Evaluation of the Alerting Effect of Light on Humans

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The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

Abstract

Light is believed to have alerting effects on human. This thesis consists of three studies that evaluate and compare alerting abilities between a blue and a green light, between three short-wavelength lights, and between two long-wavelength lights.

The first study compared electroencephalogram measures for nine participants under a blue light and a green light with equal intensity. Results reflected the current findings on the alerting effect of light and that the alerting effect is wavelength dependent. The methodology used in this study provided the basis for the next two studies.

Although the wavelength dependence of the alerting effect of light is quite well known, few studies have focused on the effect of intensity of light on alertness. The second study therefore evaluates the acute alerting ability of short-wavelength light of three different intensities (40 lx, 80 lx and 160 lx). Eight subjects participated in a 60-minute exposure protocol for four evenings, during which electroencephalogram as well as subjective sleepiness data were collected. Both objective and subjective results suggested that light of higher intensity has a stronger alerting effect than light of lower intensity. The results also suggested that further work should be done to investigate the relationship between the intensity of light and its alerting effect.

The third study explores the alerting ability of long-wavelength light at two intensities (40 lx and 160 lx) with the same experimental methodology as the previous study. Results showed that long-wavelength light is just as strong on acute alerting ability as short-wavelength light. This finding indicates that although short-wavelength light may impact alertness through the circadian system, long-wavelength light will have to achieve this effect through other pathways.

List of Abbreviations

NIF	Non-image Forming
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells
CCT	Correlated Colour Temperature
EEG	Electroencephalography
KSS	Karolinska Sleepiness Scale
CIE	Commission Internationale de l'Éclairage
SCN	Suprachiasmatic Nuclei
IF	Image-forming
AMD	Age-related Macular Degeneration
LED	Light-emitting Diode
LCD	Liquid Crystal Display
SAD	Seasonal Affective Disorder
OLED	Organic Light-emitting Diode
SI	International System of Units
MCTQ	Munich ChronoType Questionnaire
EOG	Electrooculogram
ECG	Electrocardiography
EMG	Electromyography
SPD	Spectral Power Distribution
PSD	Power Spectral Density
FFT	Fast Fourier Transform
SD	Standard Deviation
SEM	Standard Error of the Mean
ANOVA	Analysis of Variance

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Chapter 1
Introduction

Light influences a range of human biological functions, apart from vision, referred as the non-image forming (NIF) effect. Light is now known to be a potent stimulus for modulating circadian rhythm, hormonal systems, core-body temperature, sleep and even gene expression. Studies have shown that these biological effects of light are associated with the melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), that are present in the retina in addition to the conventional rods and cones [1]. Bright light exposure is shown to change the alertness-related cortical structure in the brain [2]. The alerting effect of light differs with wavelength, due to the spectral sensitivity of the ipRGCs to light. Experiments have demonstrated that short-wavelength light (460 nm) has a stronger alerting effect than shorter (430 nm) or longer wavelengths (550 nm or 630 nm)[3]. The ipRGCs have maximal sensitivity at around 480 nm, which is attributed to the presence of melanopsin. However, light can still impact NIF functions in the absence of ipRGCs through rods and cones. And animals that cannot detect light for NIF effect are still capable of image formation [4].

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 increasing sleep problems. 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.

One study considered how three different illuminances ranging from 3 lx to 9100 lx affect Electroencephalography (EEG) activity over 6.5 hours of exposure, and a dose-response relationship was found in

subjective alertness and EEG power [5]. Other studies have also demonstrated a non-linear relationship between light intensity and circadian shifts [6]. 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.

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 evening and night time. 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].

Although earlier studies have linked the alerting effect of light to its ability to suppress melatonin, more recent studies have demonstrated that melatonin change is actually not needed to produce these effects. In one experiment conducted in the afternoon, during which melatonin level is low and has little impact, light exposure still showed an impact on both objective and subjective alertness [9]. Another study conducted in the early morning hours also suggested that the alerting effects of light may be mediated by mechanisms independent of acute melatonin suppression [10]. A study suggested that both short-wavelength and long-wavelength lights increased alertness at night, as shown in EEG power change, whereas only short-wavelength light suppressed melatonin significantly [11]. Another study compared white (2568 K) light and red (630 nm) light and showed that melatonin levels were suppressed by white light only. Results also suggested that red light can increase both alertness and certain types of performance at night without suppressing melatonin [12].

Many other studies have suggested that the underlying mechanism, by which light exposure improves alertness, is not solely driven by short wavelengths through melanopsin. However, it would be difficult to determine these mechanisms because light has multiple effects on

brain activities through parallel pathways. For example, studies suggest that ‘warm’ colours such as red and yellow evoke feelings of arousal while ‘cool’ colours such as blue are associated with calming feelings. Red, especially, has been associated with feelings of danger, rage and excitement. Red is also suggested to increase human receptiveness to external stimuli, therefore affecting the emotional responses [13]. The colours green and blue, in comparison, are associated with feelings of relaxation and calmness.

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 [12]. 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 [14]. By looking into individual EEG frequencies, it was also suggested that short-wavelength light in particular enhances high alpha activity [15]. 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.

The alerting effect of intensity of light on humans has so far received relatively little attention. This work is concerned with exploring the threshold intensity of light needed to evoke acute alertness responses in humans at night time. It assumes that melatonin suppression is not the only mechanism contributing to light-induced alertness.

This study has measured both subjective and objective alertness using the Karolinska Sleepiness Scale (KSS) and EEG respectively. The alerting effects of three short-wavelength lights and two long-wavelength lights were evaluated and compared with a dim light. A multi-night within-subject protocol was used to ensure good control on the human factor. As lighting is

closely related to everyone’s daily life and public health, this study aims to help developing understanding on the light-induced alertness. What is more, methodology described in this work may also provide a basis for future related on-going research.

Chapter 2
Literature Review

2.1 Human Brain

The human brain is the central organ of the human nervous system. It consists of the cerebrum, the brainstem and the cerebellum. An adult human brain weighs about 2% of the total body weight [16,17]. The cerebrum consists of cerebral hemisphere, which is the largest part of brain and overlies other structures. The outer region of hemispheres is cerebral cortex. It made up of grey matter that consists of layers of neurons, which deeply fold to give a convoluted appearance [18]. Figure 2.1.1 illustrates lobes of the brain. Each hemisphere has four main lobes – the frontal lobe, parietal lobe, temporal lobe, and occipital lobe. Three other lobes, a central lobe, a limbic lobe, and an insular lobe, are included by some sources [19]. The central lobe is included since it forms a distinct functional role [20].

The brainstem includes the midbrain, the pons, and the medulla oblongata. The cerebellum is behind the brainstem.

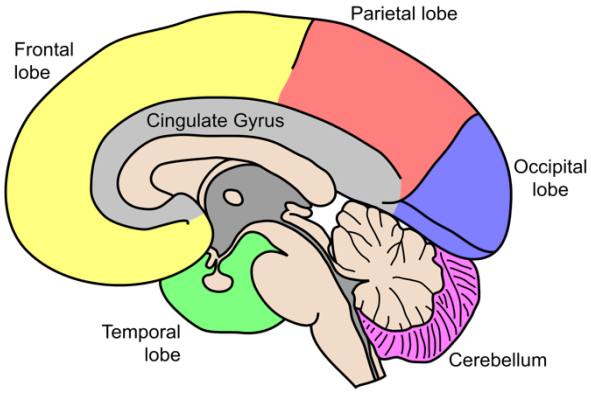


Figure 2.1.1: Lobes of the brain [21]

For humans, the brain is the source of consciousness. It does the thinking, learning, feeling and much else for the body. The brain also controls basic autonomic actions like breathing, digestion, heartbeat etc. These activities are regulated by unconscious functions of the brain and nervous system. The information gathered from outside world is sent through nerves into the

brain. The brain processes this information, allowing us to see, hear, smell, and so on. The brain also controls other activities such as muscle movement, heartbeat, and much more.

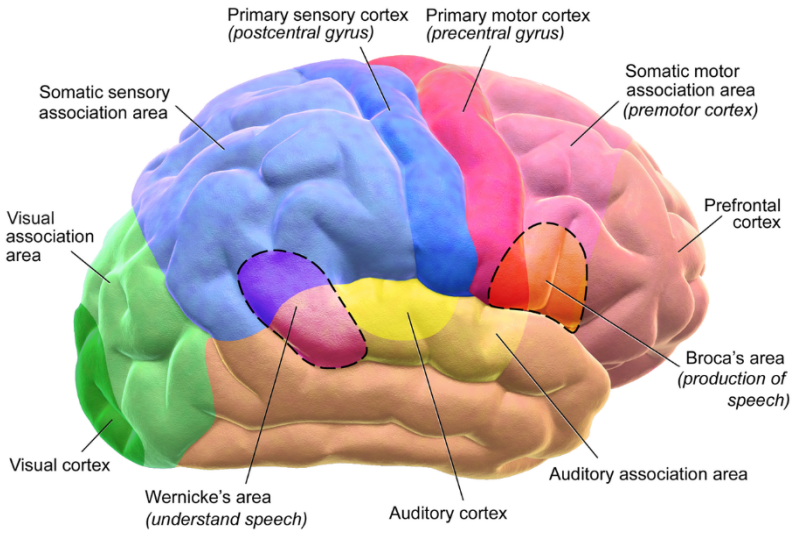


Figure 2.1.2: Functional areas of the human brain [21]

Figure 2.1.2 illustrates functional areas of the human brain. The cortex has about fifty different functional areas, of which two main functional areas are motor cortex and sensory cortex. The primary motor cortex occupies the rear portion of the frontal lobe. Primary sensory areas include the visual cortex, the auditory cortex, insular cortex, and the somatosensory cortex. The remaining parts are called the association areas. These areas receive input from the sensory areas as well as lower parts of the brain and are involved in some complex cognitive processes of perception and decision-making [22]. The main functions of the frontal lobe are to control attention, abstract thinking, behaviour, physical reactions and personality. The occipital lobe is related to visual processing, movement and colour recognition [23,24].

2.2 Circadian Rhythms, melatonin and ipRGC

2.2.1 The ipRGCs and the Non-image-forming Vision

The human eye is a paired sense organ that reacts to light and allows vision. The eye is made up of three layers, enclosing various structures. The outermost layer is composed of the cornea and sclera. The middle layer

consists of the choroid, ciliary body, pigmented epithelium and iris. The innermost is the retina. Figure 2.2.1.1 shows structure of eye.

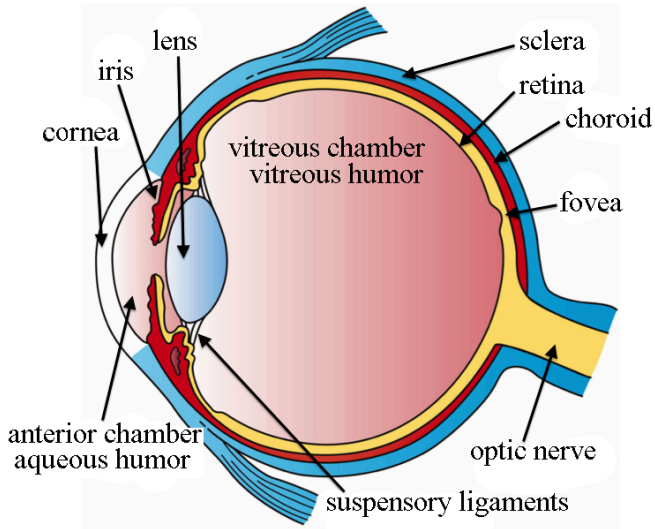


Figure 2.2.1.1: Structure of eye

The retina is the innermost, light-sensitive layer of tissue of the eye of most vertebrates and some molluscs. The neural retina consists of several layers of neurons. The primary light-sensing cells in the retina are the photoreceptor cells, which are of two types: rods and cones. the retina is considered part of the central nervous system and is actually brain tissue [25].

It is now known that human eyes, just as the ears, have two functions. The rods and cones enable sight; ipRGCs containing the photopigment melanopsin enable pupillary light responses, photic resetting of the circadian clock, in addition to many other sightless visual responses [26].

The presence of the ipRGCs, a type of neuron in human retina, were first noted in 1923. Mice without rods or cones were shown to still respond to a light stimulus, suggesting that rods and cones are not the only light sensitive cells in the retina. But it wasn't until more recent that research showed that these retinal ganglion cells are intrinsically photosensitive because of the presence of melanopsin, a light sensitive protein. Therefore they are referred to as a third class of photoreceptors, in addition to rods and cones [27].

The ipRGCs respond more slowly compared to the rods and cones. They signal the presence of light over a longer period of time [28]. Their functions

are fundamentally different from those of rods and cones. They provide an indication of the ambient light level. Although the phototransduction mechanism of the ipRGCs is not yet fully understood, they have at least three primary functions:

1. They play an important role in synchronising circadian, providing primary information on the length of day and the length of night. They pass light signal directly into the suprachiasmatic nucleus (SCN) of the hypothalamus.

2. Photosensitive ganglion also contribute to the regulation of pupil size and other behavioural responses to ambient lighting conditions [29].

3. They contribute to the regulation of, the acute photic suppression and the release of melatonin [29].

Human eyes respond to ambient light through two different systems known as image-forming (IF) and NIF vision. The IF system enables colour vision as well as night vision. Colour vision, also known as photopic vision, is mediated by three types of the cone cells, each with different peak sensitivities. Together the cones produce signals that allow us to distinguish between different wavelengths and to perceive colour. Under scotopic conditions the night vision is mediated by the rods which only allow us to sense the shape of objects. The CIE system developed in 1931 was based on the notion of trichromacy in humans [30], and is a model of how photopic vision operates. Whereas most people are trichromatic some of us are colour defective and some females are reported to be tetrachromatic [31].

The IF system was thought to be the only visual function of the human eyes until the late 20th when melanopsin was found in the ipRGCs in the human retina [32,33]. NIF vision was discovered and is thought to be activated by melanopsin. Whereas the cones and rods send signals to the visual cortex located in the back of the brain, ipRGCs primarily transmit signals to the hypothalamus, which regulates circadian rhythm as well as many other things.

However, it has been suggested that under low light condition the rods can also have an influence on human biological clock. The ipRGCs may also contribute towards IF vision [34], following findings that mice without rods

and cones were shown to be able to discriminate different spatial patterns [35]. It is believed that the ipRGCs produce signals combining input from both rods and cones together with the melanopsin-mediated responses, after which the signals are passed to various regions of human brain that related to both IF and NIF systems [36]. Figure 2.2.1.2 illustrates these (possible) pathways via which IF and NIF visual functions are mediated. It is now established that retinal light exposure has nonvisual effects in humans such as modulation of alertness [37,38].

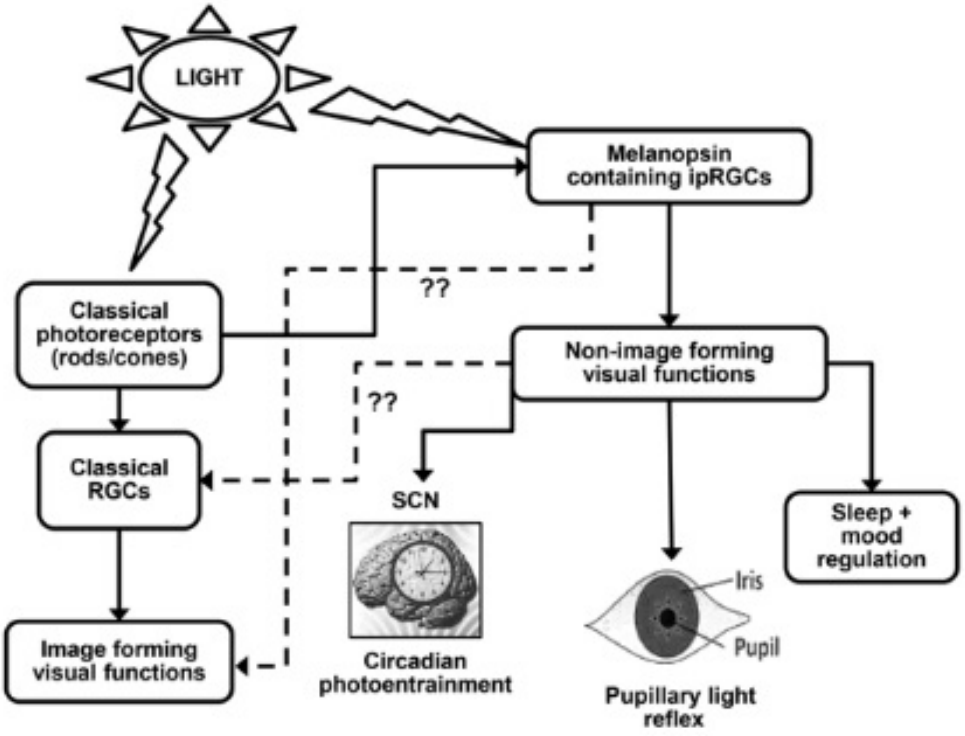


Figure 2.2.1.2: The IF and NIF Visual Functions of the Eye [39]

The NIF vision of human eyes has recently drawn a lot of attention. Research has been carried out to study the non-visual effects of colour, and of lighting, on human health, wellbeing and mood etc. [40]. Other than circadian regulation, light is also thought to be associated with some health issues such as age-related macular degeneration (AMD) [41]. Lighting is also shown to have an influence on heart rate, blood pressure [42], productivity, impulsivity, creativity and mood [43], and might also be associated with reading, learning and other disorders [44, 45].

Excessive blue light has been implicated as a risk factor in humans although there is no conclusive proof on this yet. Whereas insufficient light during the day time can cause depression and myopia, excess light at night in modern society might be partly responsible for poor sleeping quality, which could then lead to some other associated health problems such as obesity, heart disease and stroke [46].

2.2.2 Circadian Rhythms

Circadian rhythms refer to mental and physical changes that follow roughly a 24-hour cycle. It is driven by a circadian clock which has been observed in animals, plants and many microbes [47]. The rhythm is linked to the light–dark cycle. It responds primarily to light and darkness in an organism's living environment. Sleeping at night and waking up in the morning is an example. It also refers to many other biological behaviours that shows an endogenous, entrainable oscillation of daily cycle. Figure 2.2.2.1 illustrates circadian rhythms of human body.

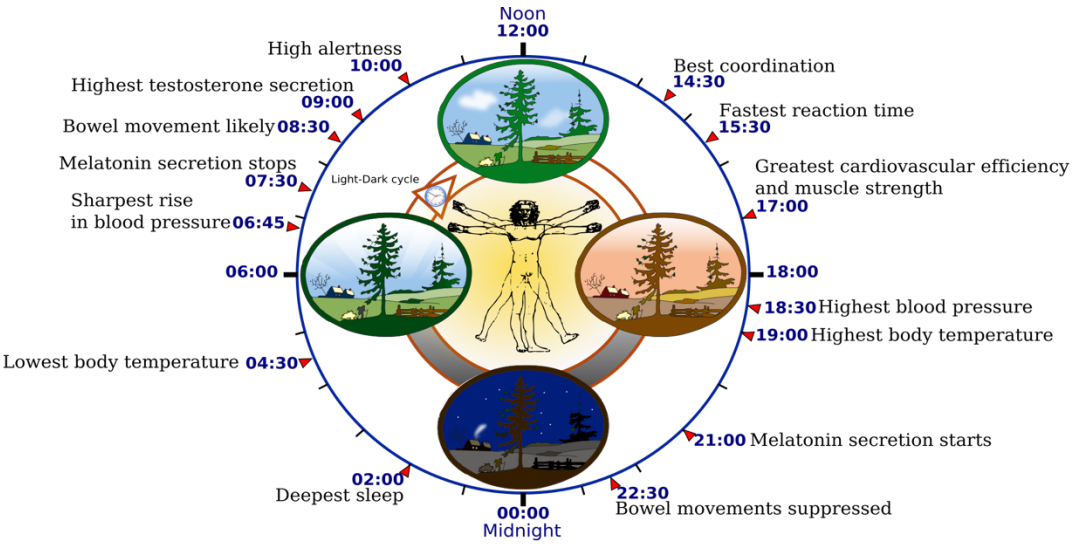


Figure 2.2.2.1: Circadian rhythms of human body [48]

Circadian rhythm affect many body functions like digestion, body temperature, blood pressure, reaction, hormone release etc.

Figure 2.2.2.2 illustrates influence of light and darkness on circadian rhythms through the SCN. The primary circadian is located in the SCN, a pair of distinct groups of cells located in the hypothalamus. The SCN receives

information through the eyes. Rods and cones on the retina of the eye enable conventional vision. Specialised ganglion cells also project directly to the SCN, where they play a role in the synchronisation of circadian clock.

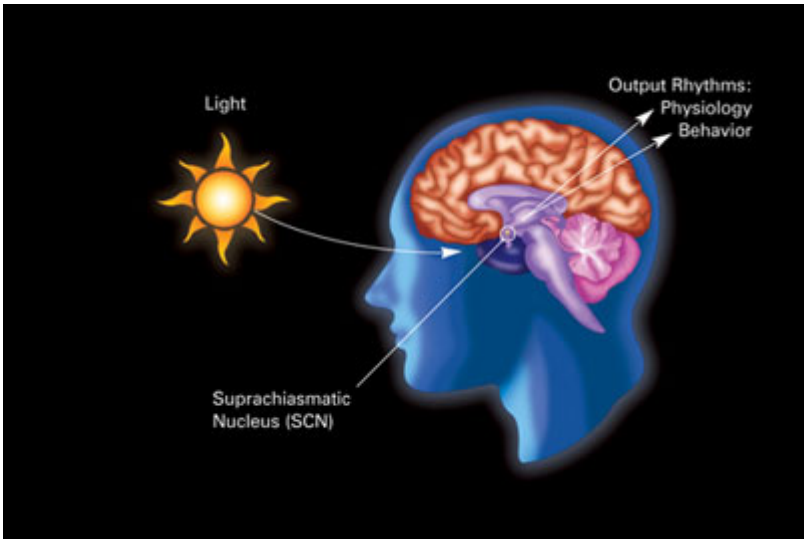


Figure 2.2.2.2: The influence of light and darkness on circadian rhythms through the SCN [48]

The ipRGCs contain the photopigment melanopsin and their signals follow a pathway called the retinohypothalamic tract, leading to the SCN. The SCN takes the information from the retina, and passes it on to the pineal gland, a pine cone shaped structure located on the epithalamus. In response, the pineal secretes the hormone melatonin [49].

The circadian rhythms of humans can be entrained to be shorter and longer than 24 hours. Researchers have shown that human subjects can at least be entrained to a 23.5-hour and a 24.6-hour cycle [50]. Phase markers for measuring the timing of the circadian rhythm include melatonin secretion, core body temperature [51] and plasma level of cortisol [52]. Other physiological changes that occur according to a circadian rhythm include heart rate and many cellular processes including oxidative stress, cell metabolism, immune and inflammatory responses etc. For example, it was found that the heart rate of young male subjects reaches its lowest average rate during sleep, and its highest average shortly after waking [53].

2.2.2.1 Circadian Rhythms and Human Health

Circadian rhythms are related to human health in many ways [54]. Timing of medical treatment in coordination with circadian clock is found to increase efficacy and reduce adverse reactions [55]. Some studies suggested that a short period of sleep during the day does not have measurable effect on normal circadian rhythms but can decrease stress and improve productivity [56-58]. It has been shown that light has a direct effect on human health due to the way it influences the circadian rhythms [59]. Lighting specification for circadian regulation are not the same as for vision, and the design of indoor lighting in e.g. offices is beginning to take this into account [60]. Studies on the effects of light intensity on animals in laboratory conditions have shown it to act as an essential regulator of biological timing [61].

Obesity and diabetes

Obesity and diabetes are associated with lifestyle and genes. However, disruption or misalignment of the clock system with the external environment might also play a role in the development of metabolic disorders. For example, animals that are forced to eat during their resting period showed increased body mass and altered expression of metabolic genes [62]. Shift work that often require irregular eating times is associated with altered insulin sensitivity and higher body weight. It also results in increased metabolic risks for cardio-metabolic syndrome and hypertension [63].

Disruption

Disruption to rhythms can result in a number of negative effects e.g. fatigue and insomnia. Bipolar disorder and some other sleep problems such as delayed sleep phase disorder are also associated with abnormal functioning of circadian clock [64]. Disruption to rhythms in the longer term is believed to have significant adverse health consequences e.g. in the exacerbation of cardiovascular disease [65].

Effect of drugs

Studies showed that there are bidirectional relationships between circadian system and abusive drugs on both animals and humans. Changes to the circadian rhythm occur once an individual begins abusing drugs. Stable

sleep and the circadian rhythm might help to reduce the vulnerability to addiction [66].

2.2.3 Circadian Rhythm and Melatonin

Melatonin is a hormone that plays an important role in the regulation of circadian rhythm [67]. It is involved in synchronising the circadian clock including sleep–wake timing, blood pressure and seasonal reproduction [68]. Melatonin is primarily made by the pineal gland [69] and is found in eyes, bone marrow and gut.

The release of melatonin tells your body when it is time to go to bed. It has become a popular supplement among people struggling with insomnia and jet lag. It is therefore often called 'the hormone of sleep'. Melatonin also helps to regulate body temperature, blood pressure and hormone levels. It is also a powerful antioxidant which provides a variety of other benefits such as supporting eye health, treating stomach ulcers and heartburn and helping with seasonal depression.

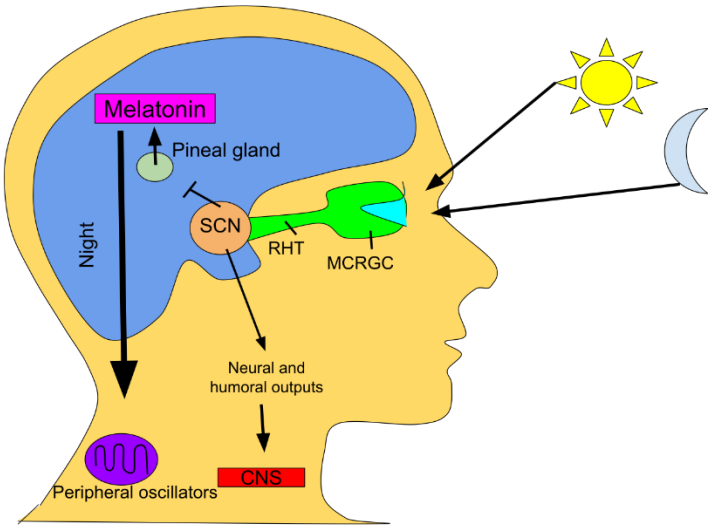


Figure 2.2.3.1: The regulation and release of melatonin

Figure 2.2.3.1 illustrates the pathway via which light regulating the release of melatonin. During the day, ipRGCs in human retina receive light signal and send it to the SCN through the retinohypothalamic tract. The SCN signify the pineal gland to inhibit the production of melatonin. When it is dark and the eyes do not receive light, melatonin is released from the pineal gland and its

levels start to rise, signifying to the body that it is time to relax and sleep. SCN also send signal to regulate the central nervous system through neural and humoral outputs. A number of factors can cause low levels of melatonin at night. These include stress, smoking, exposure to too much light at night, shift work, aging, and so on.

2.2.4 Short-wavelength Light and Circadian Disruption

Young people are spending more and more time using electronic devices. Sleep deficiency, especially in adolescents, is becoming a health concern. A large-population-based study carried out in Norway showed that the increasing time spending on electronic devices may have a negative effect on sleep. More than 10,000 individuals aged between 16-19 participated in the study and in total data from 9846 valid participants was collected. The study method was based on self-reporting data, mainly including screen time, bedtime, rise time etc. The association between sleep duration and screen hours was examined. As a result, long screen hours were significantly related to long sleep onset latency and short sleep duration [70]. The mechanisms behind this are thought to involve several factors, including bright light exposure [71]. Light was shown to have a strong alerting effects in human and it depends upon several parameters such as intensity, duration, the time slot in the day of exposure as well as the spectral composition of the light [72,73]. Light of shorter wavelength (410-500nm), in particular, is believed to have a stronger physiological effects such as human circadian disruption [74].

The secretion of melatonin is regulated by melanopsin (present in the ipRGCs). Melatonin is secreted under conditions of darkness, acting as a signal of circadian rhythm and conveying the bedtime information to the brain and body. It usually starts rising approximately 2 hours before natural bedtime [75] though it can be inhibited by the activation of the ipRGC by bright light at night. Functional magnetic resonance imaging measurements of brain have shown a greater response in the hippocampus to blue light than green light [76]. And the reason might be that melanopsin is more sensitive to blue light than green light.

Furthermore, a study examining the NIF spectral responses of the visual system conducted on two profoundly blind subjects found that the ipRGCs

are most sensitive to light of short wavelength and were shown to remain active in the absence of rods and cones. The study suggested that short wavelength light caused the suppression of melatonin and ipRGCs contribute to light sensing and help to maintain a normal circadian rhythm in blind people [77].

Another study conducted with healthy subjects also showed a strong relation between short-wavelength light and circadian physiology. Subjects were exposed to different monochromatic lights (with otherwise equal duration, intensity and timing). The circadian resetting response was measured by the suppression of melatonin, indicated by its secretory profile. Two monochromatic lights, 460nm and 555nm, were use in the experiments. The results suggested that 460nm wavelength light resulted in a significantly greater melatonin secretory suppression, which indicated a circadian rhythm delay [78].

There is evidence that short wavelength light is damaging to the retina and negatively affects the circadian rhythm, whilst it has also been proposed that a normal amount of short wavelength light is essential for maintaining the biological clock. However, research to further explore on e.g. how much light, of specific wavelengths, is actually needed for normal circadian rhythm still has a long way to go [79].

At present, the spectrum of wavelength stimulation related to circadian rhythm remains unknown. As the delay of circadian rhythm is positively related to the stimulation of melanopsin and the suppression of melatonin, looking at the responses of these two elements could be the way that helps to map the spectrum. Like the other photopigments, melanopsin is isomerised on photon absorption, upon which it converts 11-cis retinal to all-trans retinal [80]. The human retina has about 3000 ipRGCs and their response to light has a slow onset with sustained depolarisation lasting half a minute after light exposure [81].

The ability of light to suppress melatonin secretion is believed to have a spectral sensitivity, with a significant short wavelength peak sensitivity within the range of 460nm to 490nm [82,83]. It is generally agreed that maximum melanopsin stimulation happens at around 480nm with a full-width-half-maximum ranging from 50nm to 200nm [84]. The spectrum for melatonin

suppression is reported to be blue-shifted from the melanopsin stimulation spectrum by about 15 to 20 nm [85]. This might suggest that the maximum circadian sensitivity could be around 460-465nm.

A study conducted at a polar base station, where sleep problems have been reported, found that blue-enriched light exposure in the day resulted in less delay of the melatonin onset at night and significantly enhanced alertness compared to standard fluorescent white light [86]. In another study, subjects underwent waking EEG recordings together with a combination of other tests while exposed to blue (460nm) or green (555nm) light, and the results suggested that participants exposed to the blue light had higher EEG alpha frequency power and lower subjective sleepiness [87]. Most studies have been based on the application of monochromatic lights or narrow bandwidth irradiation. However, it has been pointed out that melanopsin is bistable, suggesting that the sensitivity of melanopsin might be different when exposed to monochromatic lights and to broadband irradiation [88]. This is one of the reasons that circadian sensitivity mapping can be difficult and the spectrum is not yet fully understood.

