International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

PP18

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DOI 10.25039/x46.2019.PP18

from

CIE x046:2019

**Proceedings
of the
29th CIE SESSION**

Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

The paper has been presented at the 29th CIE Session, Washington D.C., USA, June 14-22, 2019. It has not been peer-reviewed by CIE.

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DOI 10.25039/x46.2019.PP18

Abstract

Short-wavelength light has been known to have an alerting effect on human alertness in the night-time. However, there is very few study focus on the effect of intensity of light on alertness. In this study we evaluated 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 was 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 showed 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 alerting effect.

Keywords: Alertness, Lighting, EEG

1 Introduction

It is now well known that exposure to light in the evening and night-time, especially of short-wavelength (but not necessarily limited to short wavelengths), leads to an increase in alertness in humans. There is evidence that exposure to light at night promotes alertness in humans and it has been suggested that this effect is related to circadian disruption. Circadian disruption is associated with reduced levels of the hormone melatonin and is primarily mediated by activation of the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) which respond to short-wavelength light most strongly.

It has been shown that 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 (Figueiro, 2007). However, some other studies have also shown that acute melatonin suppression is not needed for light to affect alertness at night. It has also been demonstrated that both blue and red lights increase beta power and reduced alpha theta power relative to darkness, though only blue light suppressed melatonin significantly (Figueiro, 2009). These findings suggest that although melatonin level is associated with circadian clock and sleep, electroencephalogram (EEG) measures might reflect instant neuroendocrine responses and objective alertness.

Previous studies have used many measures in order to evaluate alertness. Subjective sleepiness is often rated using Karolinska Sleepiness Scale (KSS), a self-reported scale that ranges from 1 ('very alert') to 9 ('very sleepy, fighting sleep'). The KSS measures situational sleepiness and it is sensitive to fluctuations (Shahid, 2011). As a more quantitative measure, EEG has also been commonly used in the assessment of objective sleepiness. Research explored the correlation between EEG power spectrum and alertness (Jung, 1997).

It has been shown that EEG power in certain frequency ranges changes significantly as the status of the subject changes. One study investigated how 48-minute exposures to three lighting conditions (red, blue and dark) affected EEG measures in subjects; it was found that alpha and alpha theta power were both lower after the exposure to red and blue lights compared to darkness (Sahin, 2013). Another study also 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 (Okamoto, 2014). Red

and blue lights have been found to increase beta, reduced sleepiness relative to preceding dim light exposure, although these did not reach statistical significance (Plitnick, 2010). By looking into individual EEG frequencies, measuring melatonin level and conducting a vigilance test, it was suggested that short-wavelength light enhanced high alpha activity (Lockley, 2006), which is seen as a specific marker of the endogenous circadian drive for alertness (Aeschbach, 1999). It has also been shown that light can have an impact on EEG measures without affecting melatonin levels (Figueiro, 2016). As we see, the impact of light on alertness is a complex physical, physiological and psychological activity that can be resulted from different pathways, where through hormonal melatonin is one of them. EEG, however, reflects a more instant alertness fluctuation.

Short-wavelength light is becoming a critical safety concern. For example, there has been concern about home lighting in the evening, where warm Tungsten light is increasingly being replaced by cooler solid-state lighting; the use of emissive electronic displays may also be responsible for the increasing sleep problem (Chang, 2015). However, there is no consensus yet about the threshold of light intensity required to produce these effects. It is likely that the threshold will depend on the wavelength distribution of the light, how long the exposure is for, and the time of day that the exposure takes place; this may explain in part why it has so far proven difficult to measure the threshold. A study has looked at how three different illuminances ranging from 3 to 9100lx affect EEG measure over 6.5 hours of exposure, and a dose-response relationship was found in subjective alertness and theta alpha power (Cajochen, 2000). Many other such studies have demonstrated a non-linear relationship between light intensity and circadian shifts (Boivin, 1996; Zeitzer, 2000). It is generally agreed that brighter light has a stronger alerting ability than dimmer light. The question remains, however, whether there is a threshold and what that threshold is? Crucially, is the light from electronic devices we constantly use at night bright enough to trigger these effects?

Very few studies have looked into the effect of intensity of short wavelength light. Blue light of 40lx has been investigated in some studies (Sahin, 2013; Okamoto, 2014), and an alerting effect has been suggested. Some other studies, for example, have looked at light of 40lx at 2500K, 3000K and 6500K (Chellappa, 2011), and light of 295lx at 2700K and 209lx at 5600K (Nagare, 2018). These studies, however, focussed on spectral composition or exposure duration, rather than light intensity.

This work is concerned with measuring the threshold intensity of light needed to increase alertness and uses both subjective (KSS) and objective (EEG) methods, based on the notion that melatonin is not the only mechanism contributing to light-induced alertness. In this study, specifically, the objective is to investigate the effect of three intensities (40lx, 80lx and 160lx) of a blue light ($\lambda_{max} = 470$ nm), compared to darkness (<1 lx), on human alertness during the evening.

2 Experimental

2.1 Subjects

Nine participants were recruited and all of them went through a pre-screening procedure using an adapted version of Munich ChronoType Questionnaire (Roenneberg, 2003). 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/early chronotypes were excluded. The study was approved by the University of Leeds Ethics Committee and all subjects signed informed consent. An information sheet was given and participants were asked to refrain from caffeine and alcohol intake 3 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 colour blindness. One participant did not finish all experimental sessions, and their data was excluded from further analysis. In total, the result produced from eight subjects (five females, mean age 28) is reported here.

