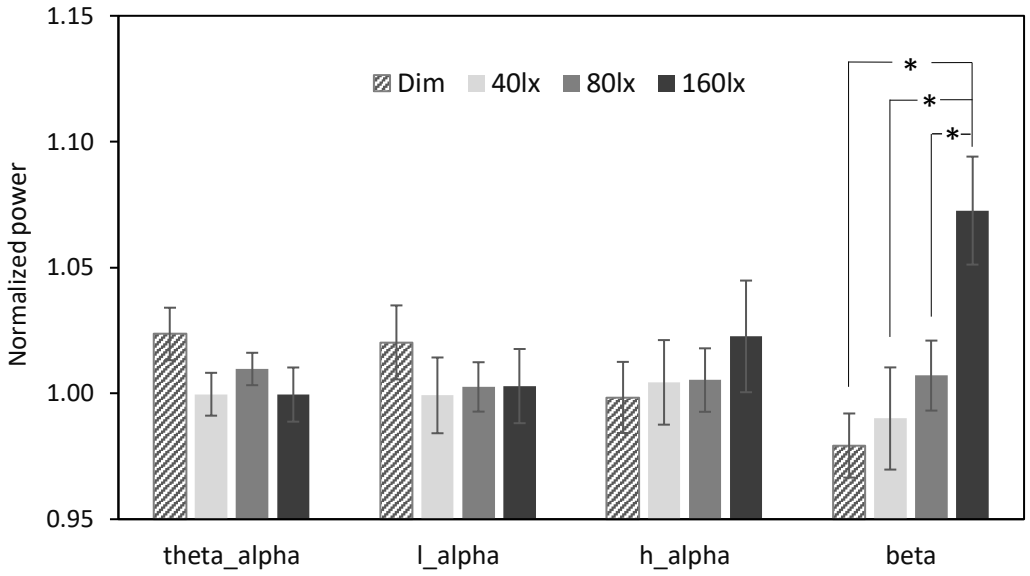

Figure 4 – Mean ± standard error of the mean normalized EEG power for four frequency ranges

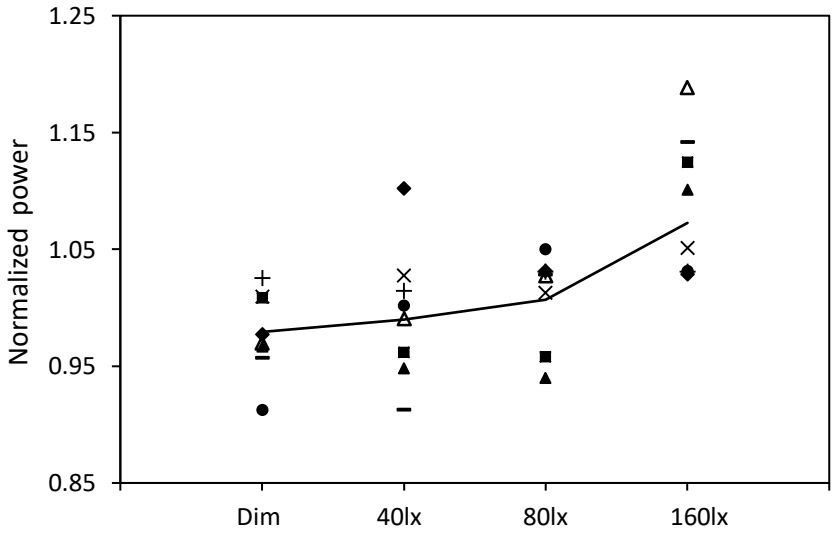

Figure 5 - Individual EEG power values in beta range (the same symbol indicates the values obtained from the same participant)

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.

Table 3 – Pairwise comparisons for KSS scores

Pairs	Sig.*
Dim-40lx	0.240
Dim-80lx	0.252
Dim-160lx	0.024*
40lx-80lx	0.973
40lx-160lx	0.209
80lx-160lx	0.198

* Statistically significant (p≤0.05).