The younger generation may be at a greater risk from light-induced circadian disruption as less melatonin suppression was found in elderly people. This might be a result of age-related lens density change in the eyes [89].

A pilot study used light-emitting diodes (LEDs) with a peak wavelength at 470nm as the irradiation source, and the results showed a significant melatonin suppression from only 18 lx of the light [90]. Another recent study showed that compared with dim light (3 lx), exposure to bright light (200 lx) at night supressed melatonin and resulted in later melatonin onset [91].

There is some concern about home lighting in the evening where there is increased replacement of warm Tungsten light; the use of emissive electronic displays may also be responsible for the increasing sleep problem [92]. The use of self-luminous devices (e.g. smartphones, tablets and computers) for over 1 hour before natural bedtime can reduce melatonin by 23% to 38% [93]. A variety of Liquid Crystal Display (LCD) screens today work with an LED backlight, which generates a high light intensity. The white light LED is formed by a blue LED dye with a layer of green and red phosphors [94]. That is why white LEDs possess an unbalanced emission

spectrum distribution that is particularly rich in short-waveband (λmax=450-460nm). This peak emission is rather close to the maximum circadian sensitivity, which makes the use of LCDs even more problematic (Figure 2.2.4.1).

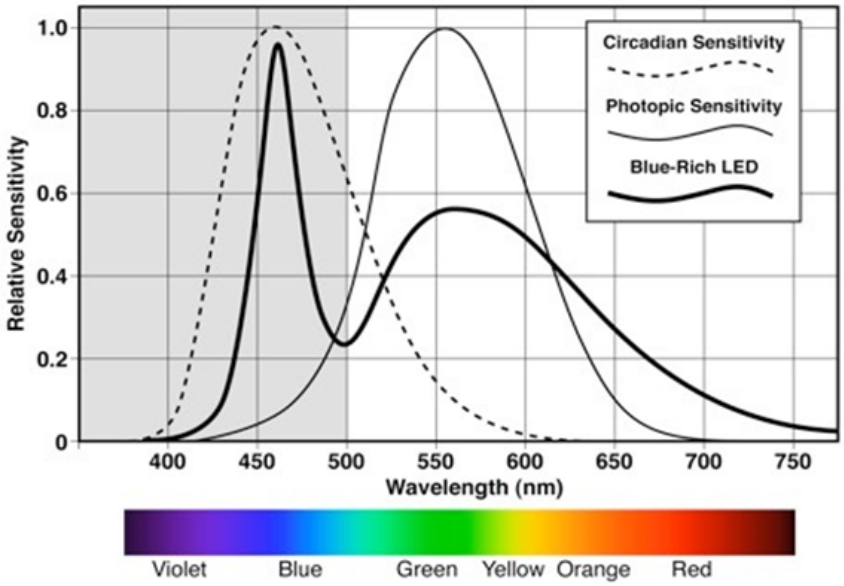


Figure 2.2.4.1: Circadian Sensitivity, Photopic Sensitivity and the Emission Spectrum of blue-rich LED [95]

Generally, the relative contribution of traditional rods, cones and ipRGCs to NIF vision under different light conditions remains to be determined in humans [96]. In more than one study both blue and red lights showed an alerting effect at night though only short wavelength blue light was observed to suppress melatonin levels [11]. In another study, both 460nm and 555nm lights were equally effective at the beginning of exposure but 555nm light then started to decay significantly, which might suggest the contribution of cones at the start of exposure [97]. Subjects who had been deprived of sleep for two days showed no difference between two lighting conditions on subjective sleepiness, suggesting that the alerting ability of traditional photoreceptors, when the fatigue is high, cannot be ruled out [98]. In a study conducted in the afternoon, red light has been shown to have a greater alerting ability than blue light [9].

2.3 Other Non-visual Effects of Light

In addition to circadian resetting, light also has a number of other non-visual effects.

Age-Related Macular Degeneration

AMD usually affects people over 50 years old [99]. It is caused by damage to macula, the central area of the retina, which contains the highest density of photoreceptors that is responsible for spatial resolution. It results in blurred vision or no vision at all in the centre of the visual field (Figure 2.3.1).

Figure 2.3.1: Vision with AMD [100]

The photoreceptors can be damaged by light, particularly short-wavelength light [101] due to the high energy at this wavelength. The macula area is naturally yellow due to the presence of carotenoids such as lutein, which acts as a notch pigment to protect the retina against blue light [102].

Mood and Wellbeing

There has much research showing that colour can have an effect on mood [103,104]. Some studies have found that mood in a living or working space can be affected by colour [105]. For example, it was found that room temperature was perceived differently depending on the colour of the lighting. The room temperature was felt to be warmer in yellow light and subjects felt more alert in blue light. There is evidence that performance and mood are

affected by non-visual flicker in some fluorescent lights [106]. Variation in mood over the year was found in countries north of the equator [107].

Seasonal affective disorder (SAD) is a bipolar disorder that normally occur annually [108]. Most cases are associated with winter depression and are linked to low light levels. Light exposure in the morning is a common treatment for SAD. For example, 2500 lx of light exposure in the morning twice daily for a week was suggested to be effective [109]. Initial treatments for SAD used broadband white light, with an increased interest in using shorter wavelength light. Since the 1990s 10,000 lx has become common for the treatment [110] although the dose was suggested to be too high if short wavelength light is used [111]. However, studies have contradictory findings on whether short-wavelength light is more effective than broadband white light. This might be due to the various experimental parameters such as light level, time of day and duration.

Cancer

The most common human photochemical damage is skin cancer. The relationship between skin cancer and sun radiation was confirmed in the early 20th Century [112]. Both UV-A (315-400 nm) and UV-B (280-315 nm) are strongly associated with skin ageing, eye damage as well as skin cancers. Light at night may also be associated with breast cancer in humans [113,114]. In addition to cancer, UV, visible and infrared radiation can also cause skin damage [115] such as burning. It was suggested that exposure to blue light, in particular, during the late evening could reduce melatonin level in the body and raise the risk of developing cancer. Melatonin has been shown to be a powerful anti-oxidant and free radical scavenger that is effective against cancer. It has been documented to ameliorate the oxidative injuries in tissue due to ionising radiation [116]. Melatonin is believed to have atoxic, apoptotic, oncostatic, angiogenetic, and anti-proliferative properties against tumours [117].

Heart Rate and Blood Pressure

Experiments have shown that bright light can raise heart rate compared with the heart rate in the dark [118]. Illumination at 1000 lx is also shown to increase heart rate more than similarly coloured illumination at 250 lx [119].

A number of studies have been carried out on whether coloured light and environments have an influence. In one study, exposure to red, white and blue light showed no differential effect of light colour on heart rate [120]. In another study, subjects were placed in a coloured lighting environment. Results showed that heart rate increased in the red condition, and decreased in the blue and green conditions, although these effects were not statistically significant [121]. However, one study where students were placed in coloured learning environments found that heart rate significantly increased in red and yellow environments and significantly decreased in blue environment [122]. Subjects exposed to light at 460nm were also found to have significantly higher heart rates than exposed to light at 550 nm during the late evening.

Reading/Learning Disorders, Autism and Headaches

Meares – Irlen syndrome is a form of visual stress which leads to difficulties such as stress and headaches whilst reading.

It is believed that the use of coloured overlays can alleviate the symptoms [123,124]. However, the efficacy of coloured overlays for Meares-Irlen syndrome have been questioned [125] by some studies that have been carried out with dyslexic patients [126,127].

Photophobia is a symptom of experiencing discomfort or pain to the eyes due to light exposure [128]. A study found that even some blind people experienced worst headaches in bright light conditions [129]. However, narrowband green light has been shown to be able to actually reduce headaches in migraine sufferers contrary to other colours, which is leading to some ideas about light therapy.

Autism is usually noticed in the early years of a child’s life. It involves impaired social interaction, verbal and non-verbal communication, and restricted and repetitive behaviour [130]. Some research suggested that colour overlays may help autistic children with reading [131]. The flicker from fluorescent lights is shown to have a negative effect on repetitive behaviours. Autistic children were shown to be much more engaged in repetitive behaviour when the environment was illuminated by a fluorescent light than by an incandescent light [132].

Learning, Productivity and Alertness in Indoor Spaces

The luminous level in living space or work place has an important influence on people's performance and mood [133]. Usually, illuminance of 500 lx is an accepted level that does not limit visual performance or cause visual discomfort. However, it has been suggested that lower light levels may also be possible to meet users' requirement [134]. In one study where two illuminance levels (300 and 500 lx) and two colour temperatures (4000 K and 6500 K) were simulated in an office environment; participants showed preference to work under the 500 lx and 4000 K lighting [135].

High CCT lighting was shown to significantly improve concentration in office workers, compared with standard office lighting [136]. A study investigating various types of space showed that people preferred different CCTs while engaged with different activities [133]. In addition, environmental workspace colour has different effect on different tasks [137]. For example, blue environment has been shown to reduce the performance for a low-demand task but in a high demand task red environment was shown to worsen the performance.

100 Hz fluorescent lighting has been shown to possibly cause headaches and impair visual performance [138]. Students showed better performance in a visual search task under light with low modulation than high modulation [139]. Workers were shown to assemble electronic devices faster under 1200 lx lighting than 800 lx, although there was no difference on error rate [140].

There has been increasing interests in dynamic lighting, which changes in illuminance and colour over time [141]. Dynamically coloured lighting (Figure 2.3.2) has been shown to effectively make people feel less bored and more relaxed in a waiting environment [142]. However, compared with static lighting, office workers showed no significant effect of dynamic light on alertness, headache and eyestrain, sleep quality or performance [143].

Figure 2.3.2: Dynamic lighting in a hospital

The colour of ambient light in a car interior has been shown to have a positive effect on people's perception of space, quality and safety [144]. In some studies the physical environment of offices has been shown to affect creativity of workers.

It has been proposed that adding additional stimulation, for example, additional colour, to a black-and-white task can effectively improve performance for hyperactive children [145]. Many railway station platforms (Figure 2.3.3) in Tokyo have installed blue lights, with the aim to reduce suicides [146].

Figure 2.3.3: Tokyo train stations use blue lights to stem suicides

Other Medical Applications

Light therapy has been suggested as an alternative to enhance wound healing. For example, blue light has been shown to decrease wound size in rats and decrease keratin-1 mRNA [147]. Low-level lasers were used as a treatment for wound healing since the 1970s [148]. Wounds generated by laser surgery have been shown to heal more quickly than wounds generated by conventional surgery [149]. Low-level laser therapy using infrared radiation has been used to treat diseases involving musculoskeletal and neurologic structures [150] such as vestibular dysfunction and tinnitus.

2.4 Lighting Technology

2.4.1 Brief History of Lighting

Lighting or illumination is the use of light to achieve practical or aesthetic effects. Lighting includes both artificial light sources such as lamps, as well as natural illumination by capturing daylight (e.g. using windows and skylights). Daylight is sometimes used as the main source of light during daytime in buildings. Indoor lighting design is an important part of interior design. Lighting have an influence on the appearance of an area, as well as the occupants' performance and other psychological aspects. The earliest form of artificial lighting used was campfires or torches, after the discovery of fire. Dating to about 15,000 years ago, prehistoric people used oil lamps to illuminate surroundings. These oil lamps were made from natural materials such as shells and stones. They were filled with grease and used animal fats as fuel.

The discovery of whale oil reduced the cost of lighting. The use of whale oil, however, had a steady decline starting in the late 19th century due to the development of better alternatives. Abraham Gesner, a Canadian geologist, first refined kerosene in the 1840s, allowing brighter light to be produced at lower cost. In 1859, crude oil was discovered and the petroleum industry started to arise [151]. Gas lighting was used in street lights starting in the early 1800s, and was also used in commercial buildings and in the home of wealthy people at that time. The introduction of electric lighting in the 1880s has seen the next major price drop in lighting industry, followed on by incandescent light bulb for both indoor and outdoor lighting.

The popular use of electric lighting especially in developed countries [152] helped to eliminate segmented sleep patterns, made more activities possible at night, and reduced urban crime by having more street lights [153, 154].

2.4.2 Forms of Lighting

Both indoor and outdoor lightings have various forms. Some of the most common forms of lighting are briefly introduced here.

Indoor lighting

Alcove lighting is an indirect backlighting, which refers to the method of illuminating subjects from the back. Alcove lighting usually use fluorescent lighting or rope light, and recently with LED strip lighting. Recessed lighting is very common, with the light fixtures installed into the ceiling structure. In this way light is concentrated from the ceiling in a downward direction as a narrow beam spotlight or a broad-angle floodlight. These downlights can be incandescent, fluorescent or LED. Track lighting are invented by Lightolier. It was much easier to install than recessed lighting. The individual fixtures are decorative and they can be easily aimed at the wall. A sconce is a type of wall-mounted light fixture where the light particularly shines up, and sometimes, directed downwards as well. A sconce may be a torch or candle. A modern electric light affixed in this way are often called wall lights. Further interior light include chandeliers, pendant lights, flush lights, and some types of lamps.

For safety and convenience purpose, steps along the aisles in a cinema are usually marked with a row of small lights. These lights are traditionally made up of small low voltage lamps in a track or translucent tube. However, today these are being replaced with LED based versions.

Outdoor lighting

Street lights are used to light roadways and walkways during night time hours. Some manufacturers are using LED and photovoltaic luminaires to provide an more energy-efficient alternative.

Floodlights are broad-beamed, high-intensity lights used to illuminate playing fields such as football field, or work ones such as airport, as shown in Figure 2.4.2.1. Some of the more focused types are used for stage lighting in live performances such as concerts. Two of the most common floodlights are metal halide and high pressure sodium lights.

Figure 2.4.2.1: Floodlights used in outdoor fields [155]

Beacon lights are modest steady lights positioned at the intersection of two roads as an aid to navigation, for example, to help drivers to see the location of a side road during low-light conditions.

Some other forms of outdoor lighting include security lighting, entry lights, and underwater accent lighting.

2.4.3 Type of Lamps

Lamps are also called light bulbs, which are the removable part of a light fixture that converts electrical energy into electromagnetic radiation. After the first practical incandescent lamp was invented by Thomas Edison and Joseph Swan in the 19th century, there has been significant improvements in different types of light bulbs and their efficiencies.

Incandescent light bulb

An incandescent bulb is an electric light glows and produces heat when electricity passes through the wire filament and heat it to a high temperature. The filament inside the bulb is usually placed in a mixture of nitrogen gas. Incandescent bulbs are manufactured in a wide range of sizes, light output and voltage, as shown in Figure 2.4.3.1.

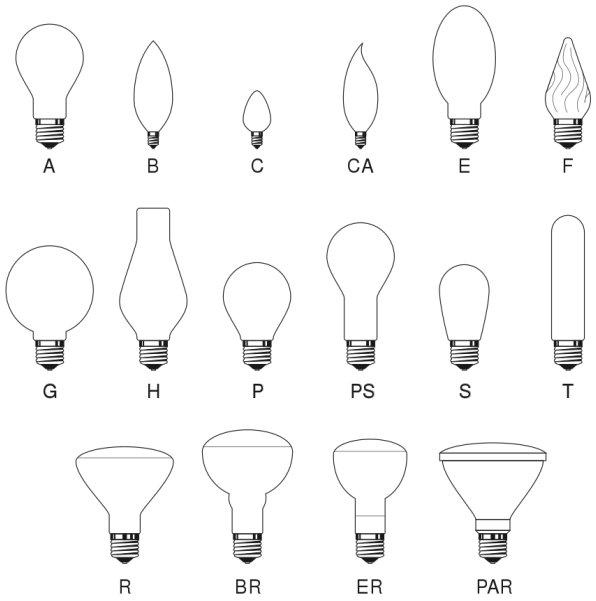


Figure 2.4.3.1: Incandescent light bulbs come in different shapes [156]

Incandescent bulbs are less efficient than other types of electric lighting, with more than 95% of the energy they consume converted into heat. Therefore they are being gradually replaced by fluorescent lamps, high-intensity discharge lamps, and LEDs which are based on new technologies to reduce energy consumption. However, some applications deliberately use the heat such as incubators, brooding boxes for poultry, infrared heating for industrial heating and drying processes etc. Incandescent bulbs typically have short lifetimes compared with other lightings. They usually last around 1,000 hours for home light bulbs.

Halogen lamp

A halogen lamp, also known as a tungsten halogen, is an incandescent lamp consisting of a tungsten filament and contains a mixture of an inert gas and a halogen such as iodine. The halogen gas and the tungsten filament produces a chemical reaction cycle which redeposits evaporated tungsten to the filament, increasing the life and the efficacy of the lamp.

A halogen lamp must be operated at a higher temperature (250° C) than a plain incandescent lamp. This produces light with higher luminous efficacy and colour temperature.

A halogen lamp produces a continuous spectrum of light from near ultraviolet to the infrared. The spectrum is shifted toward blue due to the high temperature filaments emitting energy in the UV region, as shown in Figure 2.4.3.2.

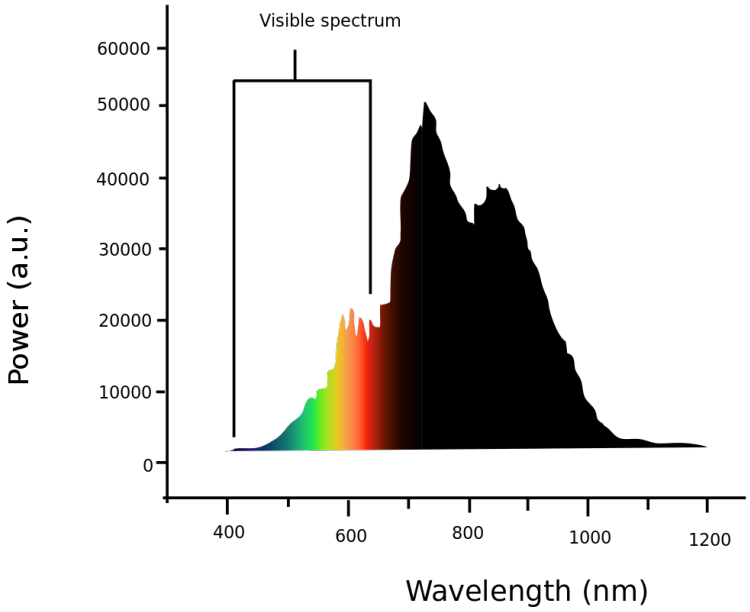


Figure 2.4.3.2: Power distribution of a halogen light [157]

Small size halogen lamps are used in compact optical systems for projectors and illumination. They are now also used in desktop lamps. Halogen headlamps are used in automobiles. Halogen floodlights provide a large quantity of light from a small source and so can be used to produce powerful lamps for lighting large areas outdoors or for architectural lighting effects.

Fluorescent lamp

A fluorescent lamp is a mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light. An electric current in the gas excites mercury vapor, producing ultraviolet light that causes a phosphor coating on the inside of the lamp to glow. A fluorescent lamp converts electrical energy

into useful light several times the efficacy of incandescent lamps. Figure 2.4.3.3 shows fluorescent tubes of various sizes.

Figure 2.4.3.3: Fluorescent tubes of various sizes [158]

The spectral distribution of light of a fluorescent lamp is the combination of light emitted by the mercury vapour and by the phosphorescent coating. This gives a combined spectrum of light that is different from those produced by incandescent lights. The relative intensity of light in each narrow band of wavelengths is in different proportions compared to that of an incandescent source.

By altering the mixture of phosphors, fluorescent lamps can be manufactured to a different CCT. For example, warm-white fluorescents have CCT of 2700 K and are popular for residential lighting. Cool-white fluorescents have a CCT of 4100 K and are popular for office lighting.

Fluorescent lamps come in various types. A compact fluorescent lamp, also called energy-saving light, is becoming more popular. A compact fluorescent lamp integrates the compact electronic ballast into the base of the lamp, allowing them to fit into the space of a regular light bulb socket. Some countries are encouraging the replace of incandescent light bulbs with fluorescent lamps or other types of energy-efficient lamps.

LED

A LED is a semiconductor that emits light when current flows through it. Electrons in the semiconductor release energy in the form of photons. LED can emit light of an intended colour without the use of colour filters. The colour of the light emitted is determined by the energy absorbed by electrons, corresponding to the energy of the released photons. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor.

Modern LEDs are available across the visible, ultraviolet, and infrared wavelengths. High-output white light LEDs have been produced for indoor and outdoor area lighting. LEDs have led to new display such as their application in advanced communications technology.

Compared with incandescent lamps, LEDs have lower energy consumption, longer lifespan, improved robustness and faster switching. LEDs are used in diverse areas such as aviation lighting, automotive headlamps, advertising, traffic signals, general lighting, camera flashes, medical equipment and so on [159].

Although the light emitted from an LED is not as spectrally coherent or highly monochromatic as a laser, its spectrum is sufficiently narrow that it appears as a saturated colour to the human eye. Figure 2.4.3.4 shows three colour of LED lights.

Figure 2.4.3.4: LED lighting [160]

By selecting different semiconductor materials, single-colour LEDs can be produced to emit light of a narrow band of wavelengths from near-infrared through the visible spectrum and into the ultraviolet.

White LED

There are mainly two ways to produce white LEDs. One is to mix individual LEDs of three primary colours, red, green and blue, to form white light. The other is to use phosphor-based material to convert monochromatic light from a blue or UV LED to a broadband white light.

Because of metamerism, even quite different spectra can appear white. However, the appearance of objects illuminated by a pair of metamers may vary, which is the issue of colour rendition. LEDs that use a mix of phosphors have less efficiency but better colour rendering. LEDs without phosphors cannot achieve good colour rendering because each LED is a narrowband source.

RGB systems

The blending of red, green and blue LED sources to produce white light are controlled by electronic circuits. However, the colour balance may change depending on the angle of view since LEDs have slightly different emission patterns. Therefore RGB diodes are not commonly used to produce white lighting. Nonetheless, this method still has many applications because of the flexibility of mixing different colours [161].

Most colours can be created by mixing certain amount of three primaries. Multicolour LEDs offer a new way to form coloured light, allowing precise dynamic colour control. However, their emission power decays with rising temperature [162], resulting in a change in colour stability. LEDs without phosphor may not be a good idea for general lighting, but is the best choice for displays. Figure 2.4.3.5 shows spectral curves for blue, green, and high-brightness red semiconductor LEDs.

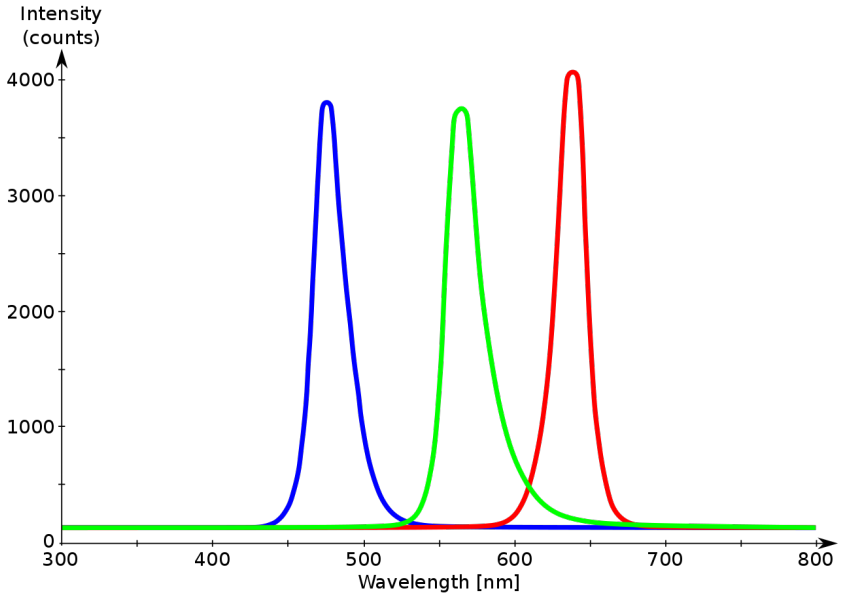


Figure 2.4.3.5: Spectral curves for blue, green, and high-brightness red semiconductor LEDs

Organic light-emitting diodes (OLEDs)

The electroluminescent material composing the emissive layer of the diode in an OLED is an organic compound. OLEDs are thin, have lower cost, low driving voltage, wider viewing angle, and wider colour gamut [163].

OLEDs have been used for portable electronic devices such as smartphones and digital cameras. It also has potential application in lighting and televisions in the future [164].

Other lamps

Some other types of lamps include metal halide lamps, neon lamps, high intensity discharge lamps, and low-pressure sodium lamps.

2.4.4 Measurement of Light

Luminosity function

Measurement of light, also called photometry, is concerned with measuring the amount of light falling on a surface and the amount of light emitting from a light source, as well as the colours that is rendered by this light. The

human eye is not equally sensitive to light of different wavelength, and this is taken into account in photometry by weighing the radiant power at each wavelength with a factor that represents the eye sensitivity of light brightness at that wavelength.

The standardised model of the eye's sensitivity to light as a function of wavelength is described by the luminosity function. It is based on subjective judgements of which of a pair of lights is brighter. Moreover, the eye has different responses when it is adapted to brightly lit conditions (photopic vision) and low lighting conditions (scotopic vision). And different luminosity functions apply under each lighting condition. In general, the luminosity function refers to the photopic luminosity function. Figure 2.4.4.1 shows CIE scotopic and photopic spectral luminous efficiency functions.

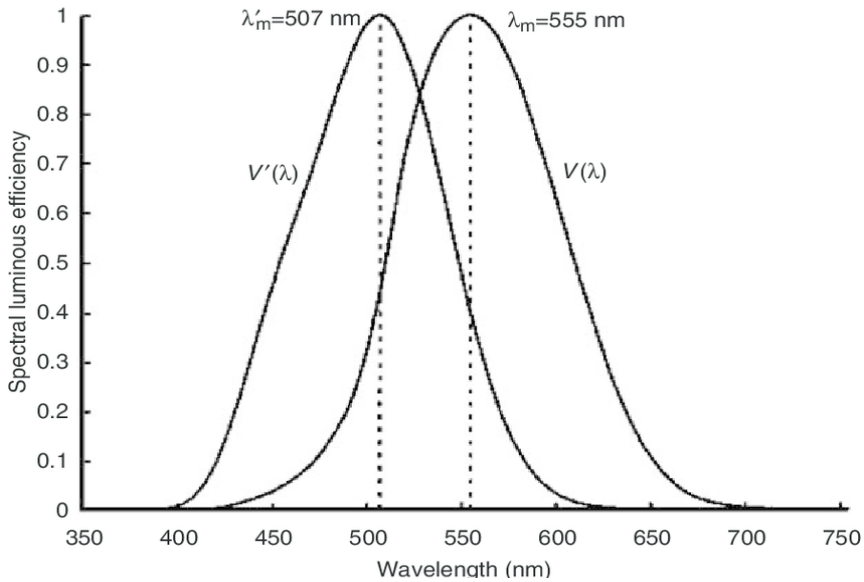


Figure 2.4.4.1: The CIE scotopic and photopic spectral luminous efficiency functions V'(λ) and V(λ) [165]

Photometric quantities

Many different units are used for photometric measurements.

The way light propagates through three-dimensional space - spreading out, getting concentrated, and reflecting from surfaces – as well as the fact that light consists of many different wavelengths, is the reason that the number of different kinds of light measurement that can be made is large. Therefore

there is also many different quantities and units that represent the measure of light.

The basic International System of Units (SI) unit of light measure is candela (cd), which describes the luminous intensity, All other photometric units are derived from the candela. For example, luminance is a measure of the density of luminous intensity in a given direction. It represents the amount of light that passes through or is emitted from a source, and falls within a given angle. The unit for luminance is candela per square metre (cd/m2). The unit of illuminance, being the luminous power per area, is measured in Lux. It is used in photometry as a measure of the intensity of light that hits or passes through a surface. Table 2.4.4.1 listed some of these units.

Table 2.4.4.1 Part of SI photometry quantities

Quantity(Name;symbol)	**Unit (Name;symbol)**	**Notes**
Luminous intensity;Iv	candela;cd	Luminous flux per unit solid angle
Luminance; Lv	candela per square metre;cd/m2	Luminous flux per unit solid angle per unit projected source area.
Illuminance; Ev	Lux; lx	Luminous flux incident on a surface

2.5 Study on Light-induced Alerting Effects

Effort has been put into examining light-induced alertness in human subjects. The representation and the measurement of alertness, a cognitive state of the brain, is not easy. However, experiments have been designed that combine various methods, including pre-experimental screening procedures, to look at both subjective and objective alertness/sleepiness of subjects.

2.5.1 Pre-study Conditions of Subjects and Questionnaire

In most studies, participants are asked to follow some pre-experimental procedure and the compliance of these instructions decide whether the data collected from the participant would be included or not. Participants are

usually asked to refrain from the use of alcohol, caffeine, nicotine, supplements, drugs or any medications, for a certain period of time prior to the study. Subjects who report major health problems or the taking of pharmaceuticals are excluded [11]. In some studies smokers are also excluded. In some study, the compliance with these requirements are verified by toxicological analysis of urine and blood sample prior to the beginning of the experiment [166]. Colour blindness tests are also included in some studies to ensure all subjects have normal (or corrected-to-normal) colour vision [10].

The sleep/rest pattern and circadian clock of subjects can also be investigated. Participants who have travelled to a different time zone during the month before the experimental session may be excluded [12]. If the experimental sessions take place over several weeks, participants may be asked to maintain a regular and constant sleep-wake schedule and this might be monitored by asking them to wear a wrist Dimesimeter continuously [167].

Another method usually used to assess the circadian clock of subjects is the Munich ChronoType Questionnaire (MCTQ) [168]. The questionnaire was developed to document individual sleep times, self-reported light exposure during the day, as well as self-assessed chronotype. A few parameters other than sleep/rise time are also incorporated in the questionnaire to allow an more accurate assessment of genetic chronotypes. Based on the experimental protocol, participants who were rated as extremely late/early chronotypes might be excluded, ensuring a homogeneous circadian-phase among subjects and more controlled pre-experimental conditions.

2.5.2 Subjective Sleepiness Assessment and Cognitive Performance Tasks

The subjective sleepiness is often rated using KSS, a self-reported scale ranged from 1- ‘very alert’ to 9- ‘very sleepy, fighting sleep’. A variety of performance tests are also frequently used to evaluate the cognitive state of subjects.

The Karolinska Drowsiness Test [169] records both EEG and Electro-Oculogram (EOG) activities of subjects (with their eyes opened) for a short

period of time (a few minutes). EEG is subjected to spectral power analysis and EOG is scored for slow rolling eye movements.

The Psychomotor vigilance task is a simple portable reaction time task to evaluate sustained attention [170]. The stimulus appears at random intervals (1-9 seconds) and subject is instructed to press a button as soon as possible after the stimulus occurred [171]. The stimulus is usually an auditory signal although can be in visual form as well, the duration of a single psychomotor vigilance task usually lasts 5/10 minutes. It can be designed as a battery of tests, consisted of vigilance tests in several forms.