2.2 Lighting conditions

Light was delivered through 12 luminaires (LEDs, provided by Thouslight Lighting System) mounted in the ceiling of a room with white walls and grey carpets. Participants were asked to sit inside the room whilst reading, with a white table in front of them (Figure 1).

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

Four light settings were used: a dark control (2000K, <1lx at eye level) and three experimental lighting conditions). The short wavelength light had a peak at about 470nm and was approximately Gaussian with a half-width half-height of 35nm. Three intensities were 40, 80 and 160lx at eye level. The spectra of the three test lights were measured with an Xrite i1 Display pro (see Figure 2).

Figure 2 – Spectra of three test lighting conditions

2.3 Experiment protocol

Each subject 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 (dark, 40lx, 80lx and 160lx) was selected randomly for each of the participants to avoid potential sequence effects. During each evening study EEG was continuously recorded over 60 minutes (20 minutes for dark adaption and 40 minutes for the blue light) and subjective sleepiness (which was assessed using the KSS) was rated every 20 minutes (three times in total). 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 data was collected using B-Alert Live Software (BLS) with wireless 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 artifact identification and decontamination algorithms which identify and remove 5 artifact types: EMG, 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.

EEG measures collected from 9 electrode sites were averaged to produce overall EEG power, and was 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 experimental lighting was normalized to the initial 20 minutes of dark adaption. One-way analysis of variance (ANOVA) was performed using the normalized power in each of the frequency ranges studied. *Post-hoc* (with LSD) was used to further compare the significance between lighting conditions. Analyses were performed using IBM SPSS Statistics 25 and the results for theta alpha and beta ranges are listed in Table 1.

Table 1 – Pairwise comparisons for EEG theta alpha and beta power

	Theta alpha	Beta
Pairs	Sig.*	
Dark-40lx	0.037 *	0.508
Dark-80lx	0.189	0.214
Dark-160lx	0.012 *	0.000 *
40lx-80lx	0.407	0.553
40lx-160lx	0.610	0.001 *
80lx-160lx	0.186	0.004 *

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

One-way ANOVA revealed a significant main effect of lighting conditions in the normalized theta alpha and beta ranges. Significant differences are found between: dark - 40lx and dark - 160lx in theta alpha; dark - 160lx, 40lx - 160lx and 80lx - 160lx in beta. Significant difference was not observed in lower alpha or high alpha range. 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 significantly lower after exposure to 40lx and 160lx blue lights than after remaining in the dark condition. Power in beta range was significantly higher after exposure to 160lx blue lights than after exposure to the other three lighting conditions. Compared to dark, exposure to 160lx 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 – Average $\pm$ standard error of the mean normalized EEG power for four frequency ranges

3.2 Subjective sleepiness (KSS)

Subjective sleepiness was rated three times (at the 20 min, 40 min, and at the end) using KSS. Subjects were asked to rate themselves as ranged from 1 (extremely alert) to 9 (very sleepy, great effort to keep awake, fighting sleep). Mean score over the experimental condition was normalized to the initial dark adaption. One-way ANOVA was performed and *post-hoc* (with LSD) was used to further compare the significance between lighting conditions. The results are listed in Table 2.

Table 2 – Pairwise comparisons for KSS scores

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

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

ANOVA showed a significant difference between dark and 160lx conditions. Figure 5 shows the results for the normalized KSS scores under four lighting conditions (where * indicates significance). Mean score in 160lx condition was significantly lower than score in dark condition (a lower KSS score means more alertness). Mean scores under 40 lx and 80 lx conditions were lower than score under the dark, and higher than score under the 160lx condition, although these differences did not reach statistical significance ($p > 0.05$).

Figure 5 – Average $\pm$ standard error of the mean normalized KSS scores (lower scores indicate greater alertness)

4 Discussion

The present study investigated how exposures to short wavelength lights of three different intensities (40lx, 80lx and 160lx) affect objective and subjective alertness during the night time. EEG showed that intensity has a significant effect on theta alpha (5-9Hz) and beta (13-30Hz) power. Exposure to 40lx and 160 lx lights significantly reduced theta alpha power compared to dark. Exposure to 160lx light significantly increased beta power compared to dark, 40lx and 80lx lights. It has been observed and agreed in many studies that the reduction in theta alpha and the increase in beta indicate greater alertness. The results of this study showed that exposure to 160lx blue light significantly increases alertness compared to dark, 40 lx and 80lx; exposure to 40lx and 80 lx might also increase alertness compared to dark, although not as significant as 160lx light. Furthermore, it did not show a large difference between 40 and 80lx exposure.

Subjective alertness (KSS) reported is consistent with EEG results. Subjects rated themselves as sleeper in the dark, and more alert under the blue lights. With the dark condition having the highest score and 160lx having the lowest, this again shows a significant alerting effect of 160lx compared to dark. 40lx and 80lx exposure were rated in between the dark and 160lx conditions, at about the same level.

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. threshold intensity that could maximum increase alertness might be identified.

5 Conclusions

The present 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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