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

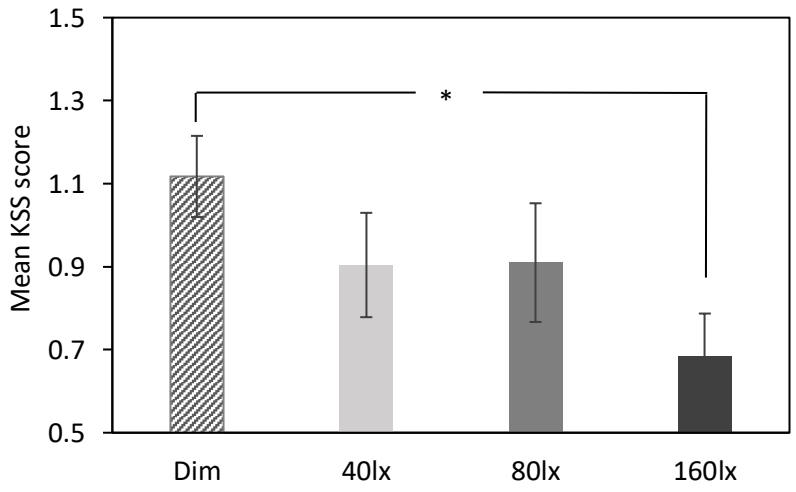

Figure 6 – Mean ± standard error of the mean normalized KSS scores (lower scores indicate greater alertness)

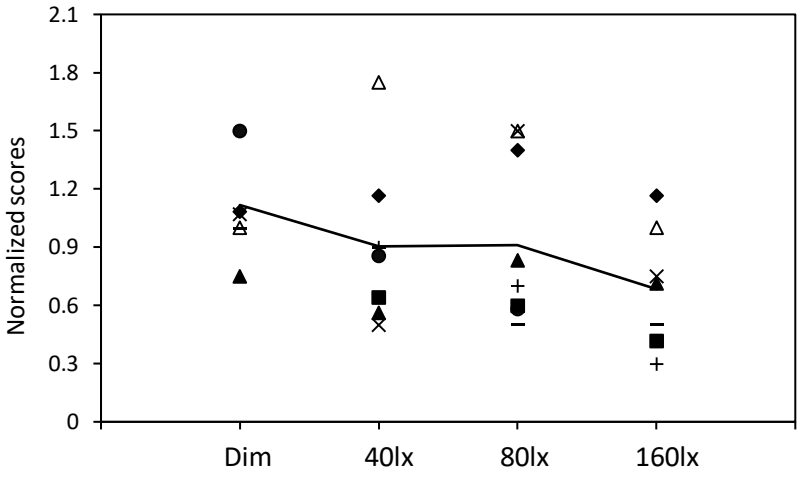

Figure 7 - Individual KSS scores (the same symbol indicates the values obtained from the same participant)

4 Discussion

This study investigated how exposures to short-wavelength lights of three different intensities (40 lx, 80 lx and 160 lx) affect objective and subjective alertness during the nighttime. Results showed the effect of intensity on EEG theta alpha (5-9 Hz) and beta (13-30 Hz) power. Exposure to 40 lx and 160 lx lights reduced theta alpha power compared to remaining in Dim condition. Exposure to 160 lx light significantly increased beta power compared to Dim, 40 lx and 80 lx light conditions. It has been observed and agreed in many studies that the decrease in theta alpha power and the 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.[23] 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 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 lx blue light significantly increases alertness compared to Dim, 40 lx and 80 lx conditions; exposure to 40 lx and 80 lx also increase alertness compared to Dim light, although not as significant as 160 lx light. Furthermore, 40 lx and 80 lx 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 was 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 it shows in Figure 4, two parts seem to have opposite patterns. In lower alpha, Dim light condition has the greatest power, whereas in higher alpha, 160 lx light condition has the greatest power. One possible explanation might be that the lower part of alpha is close to 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 figure more.

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 lx having the lowest, this again shows a significant alerting effect of 160 lx compared to Dim light. 40 lx and 80 lx exposure were rated in between the Dim and 160 lx conditions, at about the same level In addition, participants were asked to report changes on their bed time and any other unusual feelings (including 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 lx has been suggested to have an alerting effect.[10,11] Some other studies, for example, have compared light of

40 lx at 2500 K, 3000 K and 6500 K,[24] and light of 295 lx at 2700 K and 209 lx at 5600 K.[25] 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 maximum increase alertness might be identified. Lastly, these threshold intensities could be difficult to measure. Assuming that the relations between intensity and alertness is 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 limit 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 puzzles[12] 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.

Declaration of conflicting interests

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