The GO/NOGO task is used to evaluate the capacity for sustained attention and response control and investigate brain activation during operations such as error processing [172]. Subjects are asked to respond only when a certain stimulus appears e.g. a letter ‘M’ or a smiling face, when opposite stimulus e.g. a letter ‘W’ or a frowning face, is simultaneously present.

The Multi-Attribute Task Battery for Human Operator Workload can be used to measure long-term performance. It provides a benchmark set of tasks e.g. monitoring tasks, tracking task and resource management tasks [173]. The Multi-Attribute Task lasts longer (e.g. 45 minutes) than other short time performance tests such as 5-min reaction time tests and it has been demonstrated that such long-duration performance tests are more sensitive to sleep decrement [174].

The Paced Visual Serial Addition Task [175] is a task heavily dependent on the frontal regions of brain, which takes higher order of executive functioning. And the number of correct responses is calculated to produce the result.

2.5.3 Objective Sleepiness Assessment: Hormones

The objective sleepiness can be assessed by the measurement of endogenous hormones levels such as melatonin and cortisol, which is regulated by human endocrine and autonomic system. There are commercially available test kits for measuring biological secretions that are seen as circadian biomarkers such as melatonin, cortisol and alpha-amylase. The levels of these secretions can be assayed by radioimmunoassay using saliva or blood samples. Melatonin is often used as a marker of circadian

system timing. The signal transmission from photoreception to the melatonin regulation is influenced by the human circadian pacemaker and it involves a complex neural pathway [176]. It was demonstrated that humans are very sensitive to the exposure of light during the early biological night. It was believed that, if light of certain wavelengths, sufficient irradiance and duration is presented to human eyes, melatonin synthesis will be suppressed and the entrained circadian resetting will respond in a dose-dependent manner [177]. It was also indicated that humans are highly responsive to small light condition changes especially in the late evening hours. The plasma melatonin levels as well as the phase of circadian pacemaker was also significantly affected [178].

The impact of light exposure on cortisol and alpha amylase levels has also been studied. Cortisol is hormone produced by the adrenal gland and salivary alpha-amylase is an enzyme that indicates sympathetic nervous system response. Both of them have been shown to participate in the psychosocial stress response. As with melatonin, human cortisol and salivary alpha amylase secretion exhibits a regular circadian pattern, although cortisol rhythms seem to be more closely associated with the switch between light/dark condition. A study looked at melatonin, cortisol and alpha amylase responses under both narrowband blue and red lights found that although both exposures affected cortisol, only the blue light significantly reduced nocturnal melatonin levels. And it has been suggested that light-induced modulation of nocturnal melatonin suppression are not the same as those of cortisol and alpha amylase [179].

Whereas melatonin is seen as the biomarker of circadian rhythm cortisol and alpha amylase are supposed to be associated with sympathetic nervous system. Question remains as whether the nonvisual pathway regulating nocturnal melatonin suppression is the same as that regulating other nonvisual responses. The role of SCN in these responses also needs to be further investigated.

2.6 EEG

It has been long known that human cognitive states related to alertness, arousal and sleepiness are present in the EEG signals. EEG power spectrum has been used to in the measurement of the real-time level of

human alertness. Fluctuation in the level of alertness can be assessed by recording simultaneous power changes in EEG. Studies have been done to investigate the full EEG spectrum, and tried to model the accurate relationship between the EEG power spectrum and alertness.

EEG is a technique that records scalp electrical activity generated by human brain. The electroencephalogram is the electrical activity of an alternating type recorded from the scalp surface after being recorded by metal electrodes and conductive media [180].

In medical aspect, EEG is often used to diagnose epilepsy, which causes spike and wave discharges in EEG readings. It is also used in clinical circumstances to help diagnosing sleep disorders, brain tumour, stroke and brain death. Despite limited spatial resolution, EEG is one of the few mobile techniques that offers millisecond-range temporal resolution which is not possible with magnetic resonance imaging or computed tomography.

In research, EEG is extensively used in neuroscience, cognitive science, and cognitive psychology.

2.6.1 Brief EEG Fundamentals

The cerebral cortex is a dominant part of the human central nervous system. When neurons are activated, local current flows are produced. EEG measures the currents that flow during synaptic excitations of the dendrites of pyramidal neurons in the cortex. Electrical activity that is recordable on the brain surface, generated only by large populations of active neurons, is detected by the scalp electrodes. And the signals are massively amplified before they are present [181].

EEG activity shows oscillations at different frequencies. These oscillations have characteristic frequency ranges, and are associated with different states of brain functioning. These oscillations represent activity over a network of neurons. Some of these activities are understood, while many others are not.

Wave patterns

Brain waves are commonly sinusoidal and normally range from 0.5 to 100 μV in amplitude. Power spectrum is derived from the raw EEG signal by applying Fourier transform. EEG power spectrum shows the contribution of sine waves of different frequencies [182].

Brain waves have been divided into four bands (Figure 2.6.1.1). Sometimes they are further divided into sub-bands for the purposes of data analysis.

- beta (>12 Hz)
- alpha (8-12 Hz)
- theta (4-8 Hz)
- delta (0.5-4 Hz)

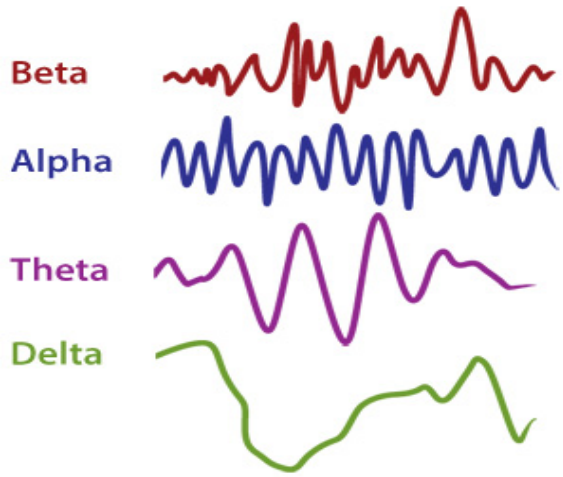


Figure 2.6.1.1: Brain Wave Bands with Dominant Frequencies [183]

In conventional EEG, the signal is recorded by placing electrodes on the scalp with a conductive gel. Many systems use electrodes that are attached to wires. Some systems also use nets with electrodes embedded, which is common when high-density arrays of electrodes are used.

International 10–20 system

10-20 electrode placement system was adopted since 1958 by the International Federation in Electroencephalography and Clinical Neurophysiology in order to standardised the physical placement and designations of EEG electrodes on the scalp [184]. The head is divided into proportional distances to ensure adequate coverage of all parts of the head.

The measurements was based on two anatomical skull landmarks: the nasion (the point in between the eyes, just above the bridge of the nose) and the inion (the lowest point of the skull in back of the head and is indicated by a prominent bump). Electrode placements are labelled according to brain areas. For example, F, C, T, P ,O and A represent the frontal, central, temporal, parietal, occipital areas and earlobes respectively. The accompanied numbers are to identify the specific positions of the electrode sites (Figure 2.6.1.2).

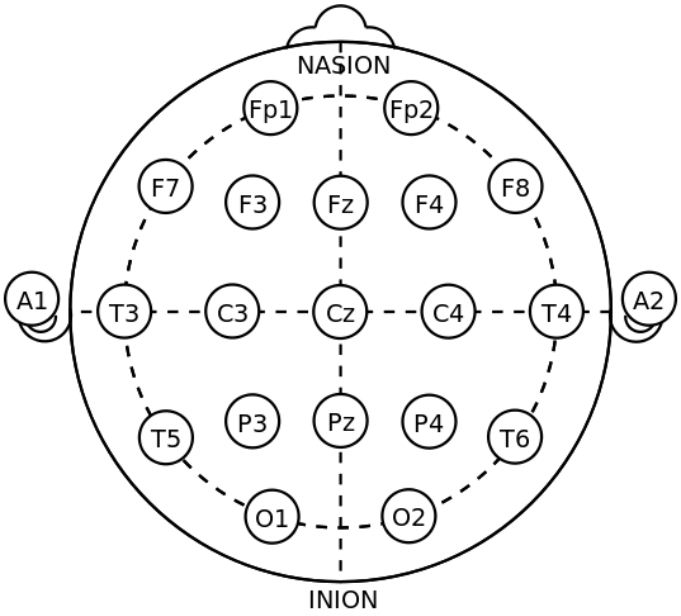


Figure 2.6.1.2: International 10–20 System [185]

Before further data processing, raw EEG signals should be checked for artifacts, which are signal distortions contaminated by activities such as body movements, eye blinks etc.

Biological artifacts

Non-cerebral electrical signals detected by EEG are called artifacts. EEG data is always contaminated by such artifacts. The amplitude of artifacts can be large relative to the amplitude of the signals we are interested. Some of the most common types of biological artifacts are:

- Eye-induced artifacts (such as eye blinks and extra-ocular muscle activity)
- ECG (electrocardiogram) -induced artifacts
- EMG (Electromyography)-induced artifacts

- Glossokinetic artifacts

Eyelid movements occur during eye blinking or vertical eye movements. It causes the fluctuation in the EOG channels above and below the eyes.

Eyelid fluttering artifacts were generated by rapid fluttering of the eyelids. They should be seen as noise in the EEG reading rather than a rhythm or wave. Therefore, currently they are referred to as an eyelid fluttering artefact.

ECG artifacts are common and can be mistaken for spikes. It allows the EEG to identify cardiac arrhythmias that are helpful in diagnosing syncope.

Glossokinetic artifacts are caused by the difference between the base and the tip of the tongue. Minor tongue movements can contaminate EEG signal.

2.6.2Estimating Alertness from EEG Power Spectrum

Human brains constantly emit waves of different frequencies simultaneously. And they are divided into several sub-bands, each is associated with a certain cognitive state.

Beta (12 to 30 Hz) is associated with being alert, engaged, and having focused mental activity, and we are likely to be in this state constantly during the day. The higher the frequencies are, the more engaged state the brain is in. For example, lower Beta range (13 to 15 Hz) correlates with being in a brooding state and high Beta range (23 to 30 Hz) represents highly complex thought or excitement.

When people are awake but in a non-engaged, more relaxed and slightly drowsy state, Alpha waves (8 to 12 Hz) are very likely to be the dominant frequencies. The next wave band, known as Theta (4 to 8 Hz), is involved with deep relaxation and possibly sleep onset. People are normally in this state while they are laying in the bed, preparing to go to sleep. The slowest wave Delta (0.5 to 4 Hz) indicates deep sleep.

It can be summarised that the higher EEG frequency correlates with more precise and accurate cognitive abilities. As a general basis we might be in 20 to 30 Hz during the day and slowdown in the evening, from early

biological night (8 to 12 Hz), sleep onset (4 to 6 Hz), to eventually deep sleep (0.5 to 4Hz).

It is now not hard to understand why it is generally a good time to investigate the effects of lights on alertness levels in the evening, more precisely, in one's early biological night. In the day time people are usually being exposed to a large quantity of lights and their brain waves are most likely to be hovering in the Beta range over the time. While at night when people go through different states from relaxation to sleep, the changes in the EEG power spectrum are much easier to be captured and interpreted. The circadian drive for sleep is the strongest at night and alertness level is the most sensitive to the change of light exposure. Therefore possibly a smaller sample size of subjects would be required at night to find the significant results [186].

Thus, Alpha and Theta frequencies in the waking EEG are of particular interest for research on alertness/sleepiness of subjects in wakefulness [187]. It has been found that subjective sleepiness correlates negatively with Alpha power and positively with Theta power in the resting awake EEG [188]. Decreased Alpha power followed by increased Theta power may indicate a motivation for sleep and represent the sleep entry [189].

High-frequency Alpha activity (11 to 12 Hz) has been proposed as a specific marker for alertness. However, in another study it was suggested that taking the whole Alpha range (8 to 12 Hz), rather than a part of the Alpha range, a decrease (rather than an increase) may be interpreted as an increase in alertness. It appears that frequency band can vary to some extent, as a function of age, memory performance and task demands. The use of fixed frequency bands windows does not seem justified, and to adjust the frequency windows for each subject by using individual alpha frequency as an anchor point might be necessary in some case [190]. In an early study subjects were participated in a dual-task simulation of auditory and visual sonar target detection, and the result indicated that the change in EEG power spectrum at several frequencies have a correlation with auditory detection performance. The correlation appears to be stable though somewhat variable between subjects [8]. It suggested that the mapping of alertness and EEG power at specific frequencies, is subject to individual differences.

Chapter 3
Methodology

This chapter describes the overall methodology used in subsequent experiments. Three experiments were done in this research. They are reported in Chapter 4, Chapter 5 and Chapter 6 respectively.

Different lighting conditions have been tested in three experiments. Experiment 1 aimed to look into the alerting ability of a short-wavelength light and a broadband wavelength light of the same light level. Experiment 2 aimed to evaluate the alerting ability of short-wavelength light of three different levels (40 lx, 80 lx and 160 lx). Experiment 3 aimed to investigate the effect of two levels (40 lx and 160 lx) of a long-wavelength light on human alertness. Table 3.1 lists lighting conditions used in three experiments.

Table 3.1 Lights used in three experiments

	Lights conditions used	names
Experiment 1	150 lx broadband wavelength light	G (Green)
	150 lx short-wavelength light	B (Blue)
	40 lx dim white light	White
Experiment 2	40 lx blue light	B40
	80 lx blue light	B80
	160 lx blue light	B160
	dim (2000 K, <1 lx) light	Dim
Experiment 3	40 lx long-wavelength light	R40
	160 lx long-wavelength light	R160

Similar methodology were adopted for three experiments. The following information provided in this chapter describes the equipment and method used.

3.1 The LED Lighting System

The lighting system used for the study is the Thouslite LEDCube provided by Thousand Lights Lighting Limited (Figure 3.1.1). LEDCube is a spectrally tunable lighting device that can create a customised standard lighting environment for lighting and colour research.

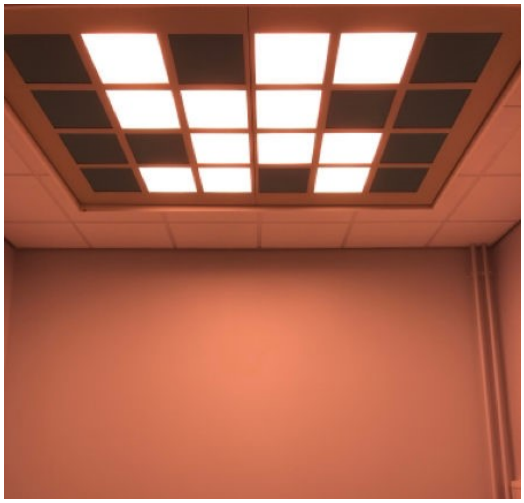


Figure 3.1.1: Thouslite LEDCube

Some of the main features of the system includes reproducing measured or imported spectral power distribution (SPD), independent control of the intensity of each channel in LEDCube and dynamic lighting. These features are briefly introduced here.

Single-channel Control

Single Channel Control allows users to set the intensity drive current of each LED channel in LEDCube, as shown in Figure 3.1.2. Users could adjust the drive current of each channel by sliding the bars or input the drive value directly. The corresponding SPD curves and colour will change correspondingly. The adjust range is from 0-100 with resolution 0.1. After the intensity of each channel is determined, users can adjust the total luminance of the light source in Light Source Reproduction module.

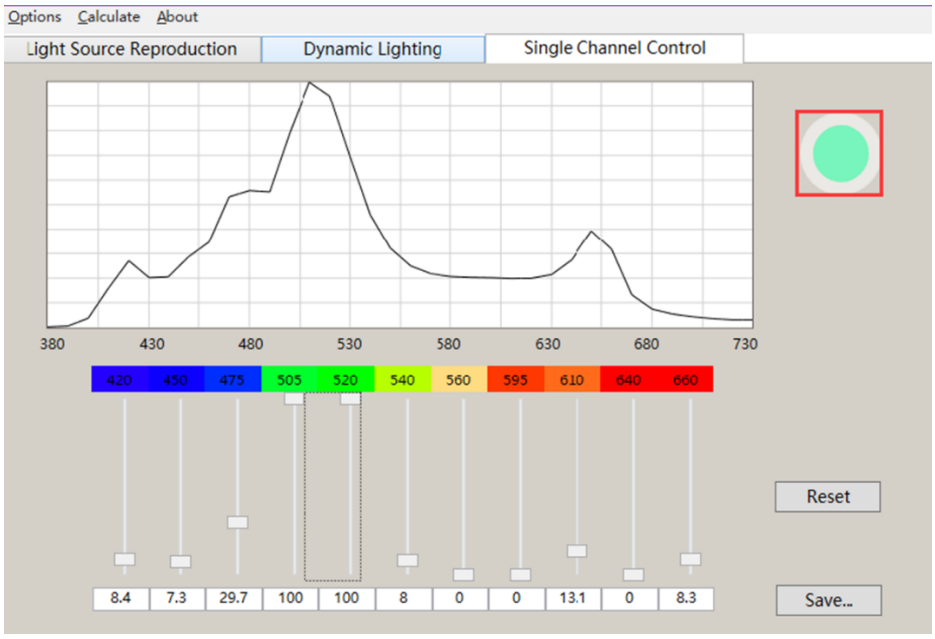


Figure 3.1.2: Interface of Single-channel Control Module

X-Rite i1 Pro

The X-Rite i1 Pro2 spectrophotometer (Figure 3.1.3) is an accessory for the LEDCube. It can be used to measure the quality of light output. Moreover, it is essential component to perform the calibration, measurement and feedback.

Figure 3.1.3: i1 Pro2 and measurement geometry

Before measurement, the i1 Pro 2 requires calibration with a calibration white tile. The measured value is illuminance (lx) with illumination head or luminance (cd/m2) without illumination head (Figure 3.1.4).

Figure 3.1.4: i1 Pro 2 calibration white tile (left) and illumination head (right)

Light Source Reproduction

Measure component

Once the i1 Pro2 is calibrated, measurement may be conducted. The measured result includes several parameters as shown in Figure 3.1.5. Meanwhile, the SPD curve will be illustrated in the SPD graphics box.

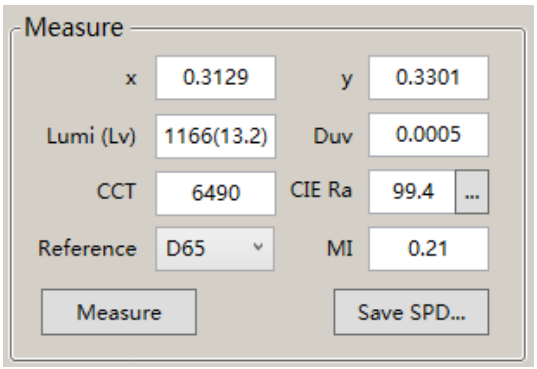


Figure 3.1.5: An example pf measure result

Match component

The match component is the key feature for light replication. There are two match types (Figure 3.1.6).

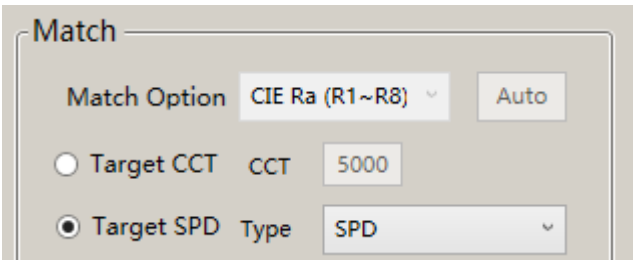


Figure 3.1.6: Match component

a) Target CCT, the system will optimise the output SPD to match Blackbody (<5000K) or Daylight (>=5000K) SPD. The input CCT is limited between 2000K and 9999K.

b) Target SPD, the system will optimise the output light according to the target SPD input by users. Meanwhile, users need to set the target light type and data source.

SPD Data Source

There are two kinds of SPD data source, i.e. by measured or by loaded (Figure 3.1.7). For loaded source the i1 Pro2 or other supported measure device is required. For loaded source a pre-saved SPD data is necessary.

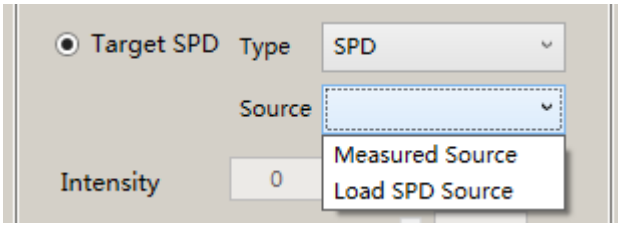


Figure 3.1.7: SPD Data Source Selection

Lightness adjustment

After SPD match, users may adjust the lightness intensity. The adjust range is 1%-100% and the minimum interval is 0.1% (Figure 3.1.8).

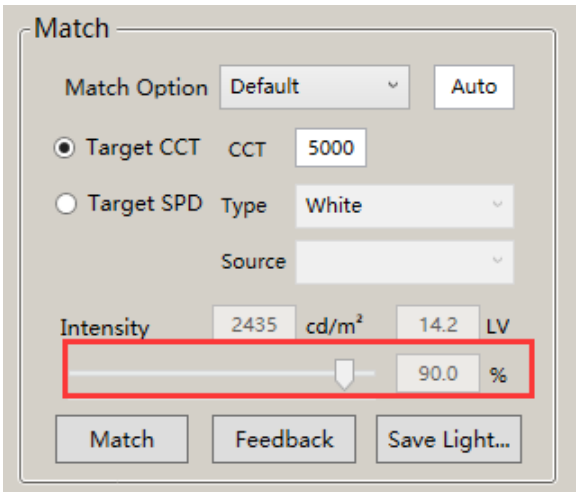


Figure 3.1.8: Lightness adjustment

Feedback

If a considerable difference between output SPD and target SPD exists, feedback should be performed to correct the difference. Generally speaking, one feedback routine should be sufficient. More feedback does not guarantee better results. In order to get a target SPD at certain light intensity, it is better to match the target SPD firstly, and then adjust the light intensity to the desired range, finally perform the feedback to correct the difference between actual SPD and target SPD.

Dynamic lighting

Figure 3.1.9 shows the interface of Dynamic Lighting Module. Up to 24 illuminants can be saved with specified time in a loop, and the unit for time is second. In addition, users can save the current setting including the illuminants and time to a loop.

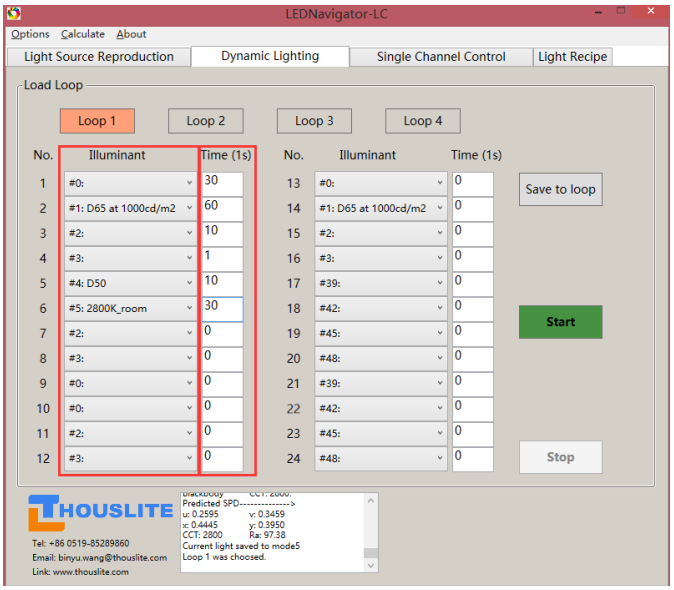


Figure 3.1.9: Interface of Dynamic Lighting Module

3.2 EEG

The EEG System used in this work is the B-Alert X10 developed by Advanced Brain Monitoring (ABM). The X10 provides wireless recording of EEG, EOG and ECG signals.

3.2.1 Equipment Handling

The X10 acquires 9 channels of monopolar EEG recordings from sensors sites at POz, Fz, Cz, F3, F4, C3, C4, P3, P4. There are also linked mastoid (the spot just under the ear) leads and ECG leads. The X10 Sensor Strip has 9 electrodes at 9 locations on the head (Figure 3.2.1.1).

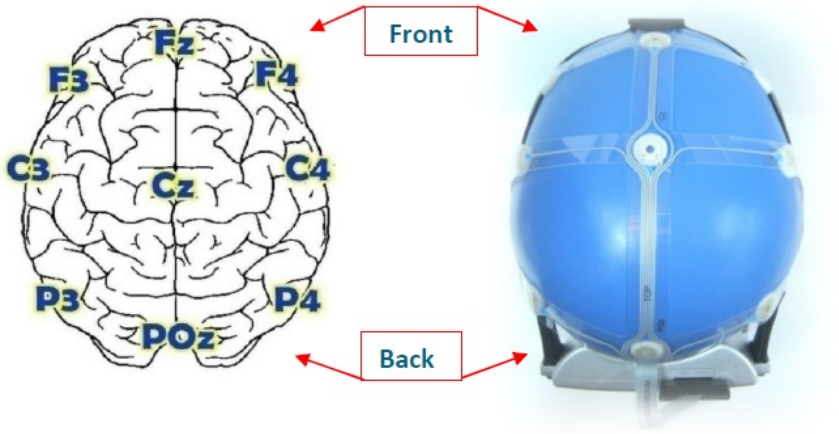


Figure 3.2.1.1: Brain Map of X10 Sensor Strip

The foam pieces are attached to the sensor site after which they are filled with conductive synapse gel using the provided syringes (Figure 3.2.1.2).

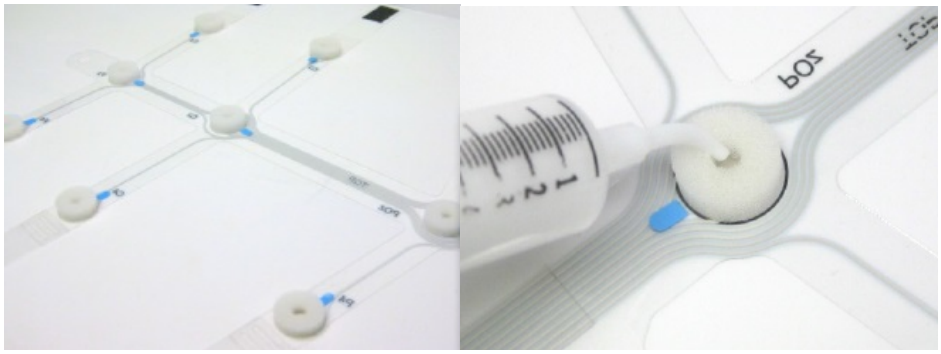


Figure 3.2.1.2: Filling Gel to the Sensor Sites

Sensor strips come in two sizes. The distance from the nasium (bone above the nose) to the inion (occipital bone in the back of the head), and the crest of helix (where the top of the ear connects with the head) to the other should be measured to determine which size to use according to a sizing chart. The sensor headset is attached to a neoprene strap and the strap is fitted to the participant's head. The sensor strip arms are attached to the neoprene strap and the connector on the back of the strip is plugged into the sensor headset.

Disposable adhesive EEG Sensors with a small amount of synapse gel are attached for each ECG and Mastoid lead. ECG Leads have right and left leads, one should be put on the participant's right collar bone and the other is put on left lower rib bone. The Mastoid Lead is placed directly on the mastoid bone. It is imperative to avoid applying the Mastoid Lead over any hair or on muscle. Signals can be compromised if not properly placed on mastoid bone. The areas where sensors are attached should be wiped with an alcohol swap (Figure 3.2.1.3).

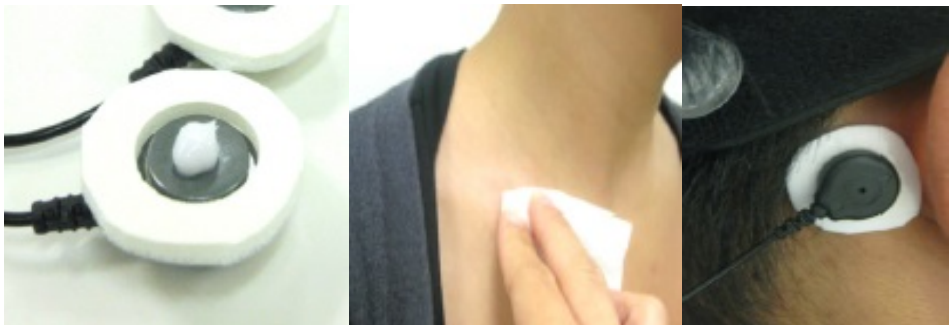


Figure 3.2.1.3: ECG and Mastoid Leads

The EEG recording is sensitive to excessive muscle activities such as teeth grinding and gum chewing etc. Instruction should be given to participants to relax their forehead, stop clenching their teeth, or biting their lips to avoid excessive electromyography. Data is compromised if the reference channel has a high impedance. In that case, the mastoid sensors should be removed to clean the attached area, and reapply the sensors.

3.2.2 Software Use: Data Outputs

B-Alert Live Software acquires physiological signals from ABM EEG devices. It provides functionalities such as 1) Computing electrode impedances, 2) Transmitting data to a remote computer, 3) Computing and displaying real-time cognitive metrics, 4) Administering metric benchmarking tasks, 5) Replaying data offline, 6) Generating summary report, and 7) Processing data offline.

The software has a modular architecture that allows the user to interact either using the Graphical User Interface provided with the installation, or programmatically via the included Software Development Kit. The data outputs are saved in EDF+ format compatible with all standard EDF+ readers.

Data Acquisition and Impedance Check

B-Alert Live provides several on-line and off-line functions. The most used online functions in current study were Acquisition and Test Impedance (Figure 3.2.2.1). The Acquisition function allows start/stop of data acquisition. The Test Impedance function allows the user to test the impedance levels at each electrode site. Low impedance (<40 kΩ) is recommend to ensure good quality of data. The lower the impedance values, the better the conductivity between the scalp and electrodes and thus the better the quality of the signal. It is strongly recommended to conduct an impedance check each time before starting data collection.

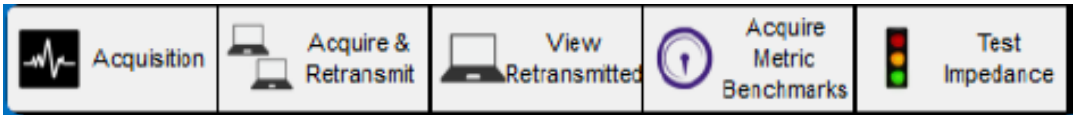


Figure 3.2.2.1: The Online Action Icons

Impedance values < 40kΩ will be highlighted in green, values 40kΩ - 80kΩ will be yellow, and impedance values > 80kΩ will be red (indicating that the sensor is outside the acceptable range) (Figure 3.2.2.2). ABM recommends sensor impedances below 40kΩ for optimal data quality. Impedances higher than 40kΩ (yellow) can still collect good quality EEG, and thus may not be reason to exclude a participant from continuing to collect. In this study both green and yellow impedance values (<80kΩ) were accepted and proceeded with data collection.

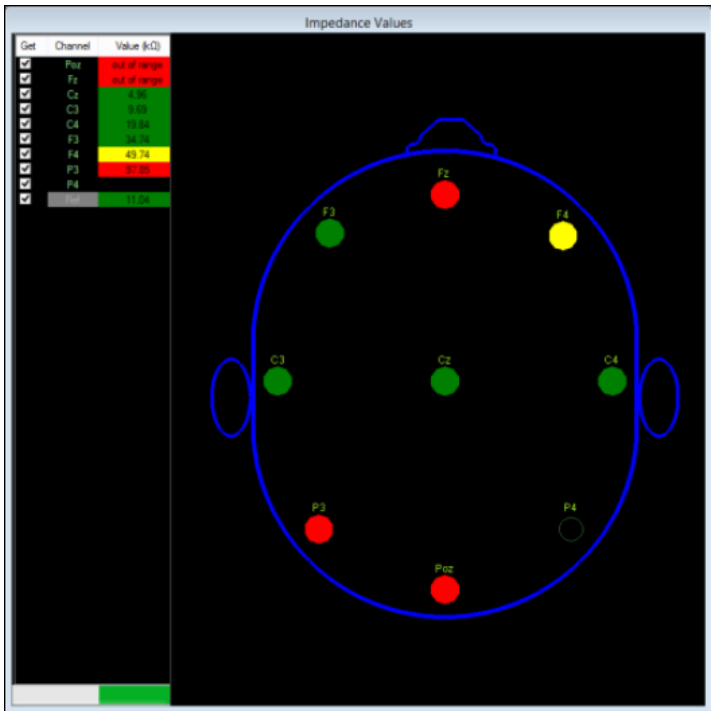


Figure 3.2.2.2: The Impedance Check

Computing Power Spectral Density

The B-Alert Live Software allows Power Spectral Density (PSD) computation and automatic decontamination.

Power spectral density is computed by performing Fast Fourier Transform (FFT) on a segment of data that is of interest, and calculating the amplitudes of the sinusoidal components for designated frequency bins. Input variables to this transformation are an EEG segment for which PSD is to be computed, and its length; output variables include PSD amplitudes. Frequency domain

variables are based on the PSD derived after application of a 50% overlapping window, and a FFT with/without application of a Kaiser window.

The B-Alert software provides two sets of PSD from 1 to 40 Hz for each EEG channel that are logged to obtain a Gaussian distribution. Selected 1-Hz bins are averaged, then logged to create conventional EEG bands (e.g., theta = 3 – 7 Hz, alpha = 8 – 12 Hz, etc.). Both sets of PSD output apply a 50% overlapping window which averages the PSD across three x one-second overlays to smooth the data. The illustration below (Figure 3.2.2.3) shows that overlays 0, 1, and 2 are averaged to provide the PSD values for epoch n:

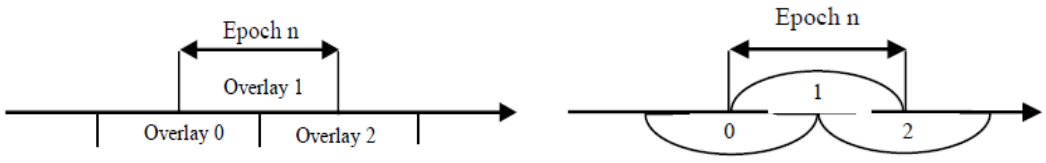


Figure 3.2.2.3: 50% Overlap without (left) and with (right) Kaiser Window

The application of Kaiser window is to accentuate the contribution of power from the signal in the middle third of the overlay, and minimise the impact of signal near each edge of the overlay. Windowing reduces the likelihood of extreme PSD values resulting from edge-effects when an EEG wave shape does not begin or end at the exact edge of an overlay.

Decontaminating Signals

Prior to computing the 1-Hz PSD bins, the raw signals are processed to eliminate known artifacts. Spikes, excursions and amplifier saturations occur when ambulatory EEG is acquired, can impact both low and high frequencies. EMG can contaminate the beta and sigma frequency ranges. Eye blinks occur in the same frequency range as theta activity.

- Excursions and amplifier saturation – contaminated periods are replaced with zero values, starting and ending at zero crossing before and after each event.

- Spikes caused by artifacts are identified and signal value is interpolated.

- Invalid Epochs – If more than 128 zero values are inserted for an overlay, the overlay is excluded from the epoch average; if 2 of the 3 overlays are rejected, the epoch is classified 'invalid' (-99999 inserted for PSD value) and should be excluded from analysis.

- EMG – a combination of High Frequency EMG (based off 70 - 128 Hz bins for each overlay) and Low Frequency EMG (based off 35 - 40 Hz) is used to identify periods with excessive EMG. If only one overlay has EMG, the PSD for the epoch is based on the average of the remaining two overlays. If excessive EMG is detected in two overlays, the second is classified as 'EMG' and should be excluded from analysis.

- Eye Blinks – wavelet transforms deconstruct the signal and a regression equation is used to identify the EEG regions contaminated with eye blinks. Representative EEG preceding the eye blink is inserted in the contaminated region.

3.3 Questionnaire, Information Sheet and Consent Form

3.3.1 Questionnaire

Questionnaire has been used in the study as a subjective measure. A few different types of questionnaires have been applied to collect either participants' personal information or subjective responses.

Experiment round 1

It is important to know about participants' sleep schedules and to understand their individual biological clock. In the first round of experiments, a full version of MCTQ was used to provide information on the participants' work schedule, usual bed/rise time and caffeine/tea/alcohol/nicotine intake, in addition to their personal details (full questionnaire see Appendix A).

Experiment round 2 and 3

From the second round of experiment, MCTQ was replaced by a simplified version, which mainly collects participant's bed/rise time, and daily cigarette/alcohol/caffeine consumption, if applicable (see Appendix B).

In the second and the third round of experiments, subjective sleepiness was rated using the KSS, where participants were asked to rate their sleepiness at that moment. Participants were also asked to rate the brightness of the lighting exposure, using a scale from 1 (dim) to 9 (extremely bright). Both rating questionnaire can be found in Appendix C. Participants rated sleepiness and brightness every 20 minutes over the experiment. Their responses were recorded in a table as in Table 3.3.1.1.

Table 3.3.1.1 Subjective measure questionnaire

Experimental Time	Rating 1 (Sleepiness)	Rating 2 (Brightness)
20 min		
40 min		
60 min		

In the third round of experiment, additionally, feedback was collected on the second day. The questions used were:

I went to bed at around pm yesterday.
I got up at around am today.
Please report any side effects (e.g. headache).

3.3.2 Information Sheet and Consent Form

As caffeine and alcohol can enhance brain excitement and have an influence on the results, participants were instructed in the information sheet not to take alcohol or caffeine within three hours prior to the experiment. In some published studies, smokers were excluded. In this study, participants were instructed not to smoke three hours before experiment, but their data

was still included. Information sheets for three rounds of experiment are in Appendix D.

A consent form was provided to obtain participant's consent prior to experiment. Ethics approval for each round of experiment was granted by the Faculty Research Ethics Committee, School of Design, University of Leeds. An example of consent form as well as ethics approvals for three rounds of experiment are in Appendix E.

3.4 Conditions Used for Each of the Three Studies

Study 1

Light was delivered through four LED light cubes (Thouslight Lighting System) placed at the top of a ceiling. The walls were covered by black curtains. Participants were asked to sit under the LED light cubes whilst reading, with a white table in front of them (Figure 3.4.1). All participants read the same book provided throughout their experiments.

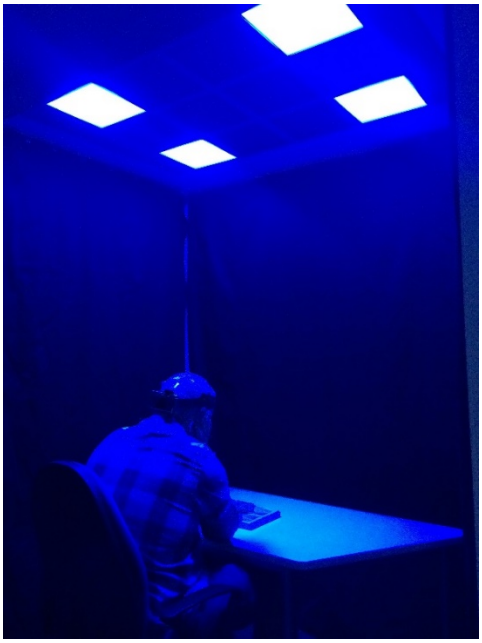


Figure 3.4.1: Lighting environment

Three lighting exposures were designed; a dim white light (D65) and two coloured lights (a narrowband wavelength blue and a broadband wavelength green) with equal intensity. The spectral profile of the blue light was designed to be narrowband and have a peak at 460-480 nm, the range that

is believed to be have the maximum circadian sensitivity. The green (yellowish) light, in contrast, was designed to be broadband across the spectrum from 500 nm to 680 nm (Figure 3.4.2). Details on the relative spectral power of three lights can be found in Appendix F.

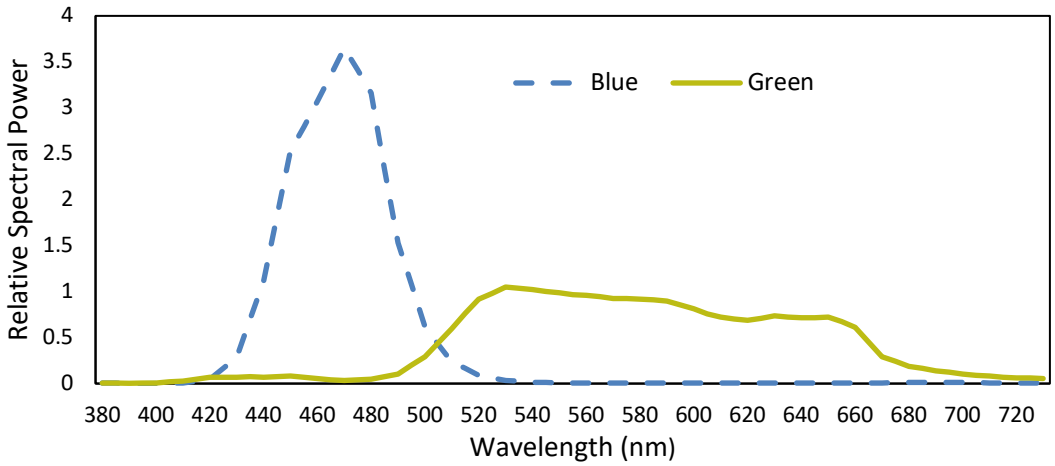


Figure 3.4.2: Spectral power distribution of two test lights

The intensity of the lights was measured using a Lux Meter (LX1010BS). The measurements were taken around the flat area where the book was likely to be while reading. Four corners as well as the central point of the rectangular area were measured (Figure 3.4.3), and the average was calculated.

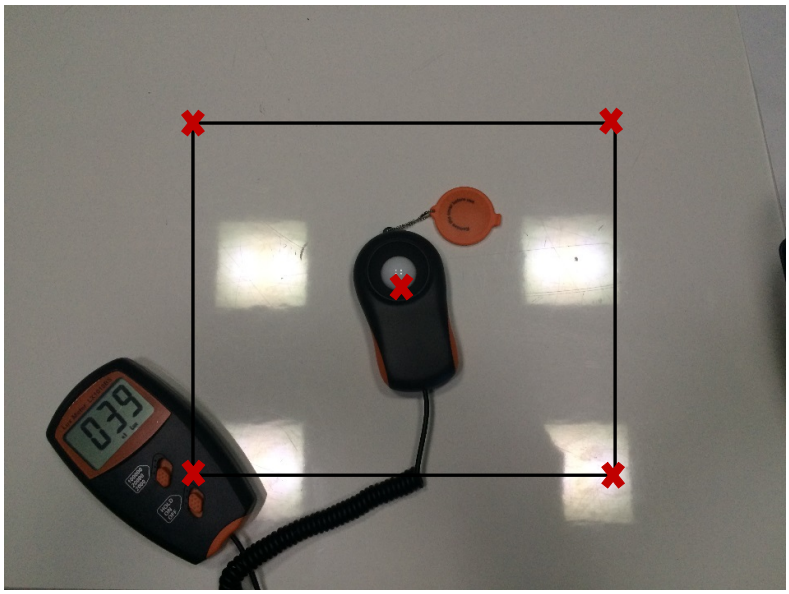


Figure 3.4.3: The five points (red crosses) measured for intensity

The average intensity of all five locations was used to represent the overall intensity measures. The targeted intensity was set at around 40 lx for the dim white light, and around 150 lx for the coloured lights. The measures were taken twice at around the same time in two consecutive days for the three lights (Table 3.4.1).

Table 3.4.1 Overall Intensity for Three Lights

	Measurement 1/ overall intensity (lx)	Measurement 2/ overall intensity (lx)	Average (lx)
White	39 ± 0	39 ± 0	39 ± 0
Blue	151 ± 0	151 ± 0	151 ± 0
Green	148 ± 0	148 ± 0	148 ± 0

Study 2

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. Participants were asked to sit under the light whilst reading, with a white table in front of them (Figure 3.4.4). The lighting measures were taken within the flat reading area on the table.

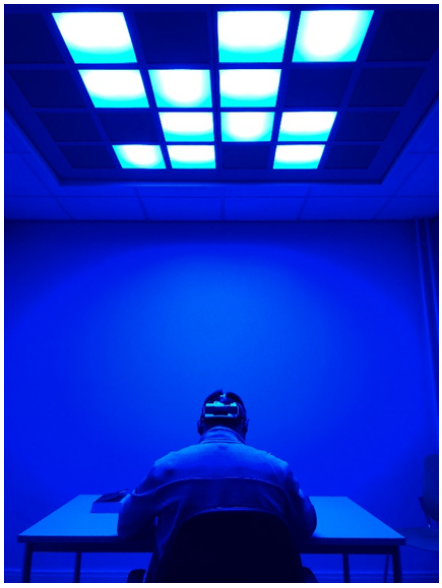


Figure 3.4.4: Lighting Room showing the position of the participant and the luminaires

Four light settings were used: a dim (2000 K, <1 lx) and three short-wavelength lighting conditions. The short-wavelength condition had a peak

at about 480nm and was approximately Gaussian with a half-width half-height of 35nm (Figure 3.4.5). For details of the relative spectral power of four lights see Appendix F.

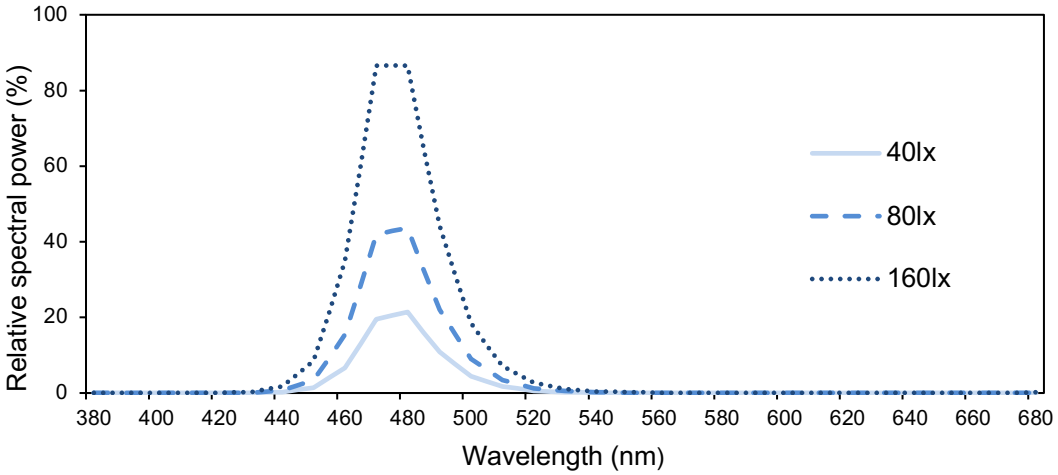


Figure 3.4.5: Spectral power distribution of three test lights

X-Rite i1Pro spectrophotometer was used to measure the light intensity. Five points around the reading area were measured as in study 1 and results are listed in Table 3.4.2. Three intensities were measured at 40 lx, 80 lx and l60 lx (±1 lx).

Table 3.4.2 Intensity measures of five points for three test lights

	B40 (lx)	B80 (lx)	B160 (lx)
Central point	40	80	160
Point 1	40	80	159
Point 2	40	80	159
Point 3	40	81	161
Point 4	40	80	161

Study 3

Light exposure was delivered through 12 LED cubes (provided by Thouslite Lighting System) mounted in the ceiling of a room with white walls and grey carpets. Participants were asked to sit under the light whilst reading, with a table in front of them (Figure 3.4.7). The lighting measures were taken within the flat reading area on the table.

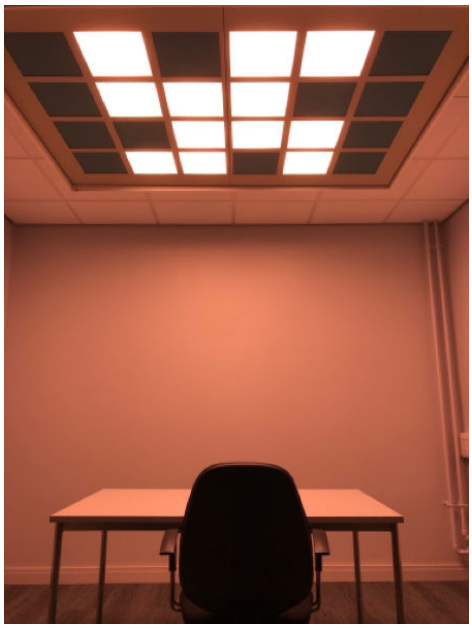


Figure 3.4.7: The lighting environment

Two long-wavelength light conditions were used. They had a peak at 630nm (40 lx) and 640nm (160 lx) with a full width at half maximum of 25nm.The spectra of the two lighting conditions were measured with an X-Rite i1Pro spectrophotometer and shown in Figure 3.4.8. Details of the relative spectral power of two lights can be found in Appendix F.

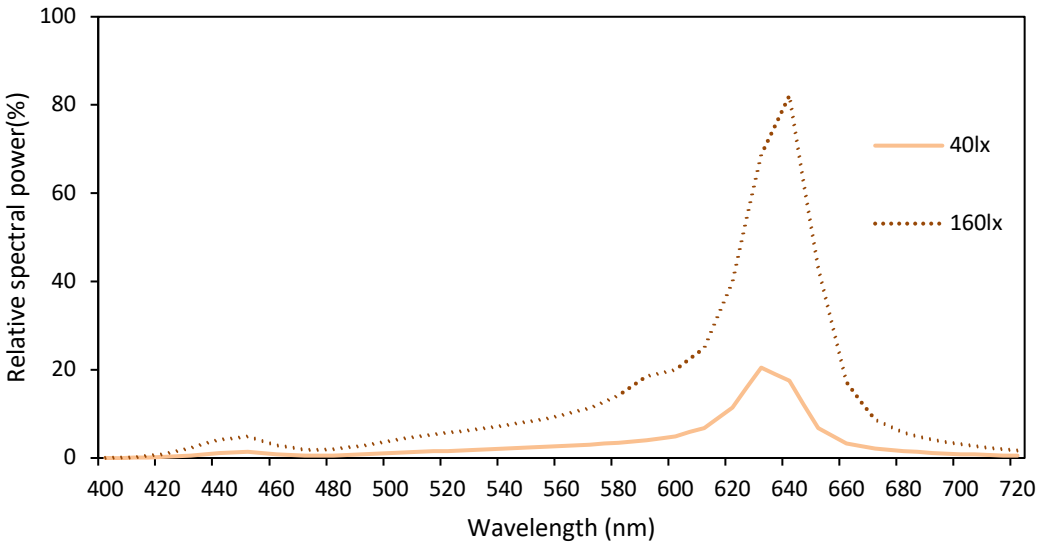


Figure 3.4.8: Spectral power distribution of two test lights

Two illuminances were measured at 40 lx and l60 lx (±1 lx) on the table. Five points around the reading area were measured and results are listed in Table 3.4.3.

Table 3.4.3 Intensity measures of five points for two test lights

	R40 (lx)	R160 (lx)
Central point	40	160
Point 1	39	159
Point 2	40	159
Point 3	41	161
Point 4	41	161

Chapter 4
Study 1: Alerting effect of a blue and a green light

4.1 Aim

This study aimed to look into the alerting ability of a short-wavelength blue light and a broadband wavelength green light of the same light level, but relatively deficient in short wavelengths. Apart from the main study, a subsequent experiment was also conducted to compare between two blue lights.

The two lights tested in the main study were a blue light and a green light with equal intensity. The blue light has a peak at 460-480 nm, the range that is believed to have the maximum circadian sensitivity, however the green light is broadband across the spectrum from 500 nm to 680 nm.

EEG was used as the main measurement in this study. The other aim of this study was to look at the relations between EEG power measures and subjects' alertness. The subsequent experiment aimed to further compare the alerting ability and EEG measures of two blue lights of different spectra.

4.2 Brief Summary of Experiments

4.2.1 Experimental Protocol

This study was designed to be a within-subject experiment, which means each participant needed to do two experimental sessions each with a different light condition, and the results from two sessions were compared within subjects. The study was approved by the University of Leeds Ethics Committee (LTDESN-068).

Each session lasted around 50 minutes. Prior to the start of the exposure, participants were fitted with EEG electrodes after they signed the consent form and finished MCTQ (only in the first session). They were then asked to remain seated, read the book that was provided, and try to reduce head movement throughout the experiment. No other activities (e.g. using

electronic devices or talking) were allowed. The exposure lasted 35 minutes in total (Figure 4.2.1). Participants first remained in the dim white light for 15 minutes, with EEG recording for the last 5 minutes. Then it was switched to coloured light exposure (either blue or green) for another 20 minutes, with EEG recording for the last 5 minutes.

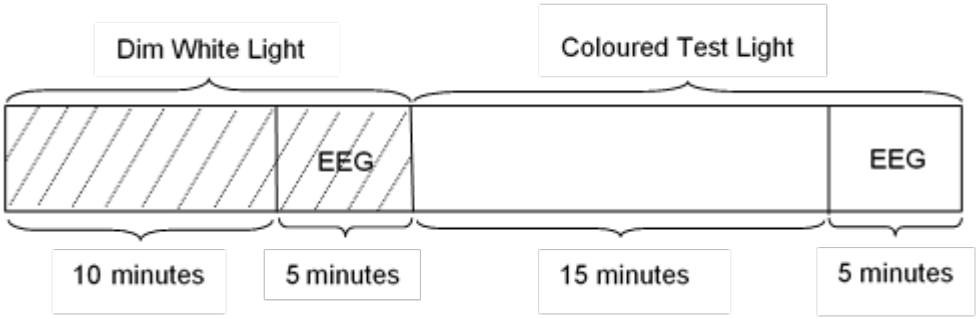


Figure 4.2.1: Experimental Protocol

All experiments happened between 20:00-22:00. Each participant completed two sessions over two nights, both starting at the same time (either 20:00 or 21:00). On each night participants were exposed to either blue or green light and the order of the two exposure conditions was random to avoid potential sequence effects. Most participants completed the two experimental sessions in two consecutive nights. When this was not the case, they were asked to maintain a regular, constant schedule between the two sessions.

The only measurement taken in this study was EEG. Melatonin tests, other performance tasks or self-reporting of subjective sleepiness such as KSS were not used. The behavioural measures (performance tests and questionnaires) tend to test variations in alertness over longer durations, whereas electrophysiological measures such as EEG record instantaneous changes. This might suggest that for this protocol electrophysiological measures can be more sensitive than behavioural measures.

4.2.2 Participant Information

A total of 9 participants were recruited. One of them was a smoker. All participants completed the study and produced valid data (4 females and 5 males; mean age ± SD = 31.3 ± 9.5 years).

All participants reported their bedtime schedule (Table 4.2.2) and none identified as having worked as a shift worker in the last three months.

Table 4.2.2 Self-reported Bedtime on Workdays

Subject No.	Bedtime (hrs)
1	00:00
2	23:20
3	01:00
4	23:30
5	23:00
6	01:00
7	00:00
8	01:30
9	23:00
Time range	23:00 - 01:30

Table 4.2.2 shows that participants reported to go to bed between 23:00 to 1:30. The experiments started at either 20:00 or 21:00, approximately 3 to 4 hours prior to the participants' bedtime. They were allocated the experimental starting time depending on how early/late their bedtime was. e.g. if a participant goes to bed before 00:00, they might start experiment at 20:00, else if they go to bed later than 00:00 they might start at 21:00. Out the 9 participants, 5 started at 20:00 and the other 4 started at 21:00.

It was preferred that a participant completed the two experimental sessions on consecutive days or on two days that were relatively close, so that participants are more likely to be in the similar sleep schedule over the two sessions. However, this was subject to their availability. When this was not possible, they were asked to maintain a regular, constant schedule between the two sessions. Out of 9 participants, 7 of them completed two sessions within four days.

5 participants (3 males) received blue exposure first and 4 subjects (2 males) received green exposure first. After the preliminary analysis on EEG data two participants were asked to repeat one of the experiment sessions. Their initial data from two sessions exhibited a certain level of inconsistency, which might have resulted from various reasons e.g. one of the participants

caught a cold the time in between two experiments, and in the other participant's experiment EEG signal had a failure. In the subsequent analysis, the initial data were discarded and replaced by the data collected from their repeated experiments.

4.3 Results

4.3.1 EEG Data Generation

Each time before EEG recording, the impedance of each recording channel was checked to make sure it is within the acceptable range (<80kΩ). When any impedance value was greater than 80kΩ, the equipment was adjusted until it was acceptable. Each time after EEG recording, a number of files were generated, including raw/decontaminated PSD, impedance data, heart rate data and artifact information etc.

The data used in the current analysis was derived from 'Ref_class.csv', which contains decontaminated referential channel PSD. In this file the raw signals are processed to eliminate known artifacts prior to computing PSDs (1-40Hz) for the 9 referential EEG channels (POz, Fz, Cz, C3, C4, F3, F4, P3, and P4) respectively are computed for each second with the Kaiser Windowing procedure described previously. One row of data is provided per second of recording time, which is called an epoch. One epoch consists of three overlays and each overlay containing 256 data points with 128 data points being shared for each overlay. The periods contaminated by excursions and amplifier saturation are replaced with zero values. If more than 128 zero values are inserted for an overlay, the overlay is excluded from the epoch average; if 2 of the 3 overlays are rejected, the epoch is classified 'invalid' (-99999 inserted for PSD value). Invalid epoch was removed and excluded from analysis. A program was developed in MATLAB R2016a (see Appendix G) to plot EEG PSDs change overtime, calculate the number of invalid epochs and mean PSD of the session. A section of the interface (Figure 4.3.1) showed PSD values of POz and Cz channels, at 1Hz, over the period of 300 seconds.

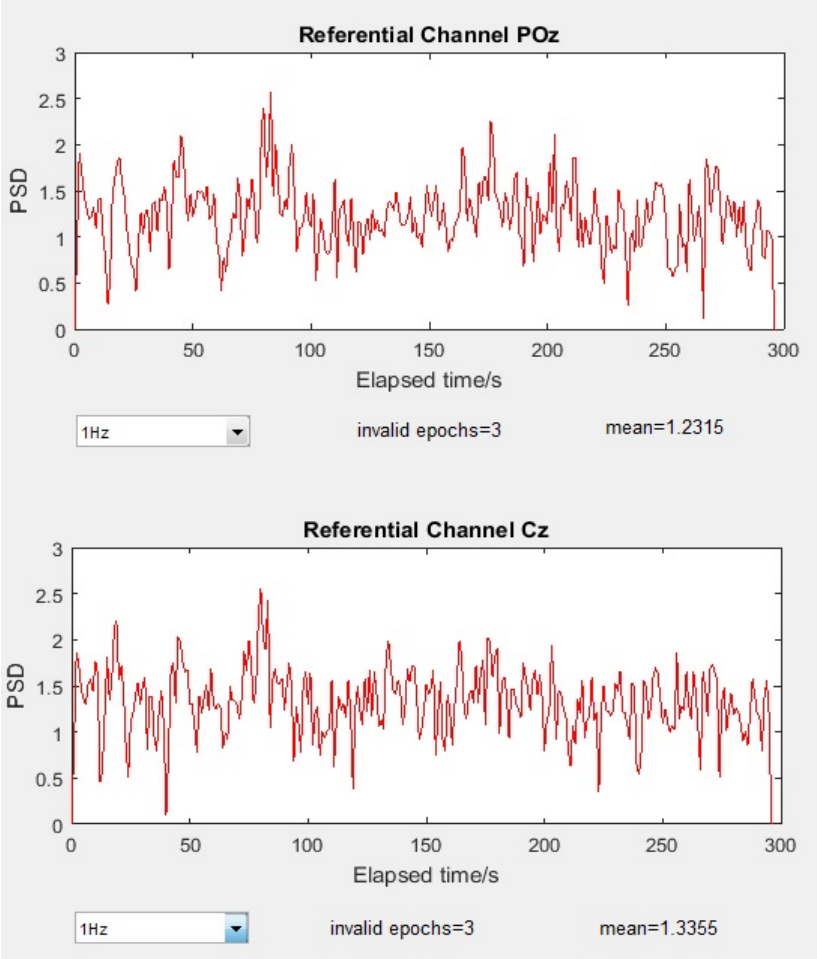


Figure 4.3.1: An Example of MATLAB EEG Interface

4.3.2 EEG Data Manipulation

EEG recording duration was 5 minutes at the end of exposure to the reference and test lights. EEG were recorded for each participant four times in total; after dim light exposure (before coloured light) and after coloured light exposure; and for two sessions respectively (blue and green lights).

PSD was calculated at individual Hz bins from 1 Hz to 20 Hz. At each Hz bin, valid PSD values from 5 minutes (300 seconds) were averaged to represent the power at this Hz bin. The PSD ratio of coloured light and preceding dim light was calculated; the data was expressed as a percentage of the PSD under the preceding dim light exposure. Data from all 9 EEG channels went through the same procedure and generated 9 set of data, which were then averaged to obtain overall power from all channels (global EEG power). The results for each of the 9 participants are shown below (Table 4.3.2.1).

Percentage data are available from 1 to 20 Hz bins, for both green (G) and blue (B) lights, and for every subject (No.1 to No.9).

Table 4.3.2.1 EEG PSD normalised to the Preceding Dim Light

		1(Hz)	2	3	4	5	6	7	8	9	10
G	1(No.)	1.12	1.08	1.05	1.04	1.04	1.08	1.07	1.04	1.03	1.03
	2	0.98	0.99	1.00	1.00	0.99	1.00	1.03	1.02	1.01	1.01
	3	0.98	0.99	0.99	0.99	0.98	1.00	1.01	1.02	1.04	1.05
	4	0.93	0.96	0.96	0.96	0.97	0.96	0.97	1.01	1.02	1.02
	5	0.92	0.95	0.96	0.96	0.97	0.97	0.97	0.99	0.99	1.00
	6	1.03	1.00	1.00	1.00	1.02	1.01	1.03	1.04	1.03	1.04
	7	1.00	1.00	0.98	0.99	1.00	1.00	1.01	1.04	1.09	1.08
	8	0.95	0.96	0.96	0.95	0.97	1.00	1.00	0.98	0.99	1.03
	9	1.03	1.00	1.01	1.01	1.01	1.01	1.02	1.00	0.99	0.99
B	1	0.98	0.97	0.98	1.00	1.02	1.05	1.03	0.99	0.99	1.01
	2	1.04	1.02	1.03	1.05	1.03	1.01	1.02	1.04	1.04	1.08
	3	1.09	1.05	1.04	1.03	1.03	1.05	1.05	1.04	1.04	1.04
	4	1.12	1.12	1.11	1.10	1.08	1.05	1.02	0.98	0.98	0.98
	5	0.95	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.99	1.00
	6	0.96	0.97	0.95	0.95	0.97	0.97	0.96	0.94	0.91	0.92
	7	1.00	1.00	1.01	1.01	1.01	0.99	1.01	1.03	1.05	1.04
	8	0.98	0.97	0.96	0.97	0.98	0.97	0.98	1.00	1.04	1.14
	9	1.01	1.00	0.99	0.99	1.01	1.03	1.00	1.02	1.05	1.06

		11Hz	12	13	14	15	16	17	18	19	20
G	1(No.)	1.02	1.01	0.99	1.00	1.00	0.98	0.95	0.92	0.92	0.92
	2	0.99	0.98	1.00	1.01	1.01	1.02	1.05	1.05	1.07	1.07
	3	1.04	1.01	1.02	1.03	1.02	1.02	1.01	1.02	1.02	1.01
	4	1.01	0.96	0.96	0.98	0.99	1.01	1.01	1.01	1.01	0.98
	5	1.00	1.01	1.01	0.99	1.00	1.00	1.00	1.00	0.99	0.99
	6	1.06	1.09	1.11	1.08	1.06	1.06	1.06	1.07	1.08	1.08
	7	1.06	1.04	1.03	1.00	0.97	0.97	0.98	0.99	1.00	0.99
	8	1.05	1.04	1.03	1.02	1.01	0.98	0.98	0.99	0.99	1.00
	9	1.01	1.01	1.00	1.02	1.02	1.03	1.03	1.03	1.01	1.01
B	1	1.05	1.08	1.07	1.05	1.05	1.06	1.06	1.03	1.05	1.05

2	1.08	1.06	1.06	1.09	1.12	1.15	1.16	1.16	1.13	1.13
3	1.04	1.05	1.08	1.12	1.13	1.13	1.10	1.09	1.13	1.12
4	0.97	0.97	0.96	0.97	0.96	0.95	0.96	0.96	0.96	0.96
5	0.98	0.98	0.96	0.96	0.96	0.97	0.98	0.97	0.96	0.96
6	0.98	0.99	0.95	0.94	0.96	0.93	0.90	0.89	0.90	0.89
7	1.04	1.05	1.06	1.05	1.05	1.04	1.02	1.02	1.00	1.00
8	1.11	1.03	1.01	0.99	1.00	1.03	1.03	1.04	1.06	1.07
9	1.06	1.04	1.03	1.04	1.05	1.05	1.06	1.07	1.06	1.08

The mean of each set of data (n=9) was calculated (for 1 to 20 Hz, blue and green). The standard deviation (SD) and the standard error of the sample mean (SEM) of each set were then calculated in Excel. The SD of the sample reflects the degree to which individuals (subjects) within the sample differ from the sample mean, whereas SEM is an estimate of how far the sample mean is likely to be from the population mean [191]. SEM is calculated by taking the standard deviation and dividing it by the square root of the sample size (n=9). This was calculated in Excel using the following formula:

=stdev(range)/sqrt(count(range))

The results are shown below (Table 4.3.2.2). Mean, SD and SEM of the sample were calculated for each individual Hz bins and for both light conditions.

Table 4.3.2.2 Mean, SD and SEM

Green		1(Hz)	2	3	4	5	6	7	8	9	10
	mean	0.99	0.99	0.99	0.99	1.00	1.00	1.01	1.02	1.02	1.03
	SD	0.06	0.04	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03
	SEM	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Blue											
	mean	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.01	1.03
	SD	0.06	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.05	0.06
	SEM	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.02
Green		11(Hz)	12	13	14	15	16	17	18	19	20

	mean	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.01
	SD	0.03	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.05	0.05
	SEM	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Blue											
	mean	1.04	1.03	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.03
	SD	0.05	0.04	0.05	0.06	0.07	0.08	0.08	0.08	0.08	0.08
	SEM	0.02	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03

The result was plotted (Figure 4.3.2.1). EEG PSD mean (± SEM) during exposure to green (n=9) and blue (n=9) lights. PSD are normalised to the PSD under the preceding dim light exposure. 1 to 20 Hz bins are shown.

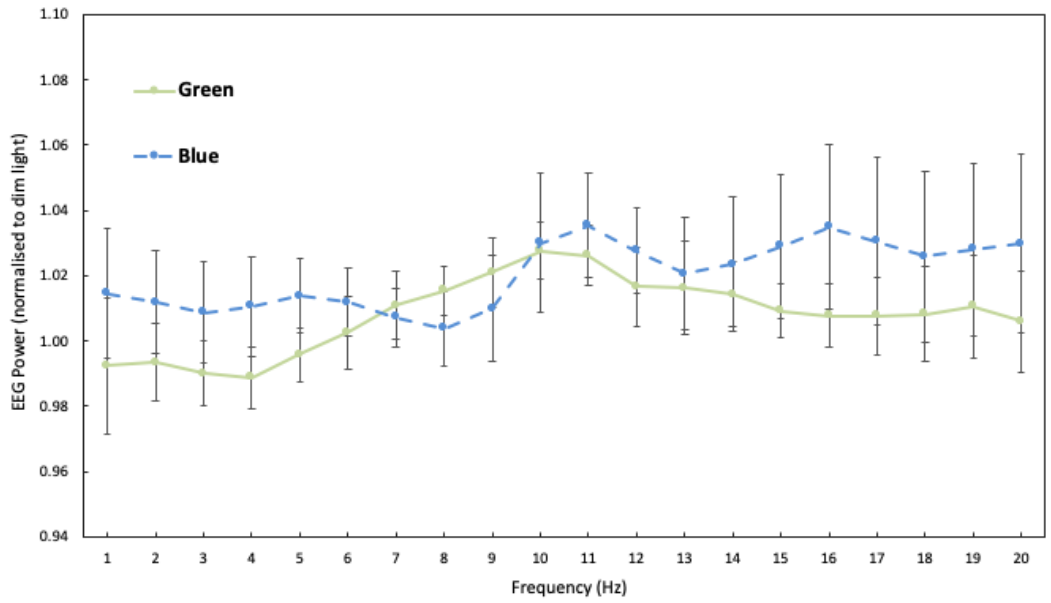


Figure 4.3.2.1: EEG Power Average over all Participants
(error bars represent ± standard error of the mean)

The vertical axis represents EEG power normalised to the preceding dim light. Therefore 100% shows the EEG power of dim light condition. The values above 100% suggested that the power has increased at this frequency after coloured light exposure (as compared to preceding dim light), the values under 100% suggested the opposite.

To estimate if there is a difference between blue and green light conditions (whether two lights have different power in changing EEG power density), the means were compared by conducting a Paired T-test at each wavelength. The Paired T-test compares two means that are from the same individual, it is commonly used to test the statistical difference between two conditions (e.g. the same subject with different treatments). In current study, only one factor/variable (light colour) with two levels (blue and green) is present, the sample population size is not big (n=9), and samples are paired (each pair is from the same subject). The purpose of the test is to determine whether there is statistical evidence that the mean difference between blue and green light exposure is significant. The p-value (probability) of each frequency is shown below (Table 4.3.2.3); $p<0.05$ indicates significance.

Table 4.3.2.3 Two-tail Paired T-test

	1(Hz)	2	3	4	5	6	7	8	9	10
p	0.52	0.46	0.41	0.29	0.28	0.51	0.89	0.48	0.6	0.91
	11(Hz)	12	13	14	15	16	17	18	19	20
p	0.61	0.59	0.87	0.72	0.41	0.33	0.44	0.57	0.58	0.45

4.3.3 EEG Interpretation

Three EEG frequency bands are commonly used to estimate brain alertness level. Lower beta (13 – 15 Hz) is associated with an engaged and brooding mental state. Alpha (8-12 Hz) represents a more relaxed and slightly drowsy state. Alpha-theta (5-9 Hz) indicates deep relaxation and the sleep onset. It can be pictured that how human brain waves might behave from the early biological night to eventual sleep: Lower beta wave is dominant in the very beginning; as brain starts to relax, beta starts to decrease while alpha goes up; brain continues to feel drowsy and sleepy, alpha power starts to drop and alpha-theta become dominant.

Therefore, it might be suggested that, during the period of evening, generally two EEG frequency power change trends can be interpreted as the alertness increase: alpha power decrease and lower beta power increase in the early biological night; alpha-theta power decrease and alpha power increase in the late biological night. Many studies have been conducted in the late evening, as it is the time when people are mostly in relaxed/drowsy state.

They are more prone to be affected by light exposure and the fluctuation in EEG power is more easily to be observed. High alpha power (11-12 Hz) has been seen as a specific maker of alertness change, assuming that subject is under the appropriate mental state. In some studies the whole alpha range (8-12 Hz) was suggested to behave contrary to high alpha power, which might be due to the opposite change trend in low alpha power (8-9 Hz). These findings reflected a certain degree of variation in the interpretation of alertness by frequencies.

If we look at the EEG power mean from 5 to 20 Hz bins individually, blue condition has greater power mean than green condition at 5 Hz, 6 Hz and all the frequencies above 10 Hz. However, none of these frequency bins showed statistical significance in T-test. Results of 5 and 16 Hz bins have relatively small p values (0.279 and 0.331 respectively). From the perspective of absolute power mean (Table 4.3.3.1), green condition has greater power in some alpha-theta frequencies (7, 8 and 9 Hz bins), while blue condition showed greater power in high alpha range (11 and 12 Hz) as well as the whole lower beta range (13 – 15 Hz).

Table 4.3.3.1 Lighting Condition with Greater Power at Individual Hz Bins

				alpha					
Wave bands	**Alpha-theta**						**high alpha**		**Lower beta**
Hz bin(s)	5	6	7	8	9	10	11	12	13-15
Condition (Green/Blue) that has greater power	B	B	G	G	G	B	B	B	B

The table also showed that alpha wave band actually covers two sections (high alpha and part of alpha-theta range) that is suggested to behave contrary to each other when alertness level changes. And that might be one of the reasons that the results from different studies where they have looked at the whole alpha band, did not necessarily agree.

The power of each frequency bands was summed and averaged (Table 4.3.3.2). It showed the relative power change difference between wave bands, which to some extent reflect the overall change trend of alertness level. Relatively, difference between two lighting conditions was the most noticeable in lower beta band; difference in high alpha power was observable though not as distinct; there was almost no difference between two lights in alpha-theta and alpha wave bands. That is to say, compared to green light exposure, blue light has increased EEG power greatly in lower beta range, and slightly in high alpha range. No distinct difference was observed in the frequency range lower than that.

Table 4.3.3.2 Power Mean and Difference by Frequency Bands

	Alpha-theta	**alpha**	**high alpha**	**Lower beta**
Green	100.90	102.20	102.24	101.05
Blue	101.01	102.22	103.21	102.88
Difference	0.11	0.02	0.97	1.84

From previous review, we summarised that as a general principle, the higher the frequencies are, the more engaged state the brain is in. Alpha-theta (5-9 Hz) indicates deep relaxation. Alpha (8-12 Hz) is associated with a very relaxed and slightly drowsy state. Lower beta (13 – 15 Hz) correlates with being in a brooding or idling mental state, whereas the activities in the mid-range beta (16 to 20 Hz) could be described as being strongly engaged (e.g. analytical problem solving).

Therefore, EEG results might have shown that compared to green light, blue light has enhanced brain engagement to a greater extent, and has made subjects more focused. This might have suggested that, at the time the experiments being conducting, subjects (as in average) might not have been in the ‘very relaxed/slightly drowsy’ state as expected. And the reason might have been that participants were reading during the time, so they were actually being quite focused.

High alpha power has been seen as a specific marker of alertness level due to its sensitivity to alertness change, however it seems to us in this study,

beta power, or certain frequencies within beta, might also be seen as a marker of e.g. concentration.

Many variables present in the study could be hard to control e.g. human factors. Were participants in reasonably consistent mental state over the two experimental sessions? Did participants read consistently during each experiment? Are there other unknown factors that potentially might have had an influence? These should all be taken into consideration in a future study.

In current study, the change trend of subjects' mental state was observed. Two lighting conditions showed a different power in shifting subjects' mental state.

Although none of the individual frequency bins has reached statistical significance, we might still conclude that short-wavelength blue light is potentially more powerful than broadband wavelength green light, in enhancing human brain concentration in the late evening.

4.4 A Pilot Experiment on a New Blue Light

The main study has compared the alerting effect of a blue and a green light. In order to further look at the wavelength-dependent alerting effect of light, a pilot experiment was conducted on one of the participants. Specifically, we wondered if light rich in 460 – 480 nm potentially has a stronger alerting effect than lights of other composition, even if they are both blue? Therefore, a third lighting condition (a new blue light) was tested and the EEG power results were compared with previous two lighting conditions.

4.4.1 Subject Condition and Light Spectrum

Subject Condition

For within-subject study, one of the most important prerequisites is to make sure that subject is in consistent state over the experimental sessions. Subjects were screened based on this requirement. One female participant was eventually chosen to do the pilot experiment because of two main reasons. Firstly, this participant (subject No.2) reported to have a rather regular daily schedule e.g. working hours, bedtime and rise time (on both

workdays and free days). Secondly, she had the earliest bedtime (as reported) among all participants. This means that she was more likely to be in a tired/sleepy state over the time when experiment was conducted. Her experimental time slot was scheduled during 21:00 to 22:00, which was approximately 2 hours before her bedtime (Table 4.4.1.1).

Table 4.4.1.1 Information on participant No.2

Subject No.	Bedtime	Experiment time
2	23:20	21:00 – 22:00

Prior to the pilot experiment, the participant was suggested to keep the same schedule as it was during the period she was taking the first two experimental sessions. She was instructed not to take caffeine before experiment and was reminded to do the reading the same way she did before.

Light Spectrum

The new tested light was designed to be short-wavelength blue (Blue 2) with a different spectrum from the first blue light (Blue 1). Light intensity was kept as close as possible to the previous two lights, especially with the first blue light (Table 4.4.1.2).

Table 4.4.1.2 Intensities of the lighting conditions used in pilot study

Light	Average intensity (lx)
White	39.0
Green	148.2
Blue 1	150.8
Blue 2	151.0

The spectral data of Blue 2 (see Appendix H) was plotted together with the other two lights (Figure 4.4.1.1). Compared to Blue 1, Blue 2 has a 'shorter' wavelength. It has much less power in 460 – 480 nm, with a peak wavelength at around 420 nm. This design was to test if short-wavelength blue lights with different spectra, especially when they differ in 460 – 480 nm, make a significant difference in alerting ability.

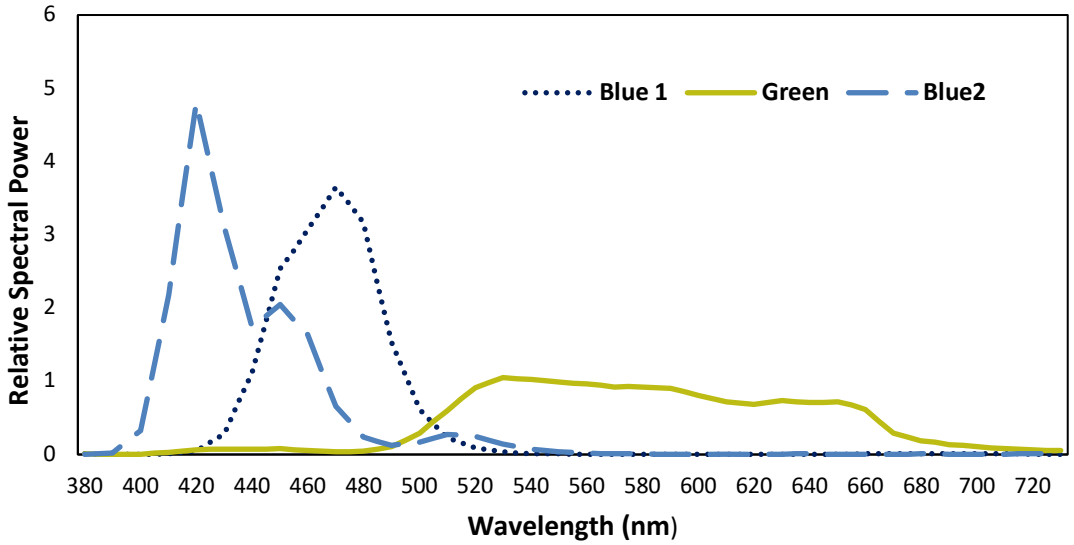


Figure 4.4.1.1: Spectra of Three Tested Lights

4.4.2 Results

The EEG PSD means of three tested lights of the participant were plotted (Figure 4.4.2.1). The data was present as the ratio of the coloured tested light (power mean of 5 minutes) to the preceding dim light (power mean of 5 minutes). The dash line (value equals to 1) can be seen as the power of dim light; values above it represent power increase at the corresponding frequency; values below it represent power decrease.

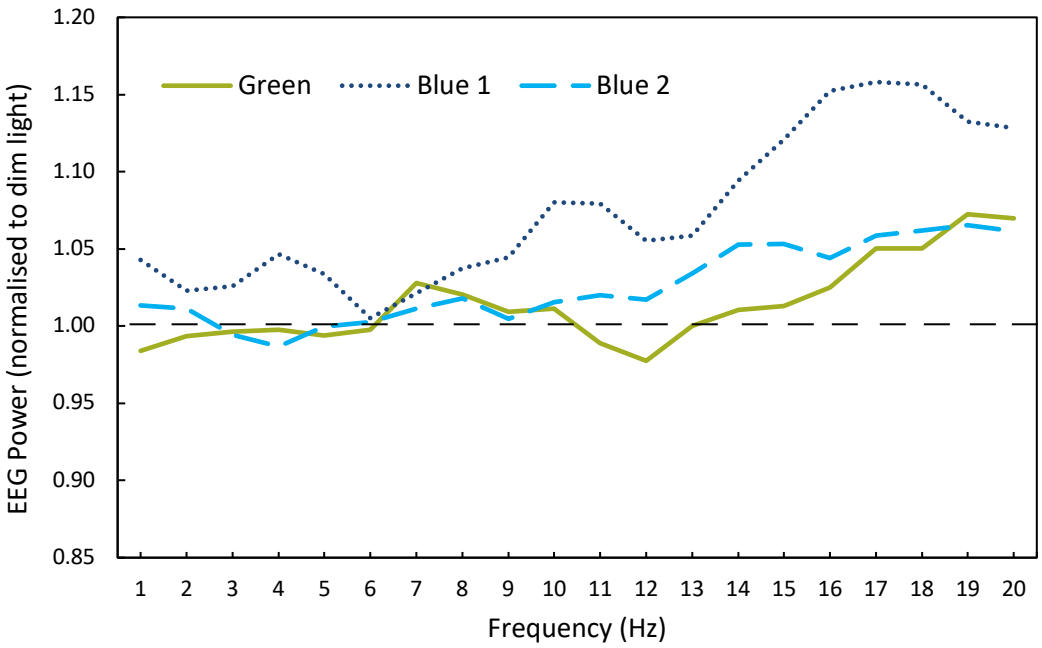


Figure 4.4.2.1: EEG Power Density Mean (ratio over dim light) of Three Lights for Subject 2

Comparatively, Blue 2 and Green showed differences in the range of 11 to 15 Hz; Blue 1 and Blue 2 were different in 9 to 12 Hz and above 15 Hz; Blue 1 and Green were distinctly different in all frequencies above 10 Hz. The power means of three frequency bins (5-9 Hz; 11-12 Hz and 13- 20 Hz) were averaged to obtain the power of three EEG wave bands (Table 4.4.2.1).

Table 4.4.2.1 Average Power Mean of Three Wave Bands for Participant 2

	Alpha-theta	**high alpha**	**lower beta**
Green	1.01	0.98	1.04
Blue 1	1.03	1.07	1.13
Blue 2	1.01	1.02	1.05

Relatively, the three lights did not show a noticeable difference in alpha-theta wave; Blue 1 has greater power mean values than the other two lights in both high alpha and lower beta waves.

Blue 1 has a greater high alpha power mean, but is there a real difference between three sets of 5 minutes' data (300 values)? In order to further compare the high alpha power mean of three tested lights, the power mean that came from 300 values (300 seconds) was manipulated in another way.

For the coloured light power mean, every 15 seconds was taken as an epoch and in this way the mean (came from 300 seconds) was broken down into 20 epochs. The mean of each epoch (15 seconds) was calculated. Each epoch mean was divided by the preceding dim light power mean, therefore 30 ratio values were produced. 11 and 12 Hz bins were manipulated in this way and the corresponding epoch ratio values were summed up. Eventually we produced 20 epoch ratio values for three tested lights in high alpha range (Table 4.4.2.2).

Table 4.4.2.2 20 Epoch Values for Three Lights in High-alpha Range

Epoch	Green	Blue 1	Blue 2
1	1.78	1.95	1.99
2	1.93	2.12	2.22
3	2.07	2.16	2.03
4	2.02	2.11	2.14
5	1.85	2.13	2.04
6	1.78	2.05	1.97
7	2.08	2.16	2.04
8	1.94	2.10	2.02
9	1.99	2.27	1.95
10	2.10	2.29	2.22
11	1.95	2.05	2.19
12	1.98	1.95	1.84
13	2.12	2.08	1.87
14	1.95	2.17	1.86
15	1.91	2.21	1.92
16	2.17	2.24	1.87
17	2.02	1.98	2.34
18	1.90	2.36	2.02
19	1.86	2.01	2.08
20	1.90	2.23	2.12

Next, one-way analysis of variance (ANOVA) in SPSS Statistics 20 was performed using epoch values to compare three light conditions (Table 4.4.2.3). The result showed that there was very significant difference between three groups ($p < 0.001$).

Table 4.4.2.3 One-way ANOVA of Three Light Conditions

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.28	2	0.14	9.655	0
Within Groups	0.827	57	0.015		
Total	1.107	59			

The Turkey HSD post hoc test (Table 4.4.2.4) further showed that there was significant difference between Green and Blue 1 conditions ($p<0.001$), and between Blue 1 and Blue 2 conditions ($p=0.04$).

Table 4.4.2.4 Post-hoc Test on Three Light Conditions

(I) light	(J) light	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Green	Blue1	-.16683690*	0.03809543	0	-0.2585104	-0.0751634
	Blue2	-0.07154128	0.03809543	0.154	-0.1632148	0.0201323
Blue1	Green	.16683690*	0.03809543	0	0.0751634	0.2585104
	Blue2	.09529562*	0.03809543	0.04	0.0036221	0.1869692
Blue2	Green	0.07154128	0.03809543	0.154	-0.0201323	0.1632148
	Blue1	-.09529562*	0.03809543	0.04	-0.1869692	-0.0036221

*. The mean difference is significant at the 0.05 level.

Taken these results together, in high alpha range Blue 1 light increased the power significantly more than green and Blue 2 lights, whereas Blue 2 and Green light did not show a noticeable difference between each other. That is to say, as far as the tested participant is concerned, Blue 1 light enhanced her alertness significantly more than Green and Blue 2 lights.

The result of this pilot study corresponded with the hypothesis that the alerting effect of light at night might be wavelength-dependent. Light of certain spectral composition might be significantly more effective than that of

other spectra. Although the pilot experiment was only done with a single subject, it gave the implication that further work might be done to study the spectral sensitivity in light-induced alertness in human.

4.5 Discussion

This study was designed to look into the alerting ability of short-wavelength blue light and broadband wavelength green light (a light of similar intensity but which was relatively deficient in short wavelengths). The subsequent pilot study aimed to further compare two short-wavelength blue lights of different spectra. The results produced from EEG power as well as questionnaires have preliminarily shown that exposure to lights of different colours/spectra late in the evening have different alerting power in subjects.

4.5.1 Experimental Design

It seems that two of the most critical concerns in designing experimental protocol are:

i. Participant control. If the study is designed to be a within-subject research and there is more than one experiment session each subject needs to involve, it is important to make sure they are in consistent state over the sessions. Therefore, it is necessary to ask subjects to maintain a regular sleep-wake schedule (with appropriate bedtimes and rising times) during the period of experimental sessions. Self-reported sleep schedule can be used to ensure compliance.

However, if there is many more than one experiment session, it might also be critical to make sure that subjects are not under the impression of the previous experiments. In this case we might want to avoid the same subject finishing all experiments in a row. It might also be helpful to randomised the order of the lighting conditions in which subjects are exposed to.

Repeating the experiment (of identical condition) can be consuming for such kind of study, therefore a good subject control is significant to the success of the research. Sample size for this type of within subject study is normally around 8 to 15 participants.

ii. The experimental start time and the duration of the experiment. This greatly affects the mental states of subjects and whether/how much power difference can be eventually observed in the expected EEG frequencies. It also decides what measures are suitable to be applied in the study.

4.5.2 Questions

It has been suggested that the alerting power of light in human is wavelength dependent. However, the spectrum of the direct light-induced alerting effect or melatonin suppression is not fully understood. Several questions are raised at the end of this study:

i. It is now found that some long wavelength colours such as red, can have alerting effect in human without suppressing melatonin level. Does this suggest that the direct alerting effect (measured by EEG power) and the circadian entrainment (indicated by melatonin levels) should be distinguished? This can have very important applications where the high alertness/concentration level is wanted for a certain period of time, particularly at night, without eventually affecting the sleep. This will also contribute to a better understanding on the roles of rods, cones and ipRGCs in human NIF vision.

ii. There has been concern about the increasing use of electronic devices in the evening playing a role in delaying normal sleep hours. This is based on the fact that there is excess short wavelength component in most home use electronic devices. However, considering the light level of these light emitting devices (smartphone, tablet etc.), we wonder if it is strong enough to produce alerting effect. In another word, if there is a e.g. threshold light level that can maximum the alerting effect?

iii. Furthermore, does the alerting effect depend on other factors such as exposure duration? How does it change over time? It is also interesting to compare these effects of long and short wavelength lights.

Chapter 5
Study 2: Alerting effect of three short-wavelength lights

5.1 Aim

Short-wavelength light is known to have an effect on human alertness in the night time. 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 [177]. However, there are very few studies that focus on the effect of intensity of light on alertness. Studies have also demonstrated a non-linear relationship between light intensity and circadian shifts [6,195]. 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.

Studies to date have linked the alerting effects of light to its ability to suppress melatonin [192]. 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 [7,11]. Studies on the non-visual effects of light have suggested that the impact of light on alertness is a complex physical, physiological and psychological activity that can result from different pathways [8]. Although melatonin level is associated with circadian rhythm, EEG measure is often used to evaluate acute alertness change.

Therefore, the aims of this study are as follows:

i. To look at how EEG power changes over experiment time and evaluate the appropriate exposure duration.

ii. To evaluate the acute alerting ability of short-wavelength light of three different intensities (40 lx, 80 lx and 160 lx) using EEG as the objective measurement.

5.2 Brief Summary of Experiments

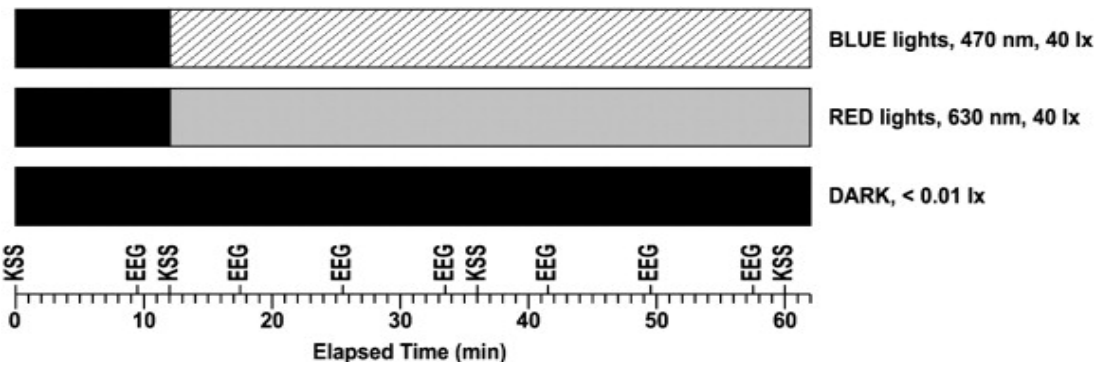
There are two experiments in this study. Experiment 1 aims to look at how EEG as well as other measures change over a relatively long exposure duration. This experiment involved fewer subjects and it was conducted to look at the effect of exposure time, aiming at finding out a good experimental time for experiment 2. The results of experiment 1 are partly included in the experiment 2, where the acute alerting ability of three level blue lights were compared.

5.2.1 Experiment 1

Experiment duration

The aim of experiment 1 was to decide a proper experiment duration for experiment 2. A good experiment duration should be long enough to show the influence of light on EEG power, and as short as necessary. A review was taken on the experimental design in some similar studies in order to find an appropriate exposure duration for experiment 1 to start with.

We can look at some related published work in order to gain insights for how to design these experiments. For example, Figure 5.2.1.1 shows experimental protocols in some previously published studies that EEG is the main objective measurement. In the first two studies, experiments lasted for 60 minutes, with 12 minutes for dark adaption and 48 minutes under light exposure [9,10]. In the third study where post-exposure effect was also examined, EEG measure was taken before light, after 60 minutes under light, and several times after light was turned off [14]. All of these studies have successfully tested some effects and reached some conclusions.



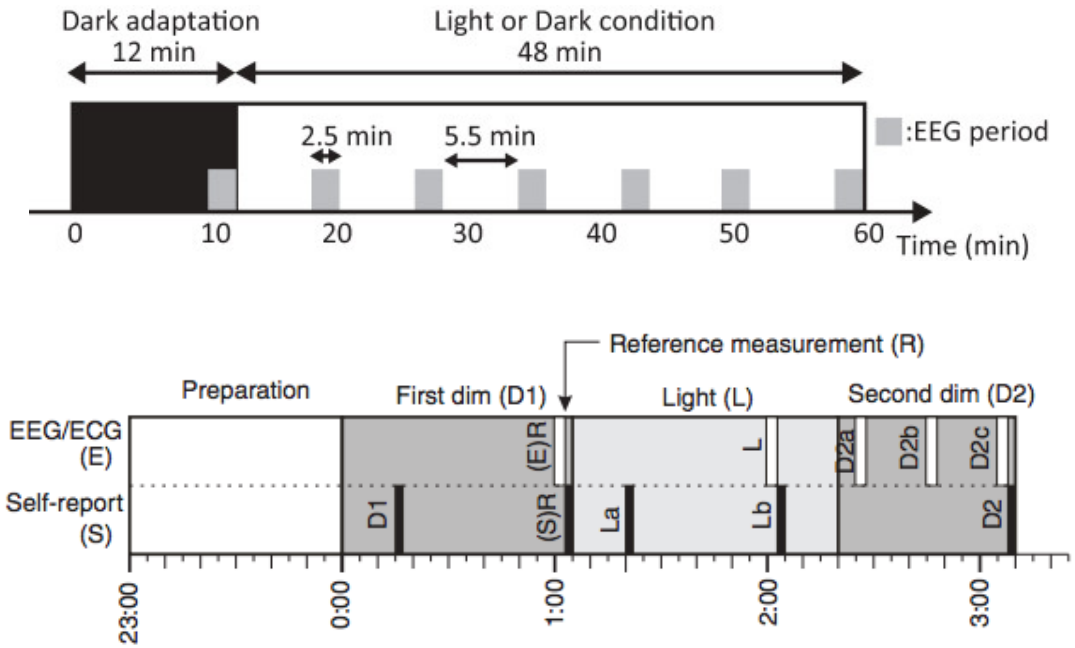


Figure 5.2.1.1: Experimental protocol examples

Figure 5.2.1.2 shows experimental protocols in some previously published studies where both EEG and melatonin level are measured. In the first study EEG was recorded three times during the first hour and saliva samples were taken three times over two hours [12]. In the second study two lighting sessions were put together. However, each light session lasted two hours [11].

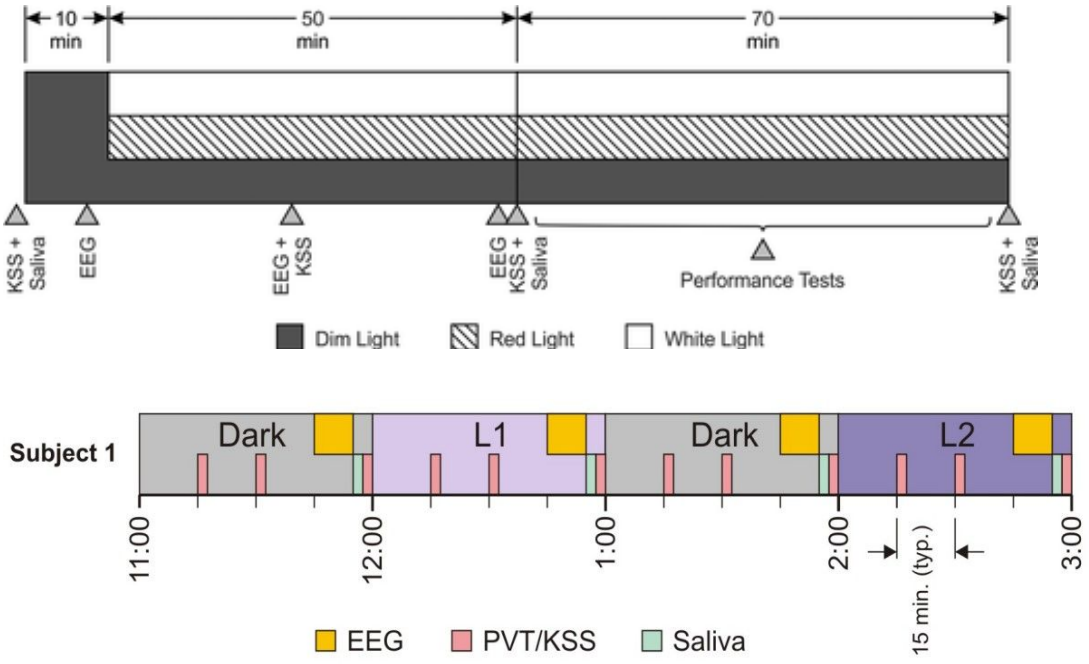


Figure 5.2.1.2: Experimental protocol examples [11, 12]

By comparing these experimental designs, it is evident that EEG measures are mostly compared over approximately 1-hour experiment duration. However, if melatonin level is also measured, the study might last at least 2 hours. The reason for this could be that the change in melatonin level takes time to happen and be traced, whereas EEG can measure brain changes that occur more quickly and is recorded almost instantly. Effects have been observed in all studies mentioned above.

For this experiment only EEG measure was taken and therefore it was decided that an hour might be a good experiment duration. However, for Experiment 1, experimental length was two hours, in order to have a better picture and produce more convincing results.

Test participants

Four participants (aged 30 ± 1.7 years; two females) were invited for this within-subject, three-session study. All participants went through a pre-screening procedure where individual sleep/rise times were collected (Table 5.2.1.1) and the daily consumption of nicotine, caffeine and alcohol was reported. 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. No participants self-reported as being smokers and all participants finished experiments with valid results.

Table 5.2.1.1 Self-reported wakeup and bedtime

Subject No.	Wakeup time	Bedtime
1	7:30	23:30
2	7:30	23:00
3	8:00	23:00
4	8:15	00:00

Experiment protocol

Each participant completed three sessions over three nights, during 20:00-22:00. Participants were fitted with EEG electrodes prior to the start of the exposure. The order of the conditions (Blue 40 lx, 80 lx and 160 lx) was

selected randomly for each of the participants to avoid potential sequence effects. Sessions were separated by at least 48 hours for the same participant to avoid potential carry-over effects. During each evening study EEG was continuously recorded over 120 minutes. Under the Blue condition, test lights were energised for 100 minutes, preceded by a 20-min dim exposure. Subjective sleepiness (which was assessed using the KSS) was rated every 20 minutes (Figure 5.2.1.3). Participants were reminded to write down their scores on the KSS and brightness questionnaire every 20 minutes. For the duration of the 120 minutes the participants were free to read a book. They were also asked to keep their eyes open and other activities (e.g. using electronic devices, eating or talking) were not allowed.

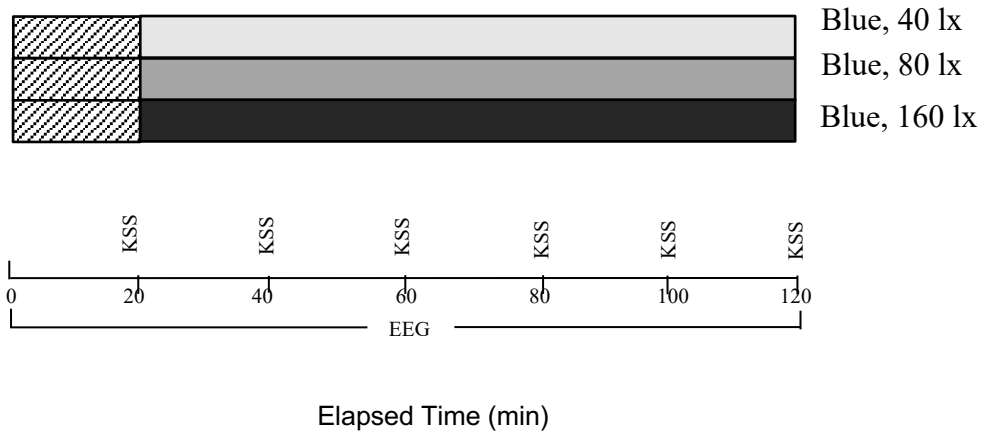


Figure 5.2.1.3: Experiment 1 design showing when KSS was recorded (EEG was measured continuously)

5.2.2 Experiment 2

Test participants

Together with the four participants from Experiment 1, nine participants (aged 28 ± 3.4 years; five females) were recruited for this four-session experiment. All participants reported individual sleep/rise time and daily consumption of nicotine, caffeine and alcohol. The study was approved by the University of Leeds Ethics Committee (LTDESN-094) and all participants signed informed consent prior to the study. 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. One participant did not finish all experimental sessions, and their data was excluded from further analysis. Thus, in total, results were obtained from eight participants (aged 28 ± 3.6 years; five females) are included for analysis as shown in Table 5.2.2.1.

Table 5.2.2.1 Self-reported wakeup and bedtime

Subject No.	Wakeup time	Bedtime
1	7:30	23:30
2	7:30	23:00
3	8:00	23:00
4	8:15	00:00
5	8:00	00:00
6	9:00	01:00
7	8:00	22:30
8	9:30	00:30

Experiment protocol

Each participant completed four sessions over four nights, all starting at the same time (20:00). 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 of the participants 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. Under the Dim condition, participants were kept in the dim light for 60 minutes. Under the Blue condition, test lights were energised for 40 minutes, preceded by a 20-min dim (<1 lx) period. Subjective and brightness was rated every 20 minutes. Participants were reminded to write down their scores on the questionnaire at the 20th, 40th and 60th minute of each session. 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 5.2.2.1).

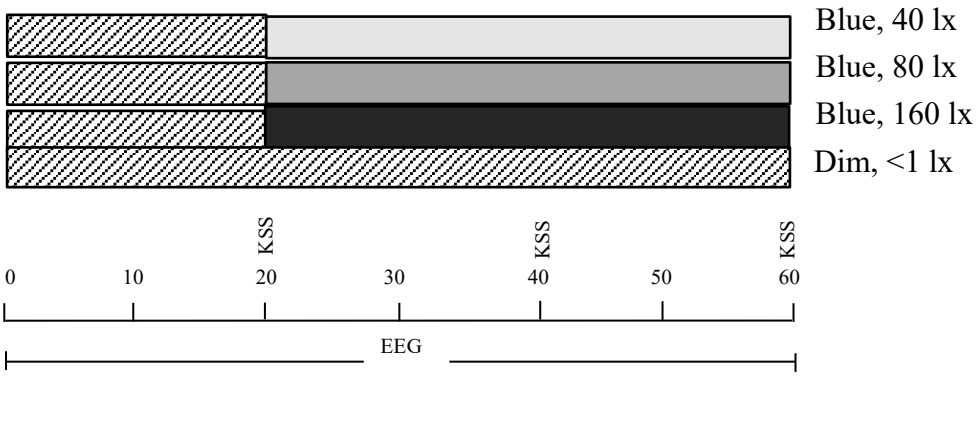
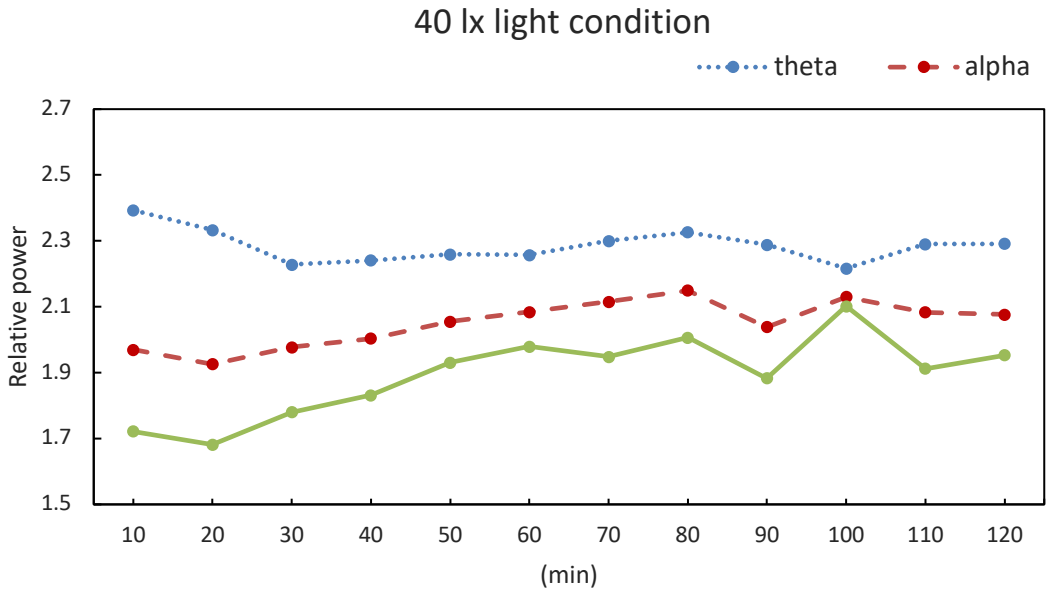


Figure 5.2.2.1: Experiment 2 design

5.3 Results

5.3.1 Experiment 1

EEG was recorded continuously over 120 minutes. Results for three frequency bins: theta (3-7 Hz), alpha (8-13 Hz) and beta (13-30 Hz) at three intensities (40, 80 and 160 lx), and for each of four participants were plotted (Figure 5.3.1.1 – 5.3.1.4). In these figures, time point (x-axis) represents the average power of a 10-minute slot e.g. '10' represents the mean EEG power over the first 10 minutes of experiment. All data in results of this chapter is listed in Appendix I.



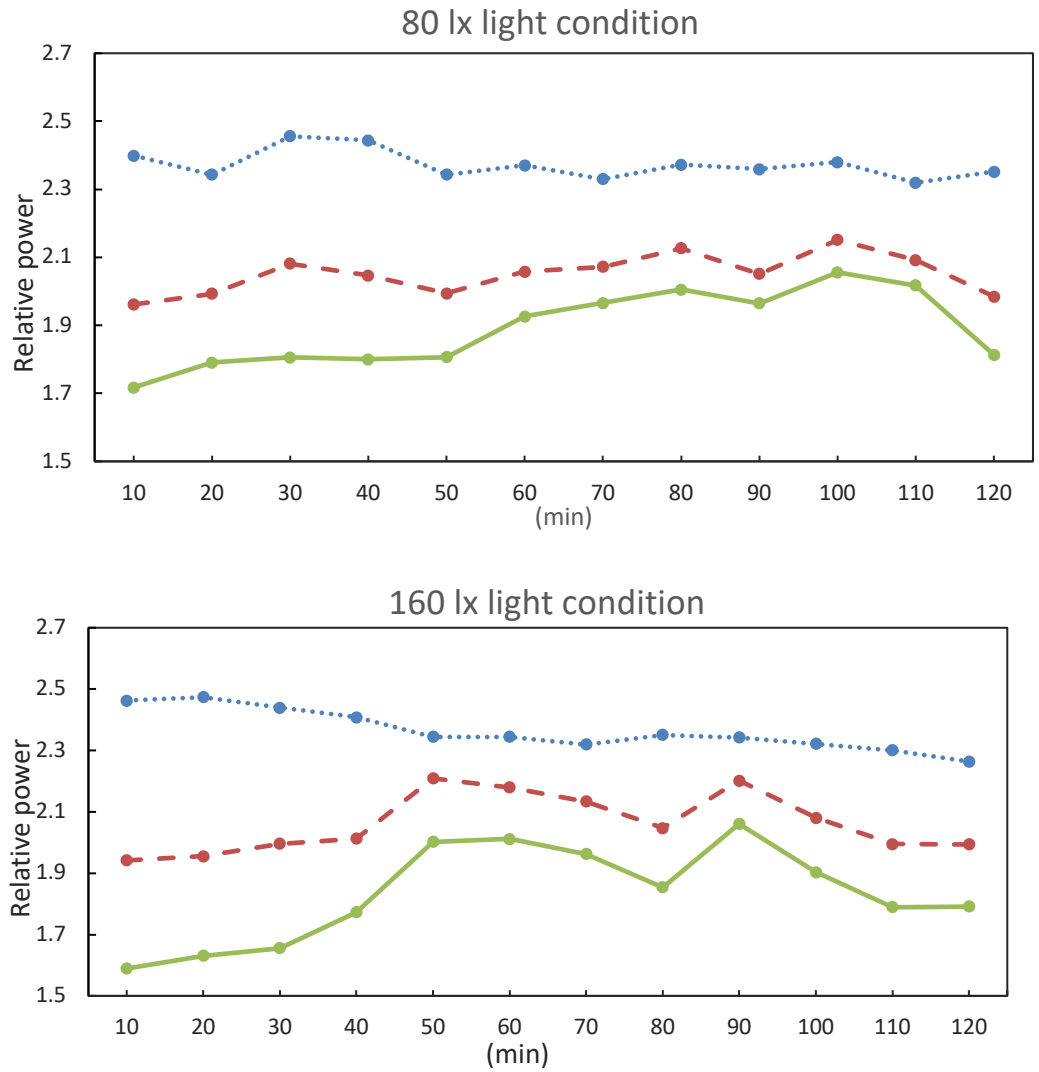
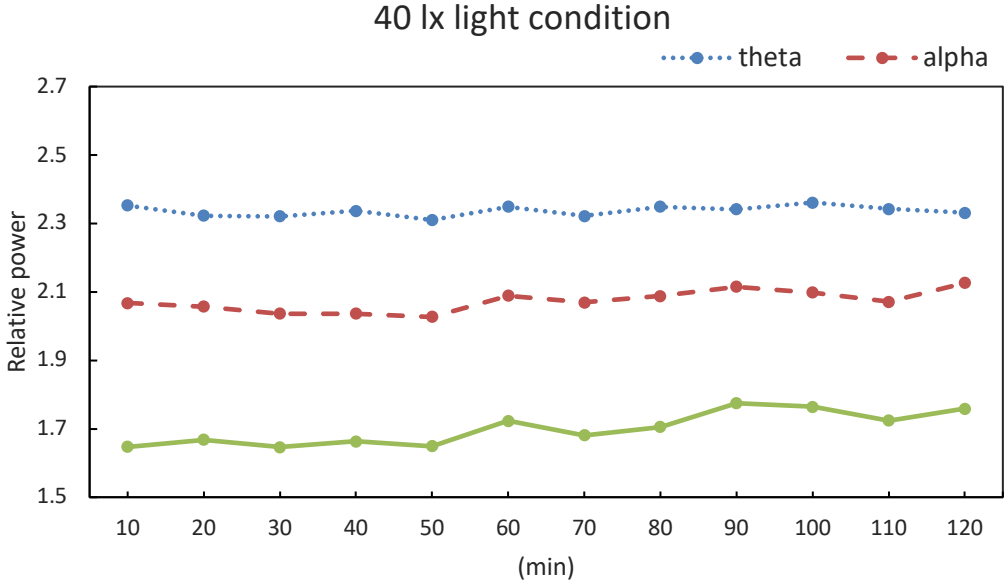


Figure 5.3.1.1: Mean EEG power for participant 1



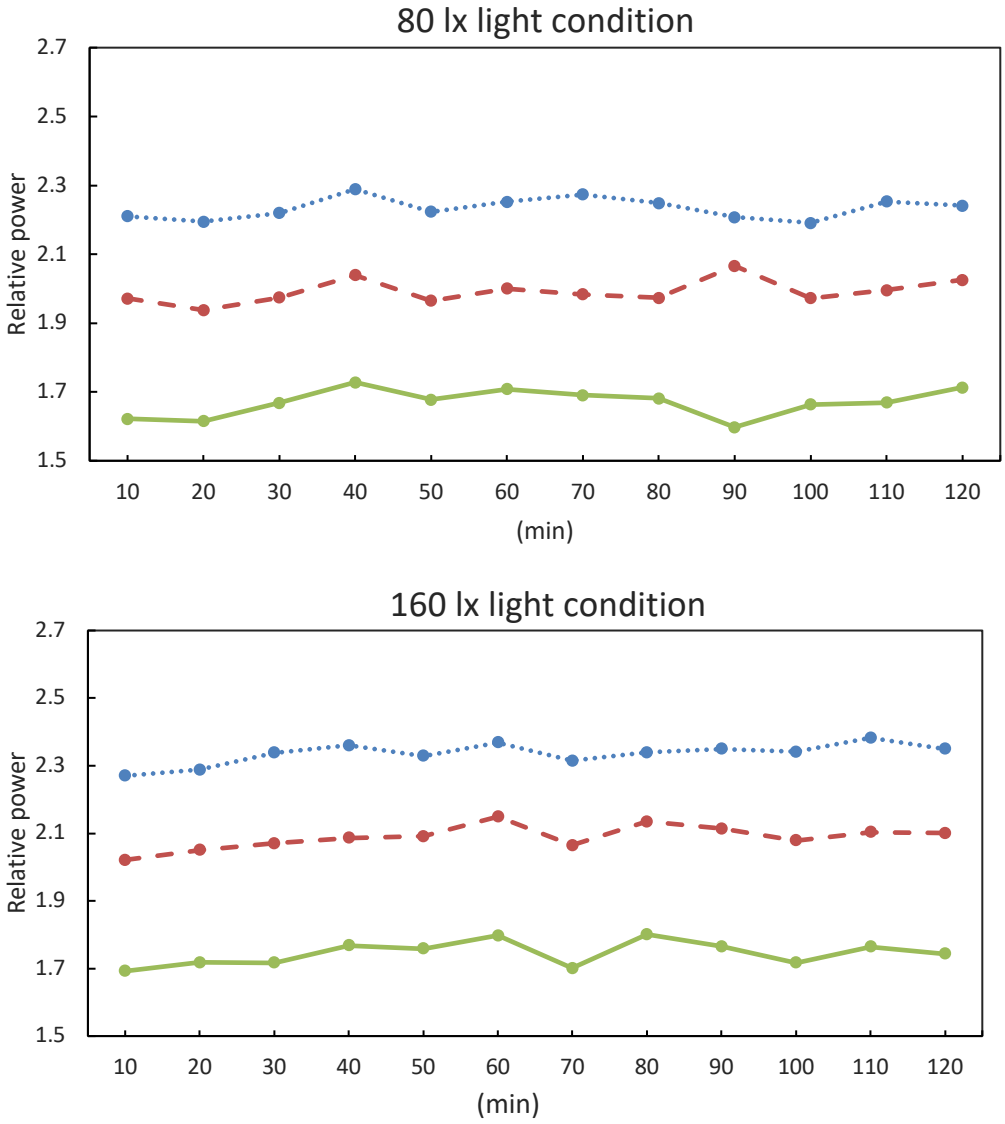


Figure 5.3.1.2: Mean EEG power for participant 2

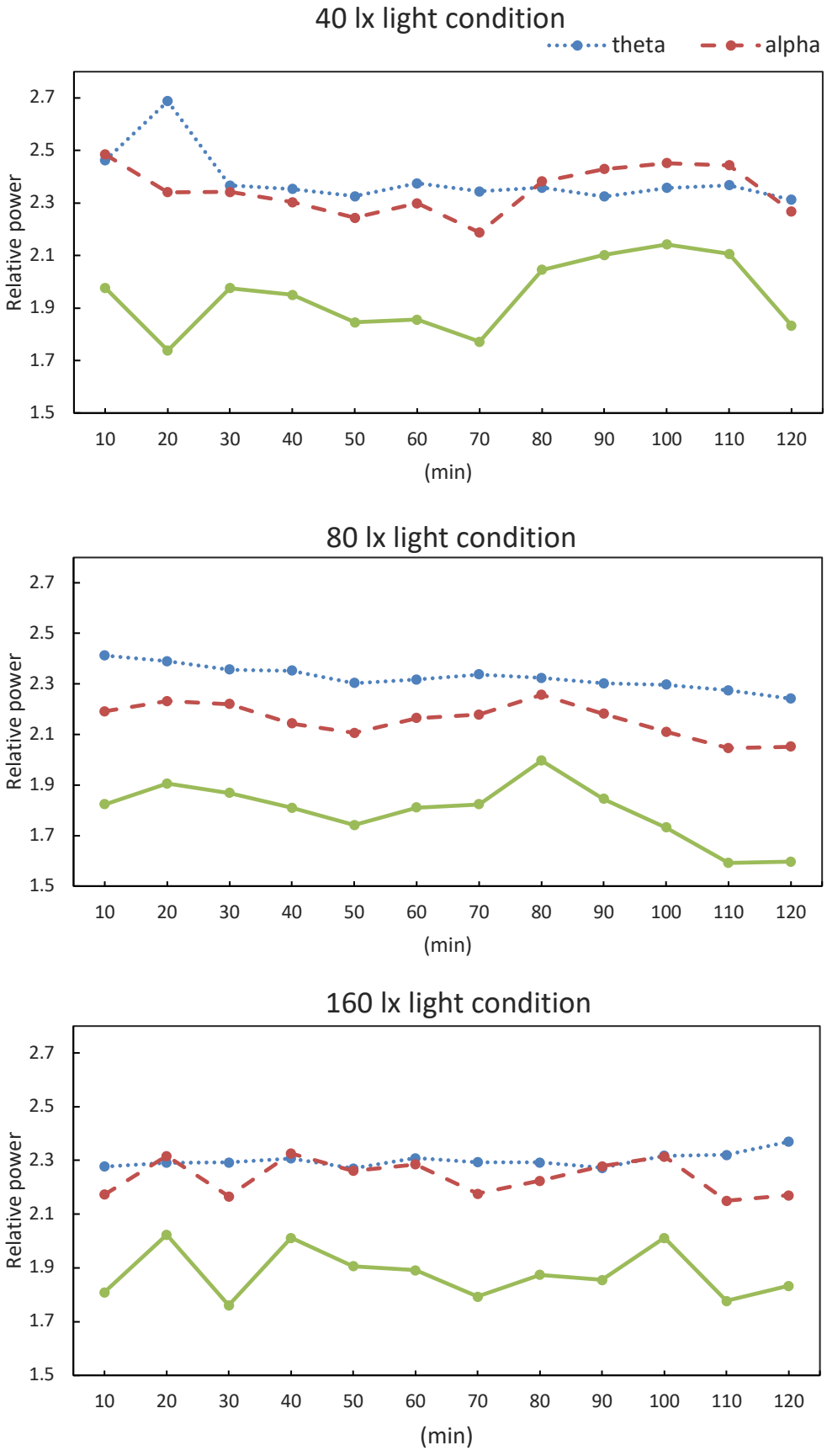


Figure 5.3.1.3: Mean EEG power for participant 3

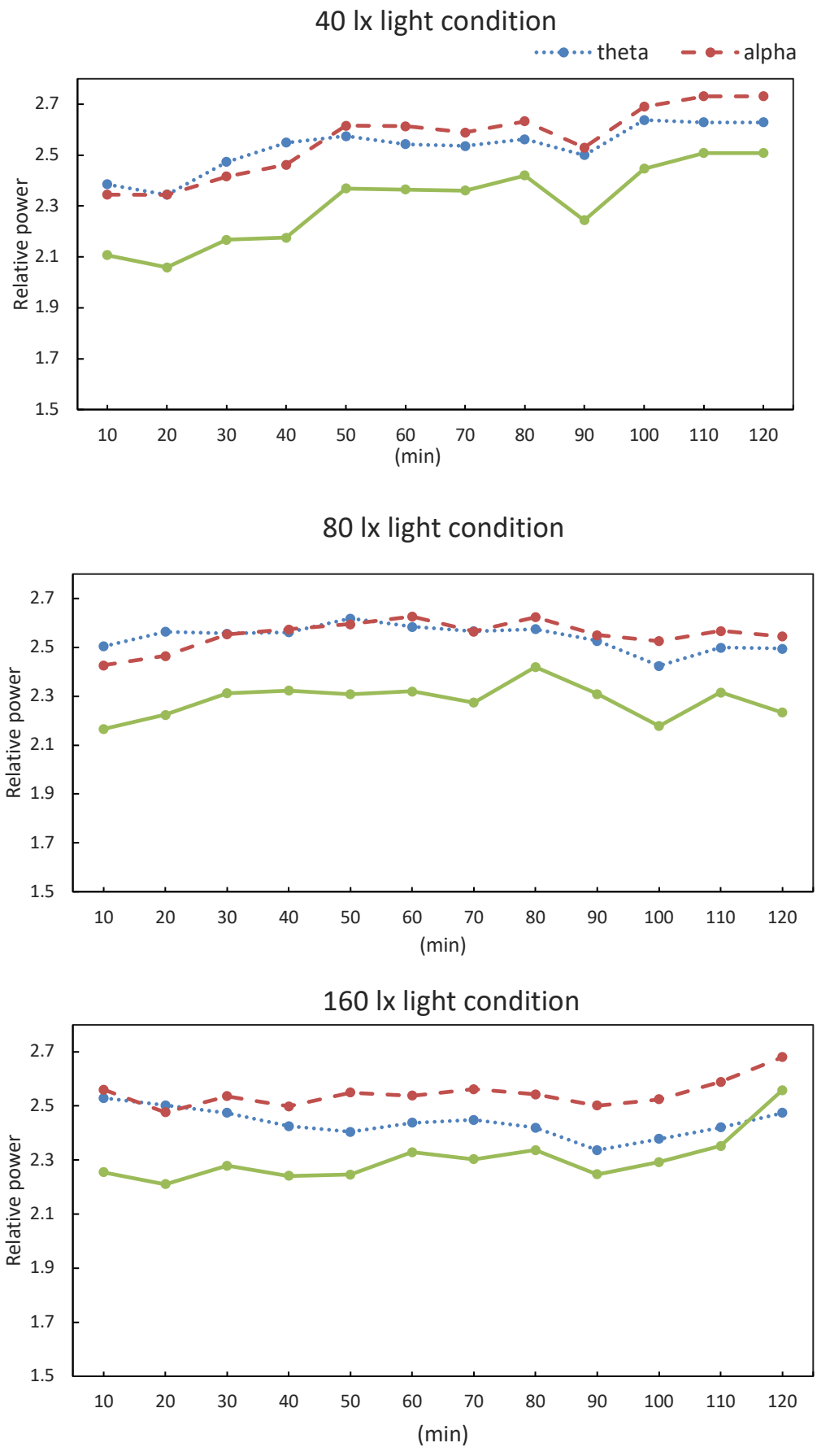
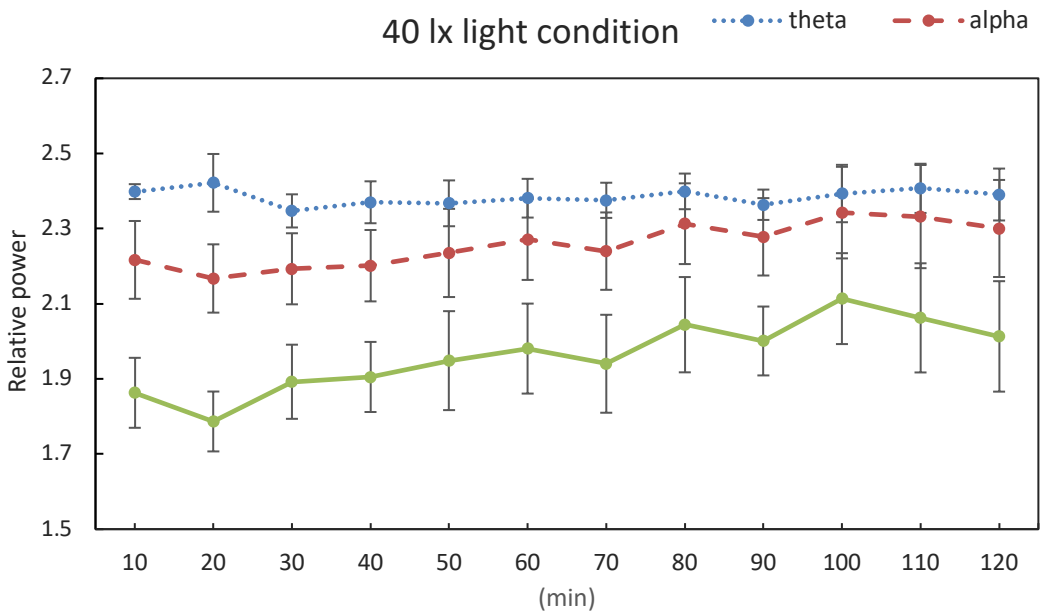
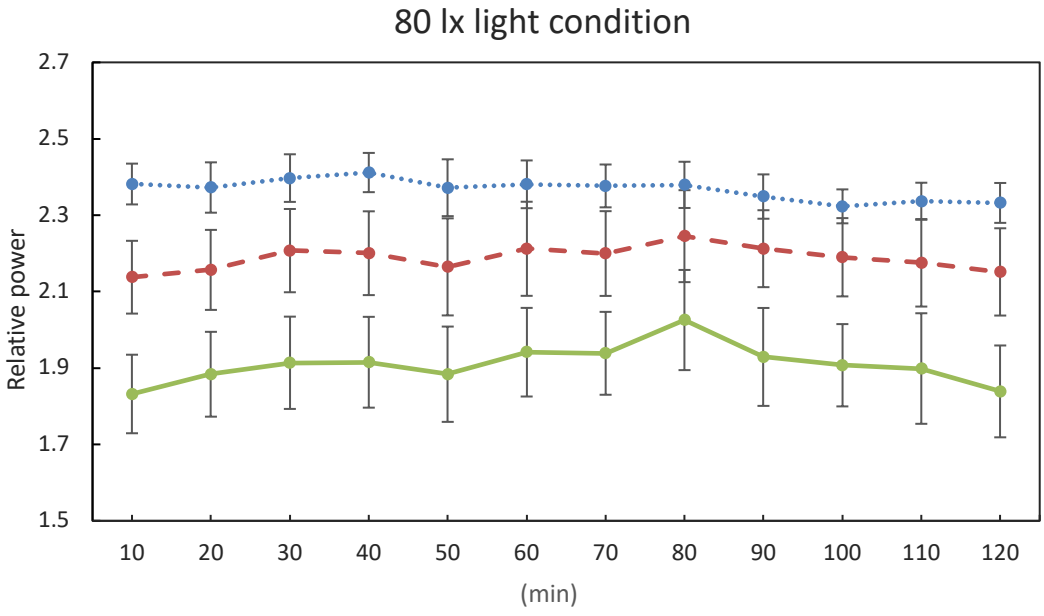


Figure 5.3.1.4: Mean EEG power for participant 4

Next, results for three frequency bins: theta (3-7 Hz), alpha (8-13 Hz) and beta (13-30 Hz) at each light condition (40, 80 and 160 lx), averaged from four participants were plotted (Figure 5.3.1.5). Recall that EEG waves have been divided into different bands, in which theta, alpha and beta frequencies are of particular interest for research on alertness/sleepiness of subjects.





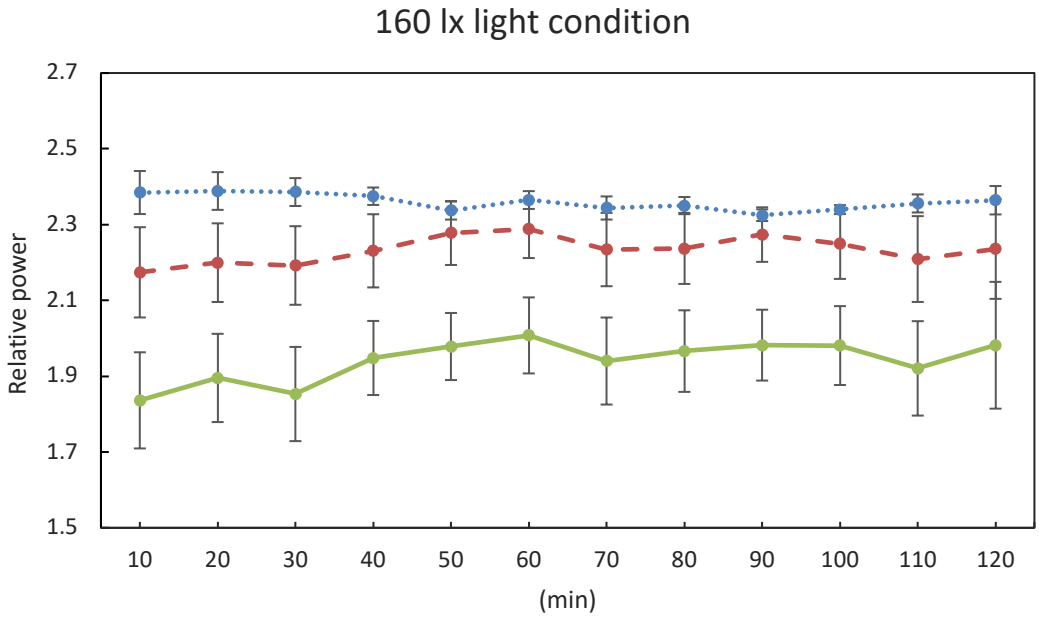
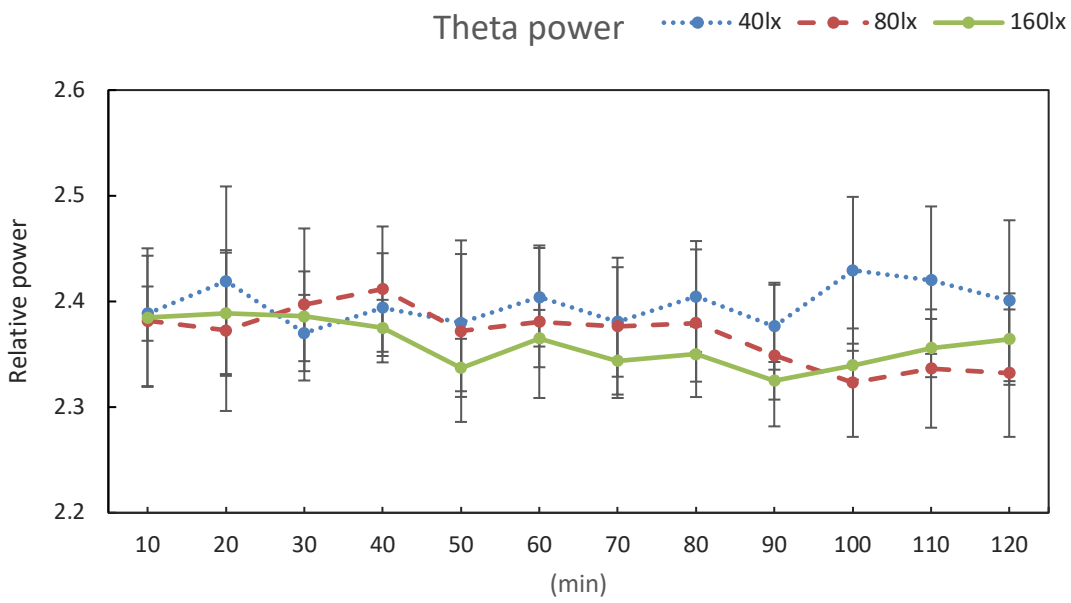
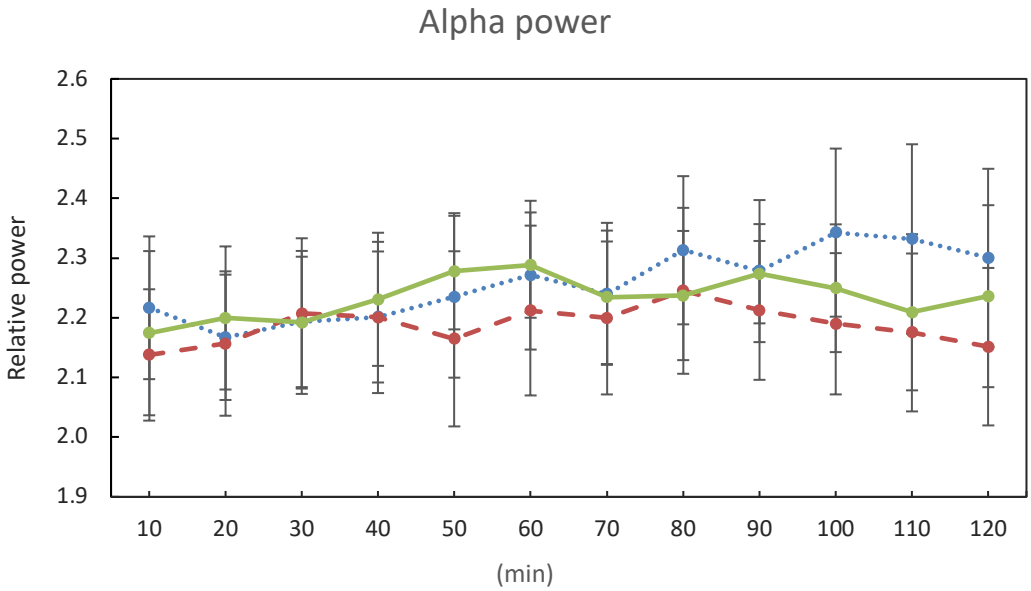


Figure 5.3.1.5: Theta, alpha and beta power pooled over all four participants shown for each light condition

As can be seen, point 60 and point 120 (representing EEG power during the 50th to 60th minute and the 110th to 120th minute respectively) in each diagram shown in Figure 5.3.1.5 are not very different. More importantly, the change trend from point 10 to point 60 is consistent with that from point 10 to point 120. This suggested that there was not a turning point during the second hour of exposure. Power change trend in the first hour is the same with that in the second hour. In other words, if EEG power increased during the first hour, it either keep increasing or stay steady during the second hour. This might give some insights as to why in most studies the exposure duration is no more than an hour, as an hour might be sufficient for the effect to be observed and prolonging it to two hours does not seem to be necessary.

In Figure 5.3.1.6 results for three light conditions at each frequency bins, averaged from four participants were plotted.


Theta power
40lx
80lx
160lx
Relative power
2.6
2.5
2.4
2.3
2.2
10
20
30
40
50
60
70
80
90
100
110
120
(min)


Alpha power
Relative power
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
10
20
30
40
50
60
70
80
90
100
110
120
(min)

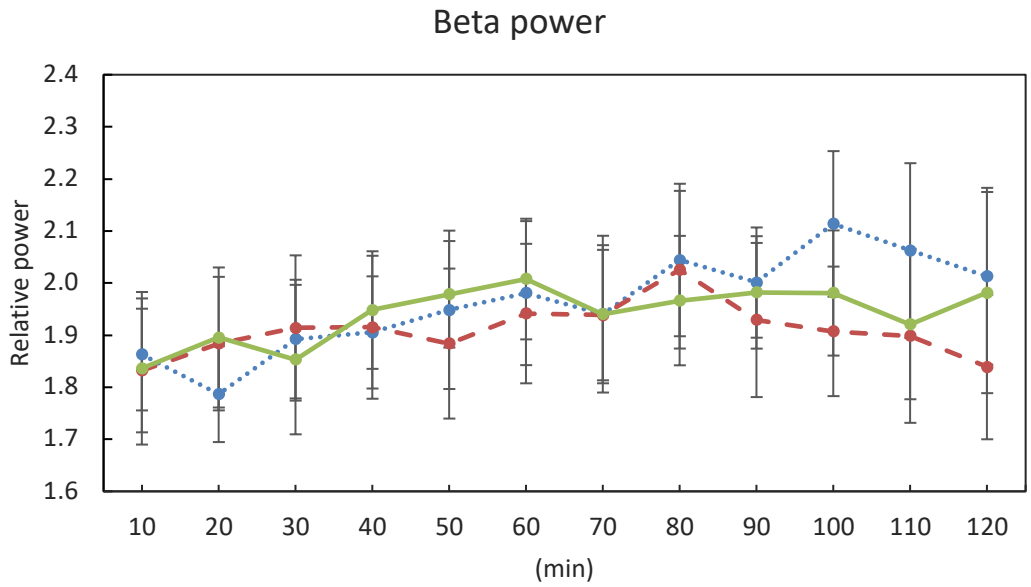


Figure 5.3.1.6: Theta, alpha and beta power pooled over all participants for different light intensities

Note that in Figure 5.3.1.6 there is no significant obvious difference in the power signals at point 60 (after one hour) and point 120 (after two hours).

Finally, power at all EEG frequencies and under all light conditions from 4 participants were averaged together to see the overall effect (Figure 5.3.1.7).

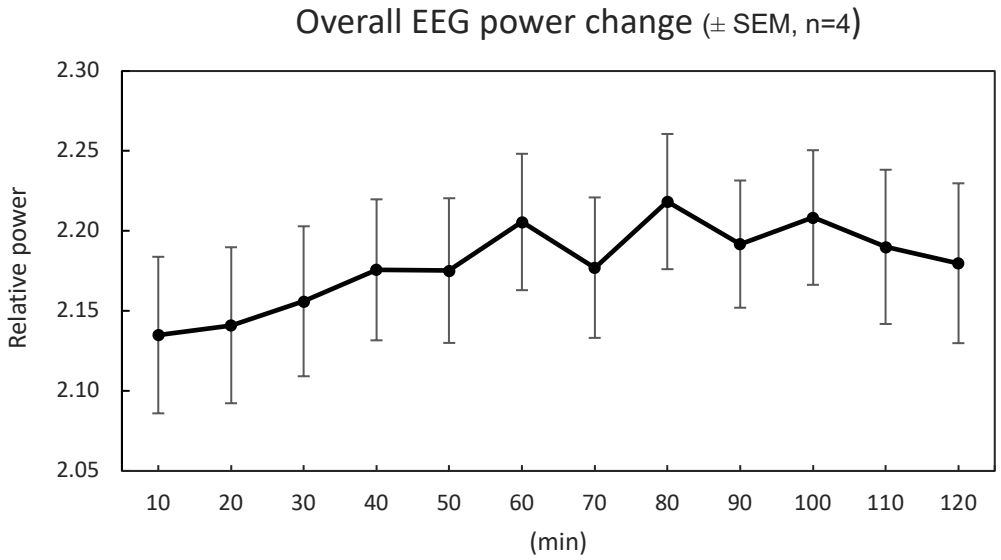


Figure 5.3.1.7: Mean power pooled over all participants and light intensity levels

In Figure 5.3.1.7 the power increase from point 10 until point 60. From point 60 the power fluctuated but did not exhibit any substantial increase or decrease. Although this study only involved a small number of participants, there is some evidence that it would be reasonable to keep the experiment duration around 60 minutes instead of making it longer. This is also consistent with the experiment duration in other studies that have effectively observed similar results. Therefore, in Experiment 2 exposure duration was fixed at 60 minutes. Part of the results in this experiment (data in the first hour) was also included in Experiment 2 for further analysis. This also includes subjective measures such as KSS questionnaire responses.

5.3.2 Experiment 2

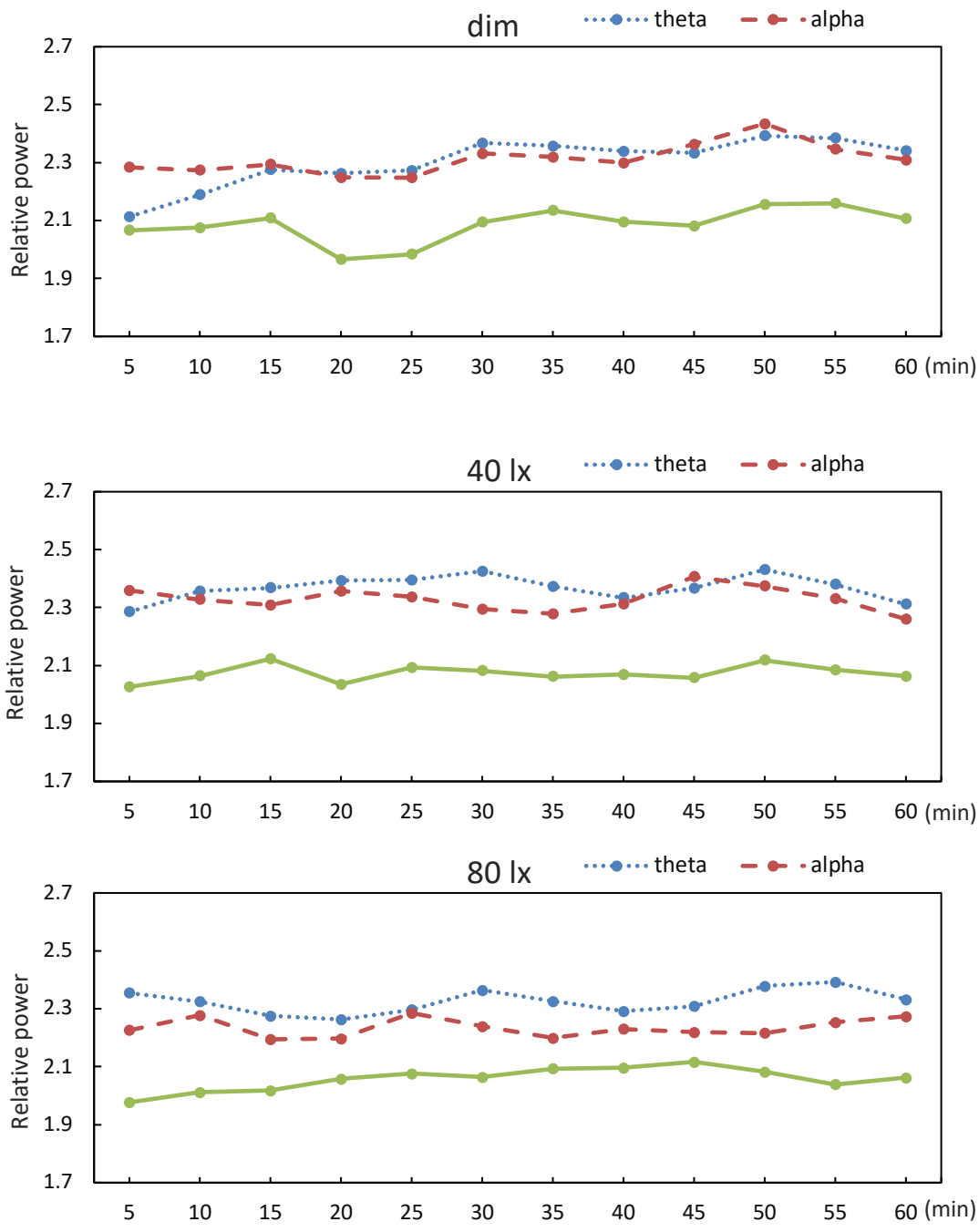
Experiment 2 has four light conditions (dim, 40 lx, 80 lx and 160 lx). Four participants from Experiment 1 have completed the three coloured light conditions (40 lx, 80 lx and 160 lx) and were then invited to finish the dim light condition as well. As the experiment protocol and conditions are consistent, these data were included in Experiment 2, together with four further participants who completed Experiment 2 with valid data.

EEG

EEG data were collected using B-Alert Live Software 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 artefact identification and decontamination algorithms which identify and remove 5 artefact types: EMG, EOG, excursions, saturations, and spikes. PSD was computed by performing 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 were collected from nine electrode sites and averaged to produce overall EEG PSD, and then grouped into 5-9 Hz (theta alpha), 8-12 Hz (alpha) and 13-30 Hz (beta) frequency bins.

EEG power (theta, alpha and beta waves) change during the 60-minute exposure for four light conditions (dim, 40 lx, 80 lx and 160 lx) were plotted. Figure 5.3.2.1 shows the power change every 5 minutes (where EEG power is averaged over every 5 minute). Figure 5.3.2.2 shows the power change every 10 minutes (where EEG power is averaged over every 10 minutes).



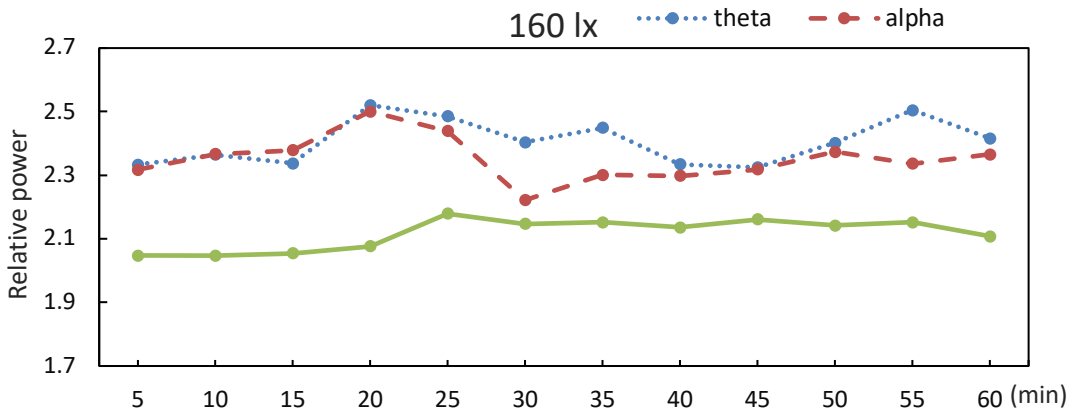
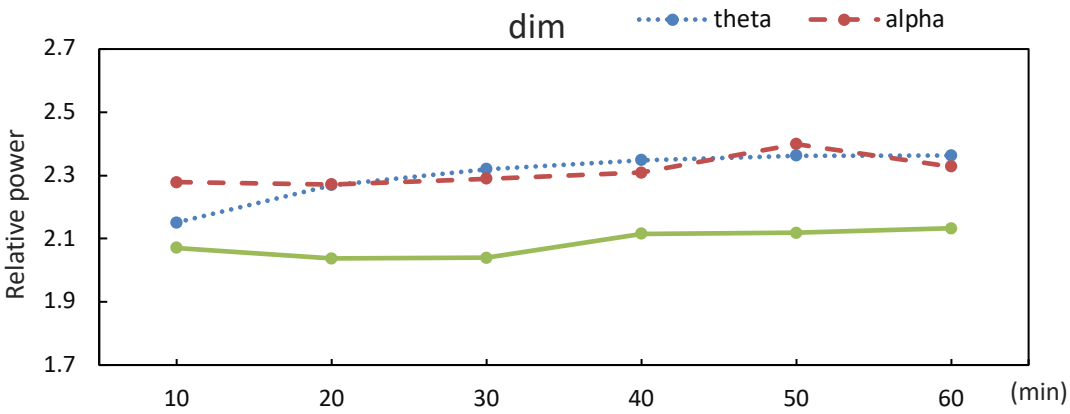
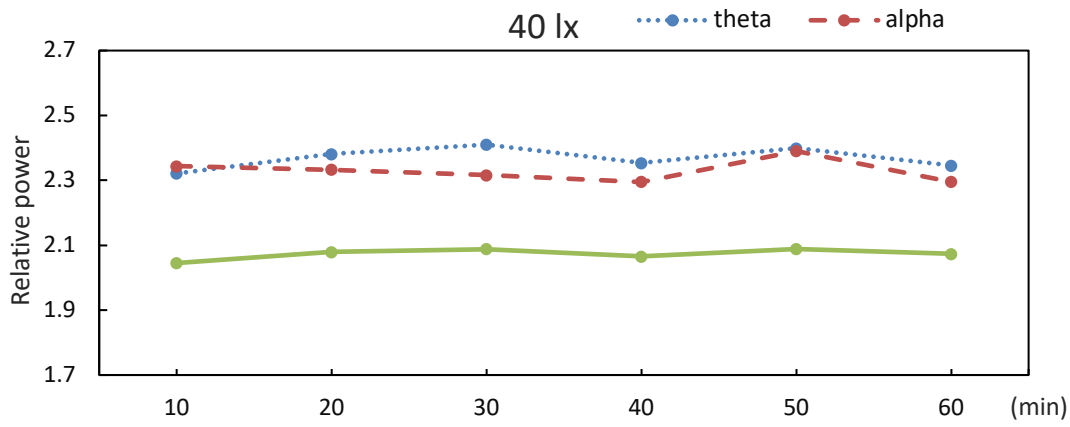


Figure 5.3.2.1: EEG power pooled over all 8 participants shown at 5-minute intervals





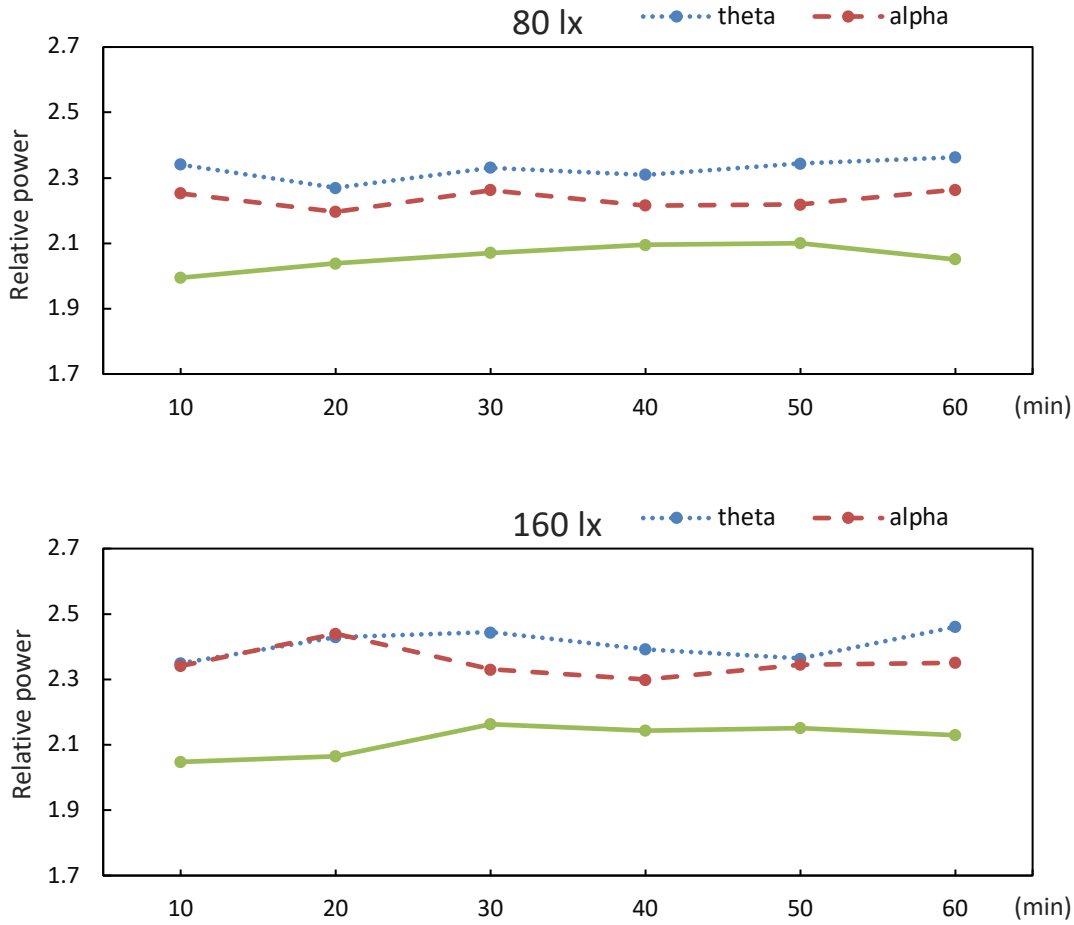


Figure 5.3.2.2: EEG power pooled over all 8 participants shown at 10-minute intervals

In each frequency range, EEG power averaged over the 40 minutes under test lighting was normalised to the initial 20 minutes of dim light period. In addition to conventional theta, alpha and beta frequencies, some sub-bands like theta-alpha (5-9Hz), lower alpha (8-9Hz) and higher alpha (11-12Hz) are also examined in the subsequent statistical tests. One-way ANOVA was performed using the normalised 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 5.3.2.1.

Table 5.3.2.1 Pairwise comparisons for EEG beta power

Pairs	Sig.*
Dim-40 lx	1.000

Dim-80 lx	1.000
Dim-160 lx	0.001*
40 lx-80 lx	1.000
40 lx-160 lx	0.005*
80 lx-160 lx	0.025*

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

One-way ANOVA revealed a close to significant main effect of lighting condition in the normalised 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, 80 lx and 160 lx in beta range (Table 5.3.2.1). Figure 5.3.2.3 shows the results of normalised 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 ($p>0.05$).

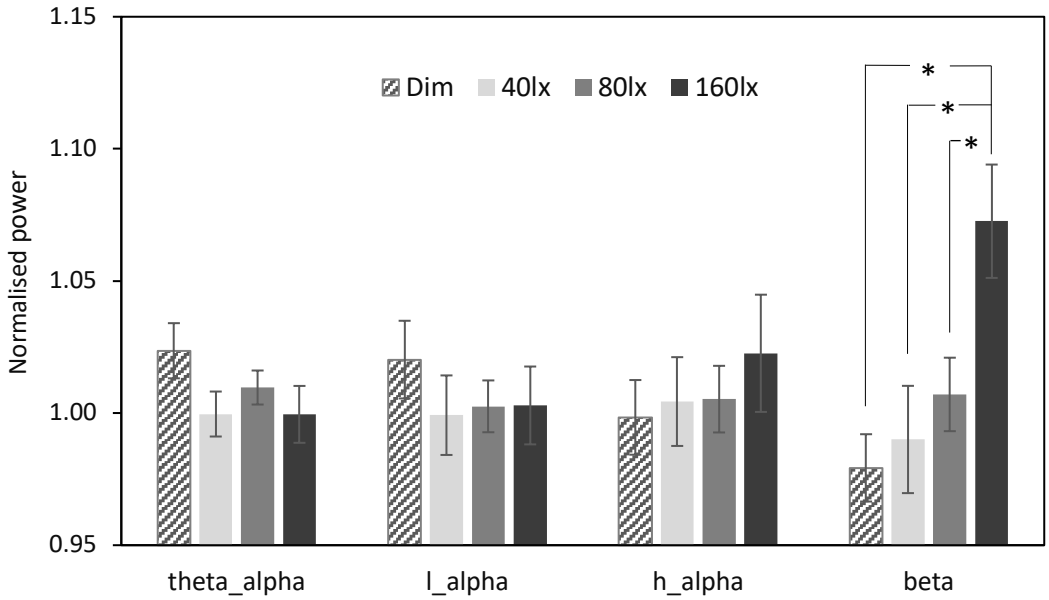


Figure 5.3.2.3: Mean ± standard error of the mean normalised EEG power for four frequency ranges

Some significant results were found in the beta frequency range. To give more details on beta power result, individual beta power of eight participants under four light conditions are shown in Figure 5.3.2.4.

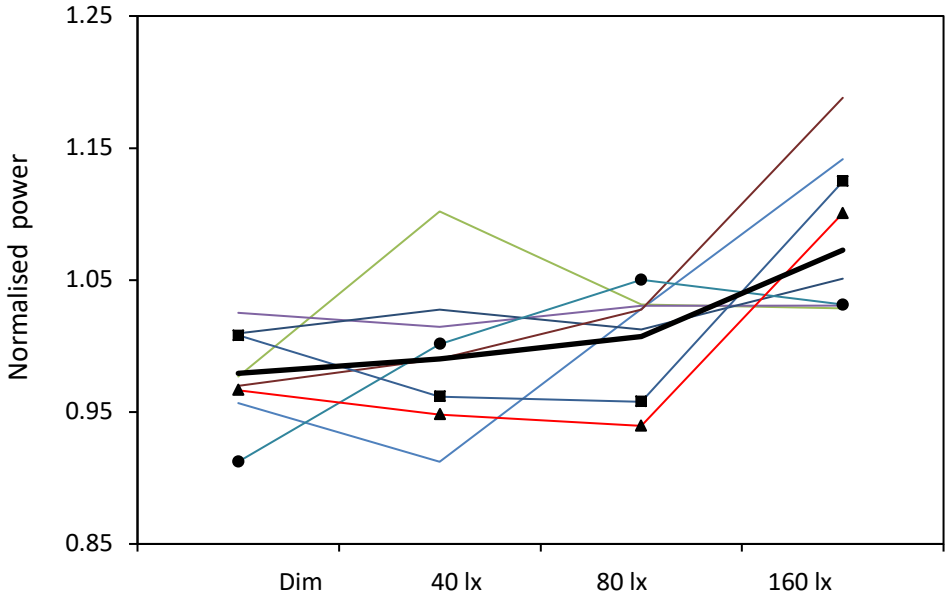


Figure 5.3.2.4: Individual EEG power values in beta range (the same symbol connected in a line indicates the values obtained from the same participant, the bold black line indicates mean values)

Subjective sleepiness (KSS)

Subjective sleepiness was evaluated using the Karolinska Sleepiness Scale, a self-reporting scale that ranges from 1 (‘extremely alert’) to 9 (‘very sleepy, fighting sleep’). This scale has previously been shown to be sensitive to changes in sleepiness and the alerting effects of lights [15,193].

The KSS was rated three times (at the 20th, 40th, and 60th min) during each session. Subjects were asked to rate themselves from 1 to 9, according to their sleepiness. Mean scores over the experimental condition were normalised 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 5.3.2.2.

Table 5.3.2.2 Pairwise comparisons for KSS scores

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

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

ANOVA revealed a significant difference between Dim and 160 lx conditions. Figure 5.3.2.5 shows the results for the normalised 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 ($p>0.05$).

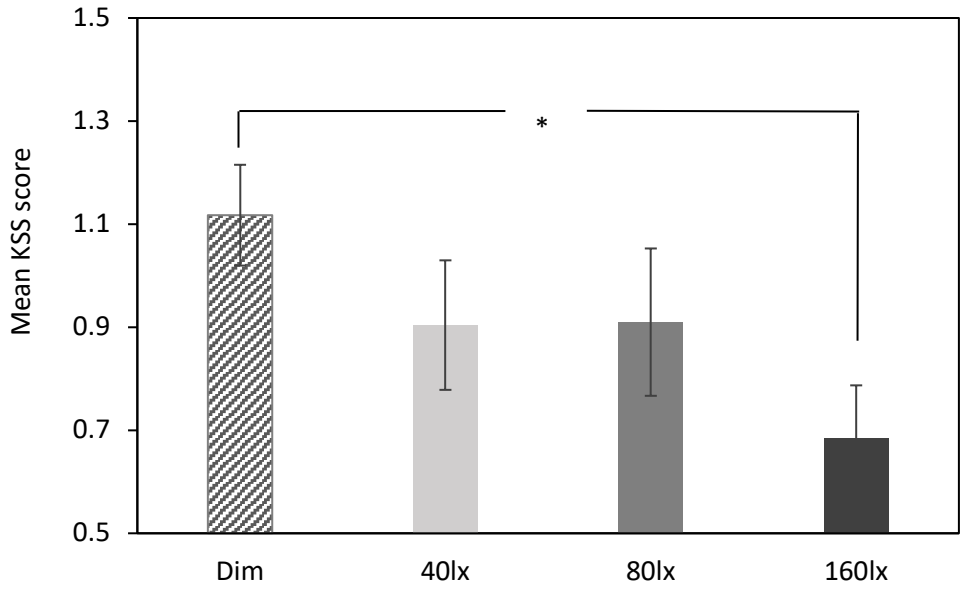


Figure 5.3.2.5: Mean ± standard error of the mean normalised KSS scores (lower scores indicate greater alertness)

As for EEG result, to give more details on KSS result, individual scores of eight participants under four light conditions are shown in Figure 5.3.2.6.

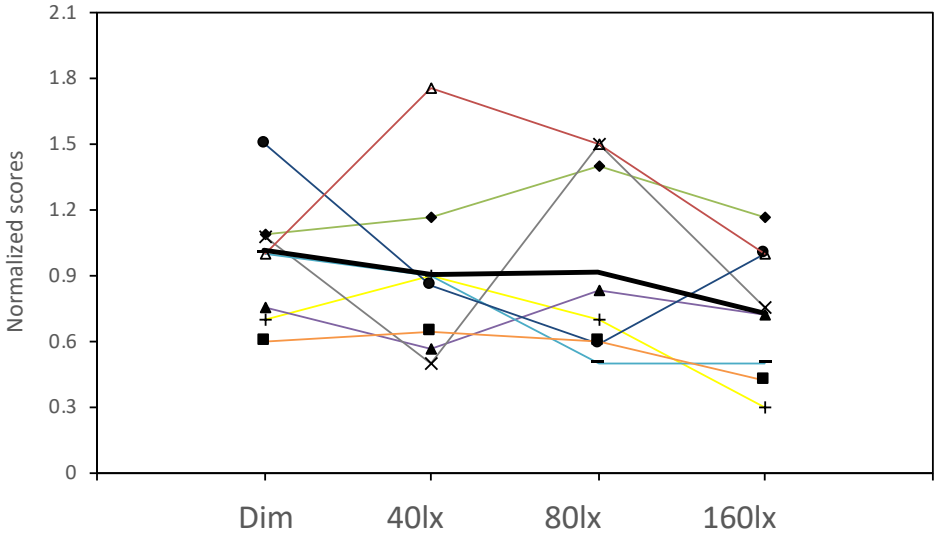


Figure 5.3.2.6: Individual KSS scores (the same symbol connected in a line indicates the values obtained from the same participant, the bold black line indicates mean values)

Brightness score

In addition to KSS, participants were asked to score the brightness of the light. The question being ‘how bright do you feel the light is’ and the scores ranged from 1 (‘dim’) to 10 (‘extremely bright).

Along with KSS, brightness was rated three times (at the 20th, 40th, and 60th minute) during each session. Subjects were asked to rate from 1 to 10, according to how they perceived the light brightness. Mean scores over the experimental condition were normalised 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 5.3.2.3.

Table 5.3.2.3 Pairwise comparisons for brightness scores

Pairs	Sig.*
Dim-40 lx	1.000
Dim-80 lx	0.634
Dim-160 lx	0.037*
40 lx-80 lx	1.000
40 lx-160 lx	0.642
80 lx-160 lx	1.000

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

ANOVA revealed a significant difference between Dim and 160 lx conditions. Figure 5.3.2.7 shows the results for the normalised brightness scores under four lighting conditions (where *indicates significance). Mean score in 160 lx condition was significantly higher than score in Dim condition (a higher score means the light was perceived brighter). Mean scores under 40 lx and 80 lx conditions were higher than score under the Dim, and lower than score under the 160 lx condition, although these differences did not reach statistical significance ($p>0.05$).

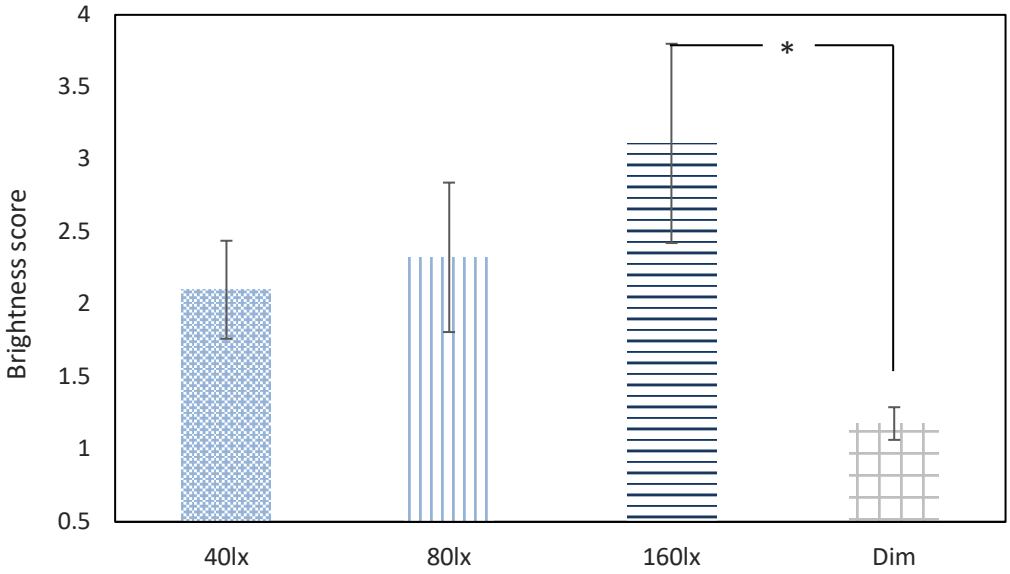


Figure 5.3.2.7: Mean ± standard error of the mean normalised brightness scores

Again, individual scores of eight participants under four light conditions are shown in Figure 5.3.2.8.

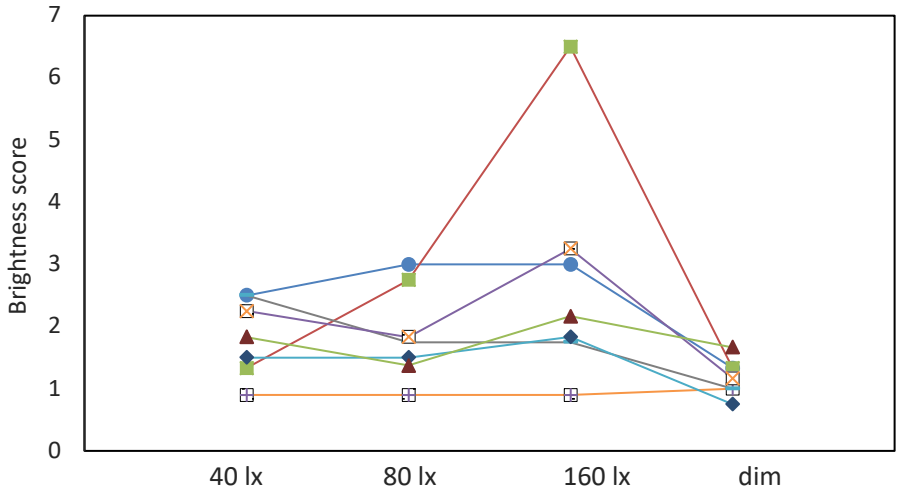


Figure 5.3.2.8: Individual brightness scores (the same symbol connected in a line indicates the values obtained from the same participant)

5.4 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 late evening.

Experiment 1 implemented a 120-minute protocol to look at how EEG power changes over a relatively long period of exposure time. Four participants completed three sessions in this study and their results were plotted in various ways to show how different EEG frequency power changes and how they change under different light conditions over 120 minutes. Considering the method used by other papers and literature, results suggested that 60 minutes exposure is very likely to be sufficient for such study to observe the effect as far as EEG power is concerned. Therefore, the exposure duration for Experiment 2 was set to be 60 minutes.

The results of Experiment 2 showed the effect of intensity on EEG theta-alpha (5-9Hz) and beta (13-30Hz) 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 (8-12Hz) is related to alertness increase, and the increase in high-frequency alpha activity especially is associated with the circadian regulation of arousal [194]. There was no 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 subjects, 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.

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. For lower alpha, the Dim light condition elicited the greatest power, whereas in higher alpha, the 160 lx light condition elicited 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, more data from more participants is needed to conclude more clearly.

The subjective alertness (KSS) reported is consistent with the above EEG results. Subjects rated themselves as sleepier in the Dim condition, and more alert under the blue lights. The Dim condition had the highest score and 160 lx had 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 was no report of unusual bed time shifts after exposure; however, one participant reported suffering from headache at night every time after being kept in blue lights.

Brightness scores reported by participants are consistent with the actual light levels. Dim light has the lowest score and 160 lx light has the highest score; the 40 lx and 80 lx light scored in between and at about the same level. This suggested that participants find it least bright under the dim light condition and most bright under the 160 lx light condition; and the difference is significant. These results are also statistically consistent with the KSS results. In other words, participants are conscious of the brightness of the lights, especially when the brightness changes significantly; they also rated themselves as more alert under brighter conditions.

Very few studies have so far looked into the effect of intensity of short wavelength light on alertness. In some published studies, blue light of 40 lx has been suggested to have an alerting effect [9,10]. Some other studies, for example, have compared light of 40 lx at 2500 K, 3000 K and 6500 K, and light of 295 lx at 2700 K and 209 lx at 5600 K [183]. These studies, however,

have tended to focus on spectral composition or exposure duration, rather than light intensity.

One previous study 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 [5]. Some other such studies have also demonstrated a non-linear relationship between light intensity and circadian shifts [6,195]. 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.

This study extends the research on the effect of intensity on light-induced alertness. The findings suggest 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). However, this dose effect may also be a combination of intensity and duration. 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. However, we cannot say that the threshold is within the intensity range we tested, e.g. between 80 and 160 lx. 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. A 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 [14] over the relatively long exposure hours. However, in this study 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.

The 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.

Chapter 6
Study 3: Alerting effect of two long-wavelength lights

6.1 Aim

A previous study investigated the alerting effect of short-wavelength light at three light intensity levels (40 lx, 80 lx and 160 lx) in the evening. Results showed that the 160 lx light significantly increased alertness, as evaluated by EEG and self-rating questionnaire (Karolinska Sleepiness Scale). This study aims to expand on the previous work by investigating the impact of long-wavelength on the measures of EEG power as well as subjective measures.

Although earlier research has linked the alerting effect of light to its ability to suppress melatonin, more recent studies have demonstrated that melatonin change is actually not needed to produce these effects. Many other studies have suggested that the underlying mechanism, by which light exposure improves alertness, is not solely driven by short wavelengths through melanopsin.

Some studies have looked into how exactly short-wavelength and long-wavelength light exposure impacts EEG power. Red light is even suggested to be a stronger alerting stimulus in the afternoon than blue light, which might be explained by the idea that long-wavelength cones mediate the alerting effects of red light during the daytime [9]. Studies have shown that both long-wavelength and short-wavelength light of the same corneal illuminance evoked similar alerting effects (i.e. increased EEG beta power); however, the pathway mediating nocturnal melatonin suppression might not be the same as that mediating other physiological responses to light exhibited by the endocrine and the autonomic nervous systems [196].

The objective of this study, specifically, is to investigate the effect of two levels (40 lx and 160 lx) of a long-wavelength light (λmax = 640nm),

compared to remaining in darkness (<1 lx), on human alertness during the evening.

6.2 Brief Summary of Study

Test participants

Eight participants (aged 28 ± 3.6 years; five females and three males) were recruited for this within-subject, two-session study. In order to give comparable results later, these are the same eight participants who also took part in the previous study 2. All participants reported their individual sleep/rise time as well as their daily consumption of nicotine, caffeine and alcohol before taking part in the experiment. Smokers, and those who were rated as extreme late chronotypes, were excluded (the bedtime reported by participants ranged between 21:30 and 00:30). The study was approved by the University of Leeds Ethics Committee (LTDESN-113) and all participants signed informed consent prior to the experiment. An information sheet was also given to participants and they were requested to refrain from caffeine and alcohol three hours prior to the experiment, and to try to maintain a regular, constant sleep/rise schedule during the experimental period of time. The results produced from these eight participants are included. Table 6.2.1 lists self-reported wakeup and bedtime of participants.

Table 6.2.1 Self-reported wakeup and bedtime

Participant No.	Wakeup time	Bedtime
1	7:00	23:00
2	8:00	23:00
3	8:30	22:30
4	9:00	00:00
5	8:30	23:00
6	8:00	00:00
7	8:00	23:00
8	8:30	00:30

Experiment protocol

The experiment protocol of this study is consistent with the previous study. Each participant completed two sessions over two nights, starting at around the same time (20:00). Participants were fitted with EEG electrodes prior to the start of the exposure. The order of the conditions (40 lx and 160 lx) was presented 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.

EEG was continuously recorded over 60 minutes during the experiment. Participants were exposed to light for 60 minutes in each session. Red lights were turned on for 40 minutes, preceded by a 20-min dim (<1 lx) period.

Subjective sleepiness was evaluated using the KSS that ranges from 1 (‘extremely alert’) to 9 (‘very sleepy, fighting sleep’). KSS, along with brightness, was rated three times (every 20 minutes - at the 20th, 40th and 60th minutes) during each session. Participants were asked to rate themselves according to their sleepiness and their perception on light brightness. 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 6.2.1).

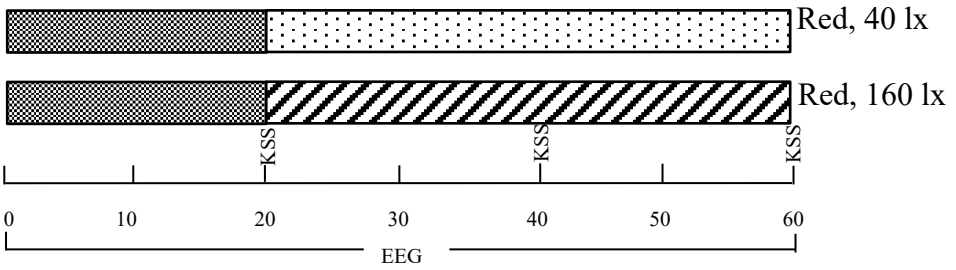


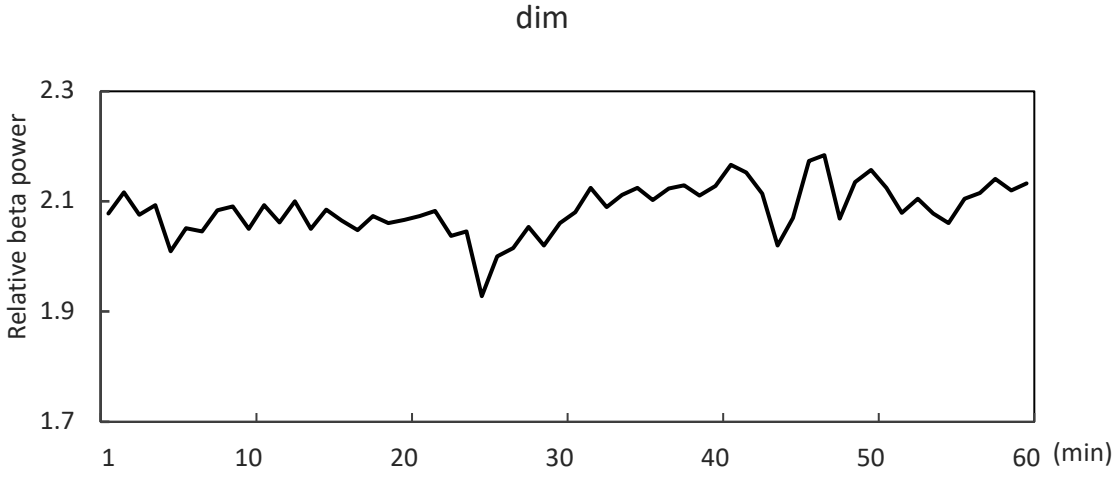
Figure 6.2.1: Experimental design

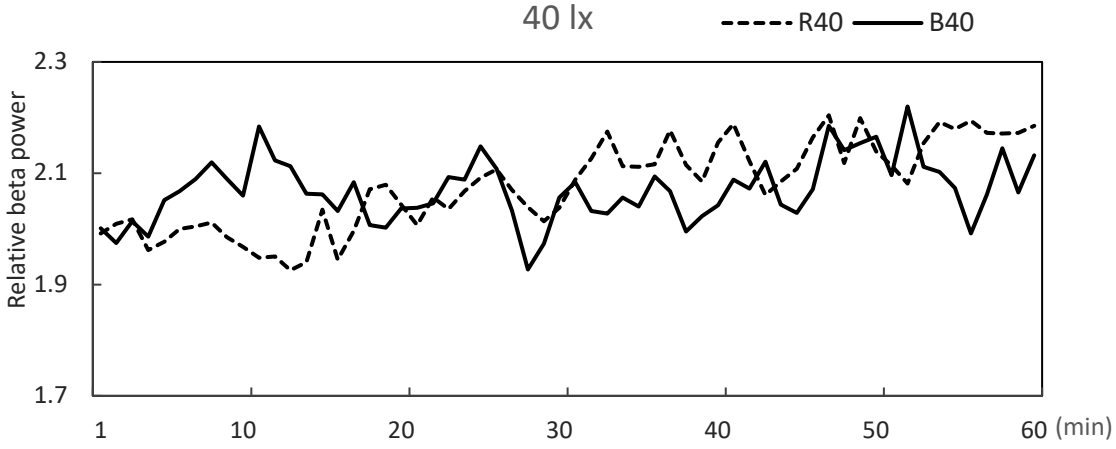
6.3 Results

EEG

EEG activity was collected from nine electrode sites and averaged to produce overall EEG PSD, and then grouped into alpha power (8-12 Hz), 5-9 Hz (theta alpha) and 13-30 Hz (beta) frequency bins.

EEG beta power change during the 60-minute exposure was plotted (Figures 6.3.1-6.3.3). Six lighting conditions, including dim light condition, two red lights in this study (R40 and R160) and three blue lights in experiment 2 (B40, B80 and B160), are shown. Figure 6.3.1 shows the beta power change every minute (where beta power is averaged over every minute). Figure 6.3.2 shows the power change every 5 minutes (where beta power is averaged over every 5 minutes). Figure 6.3.3 shows the power change every 10 minutes (where beta power is averaged over every 10 minutes). All data in results of this chapter is listed in Appendix J.





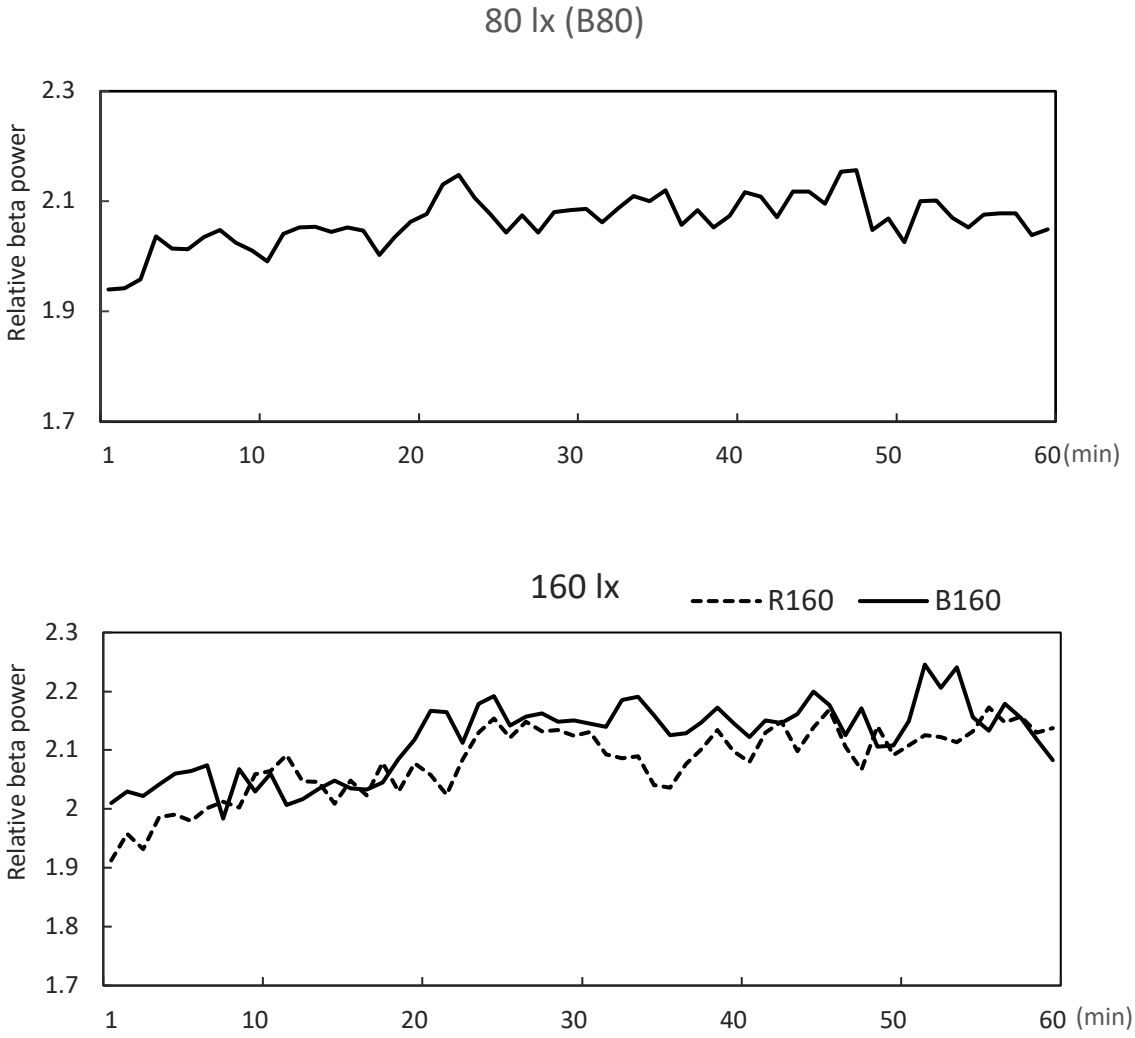
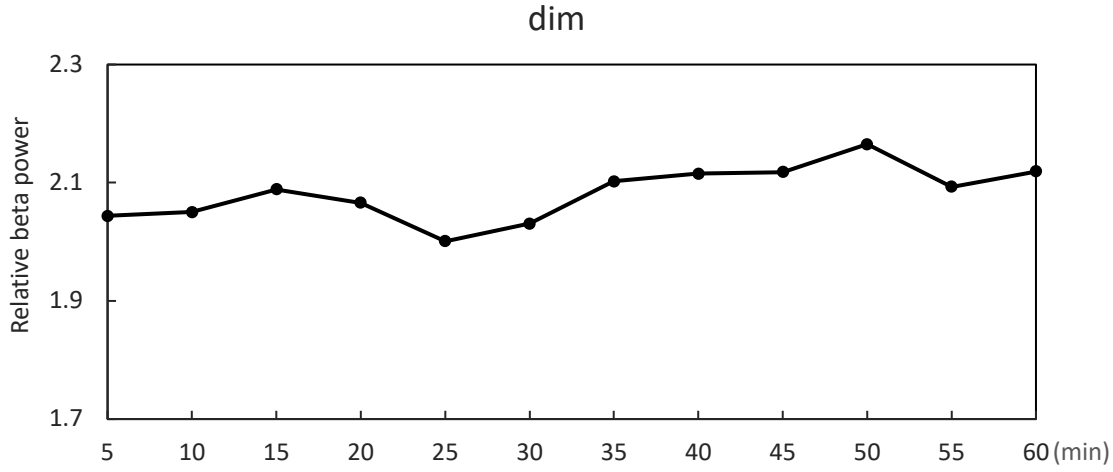


Figure 6.3.1: Beta power change pooled over all 8 participants shown at 1-minute intervals



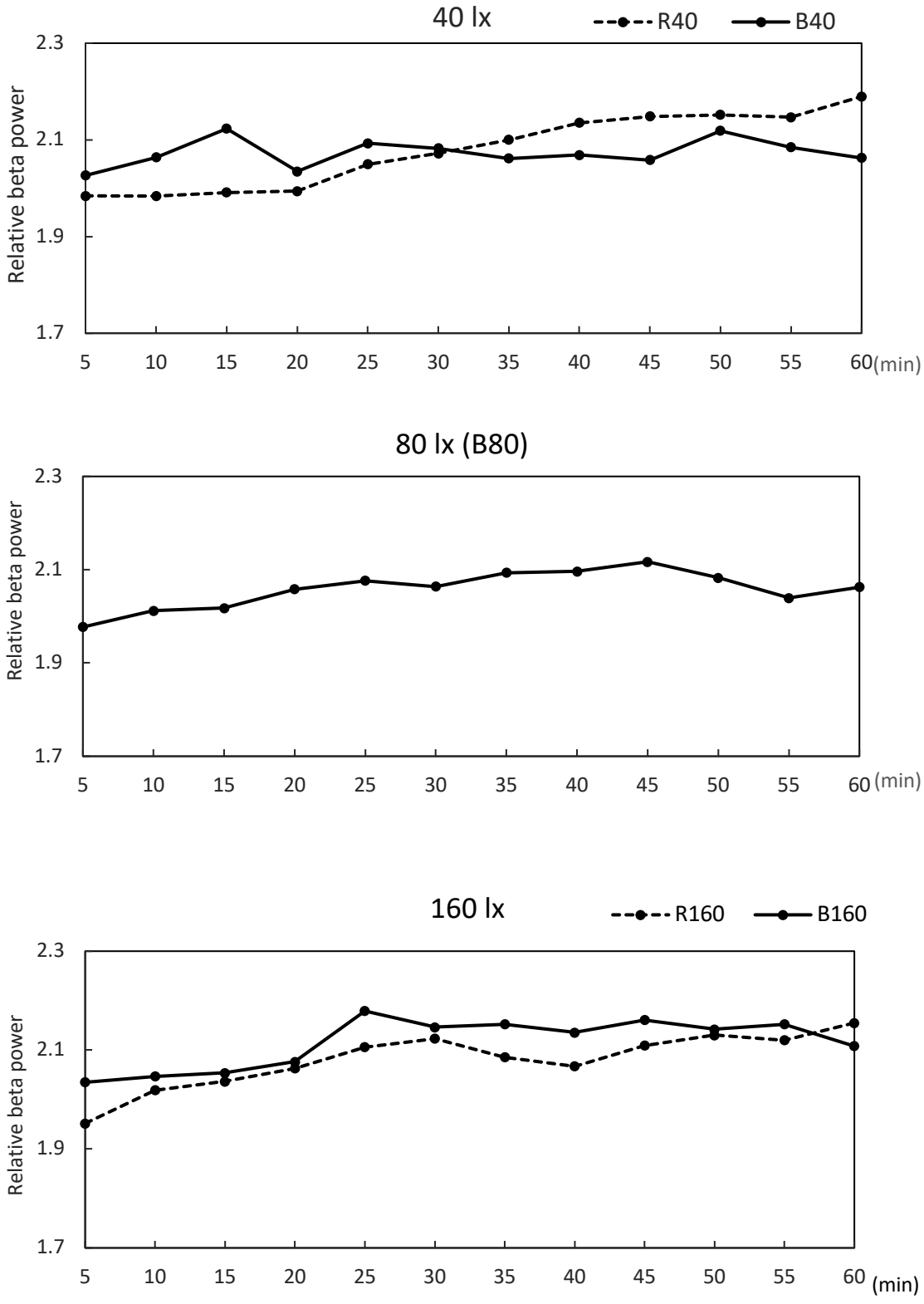
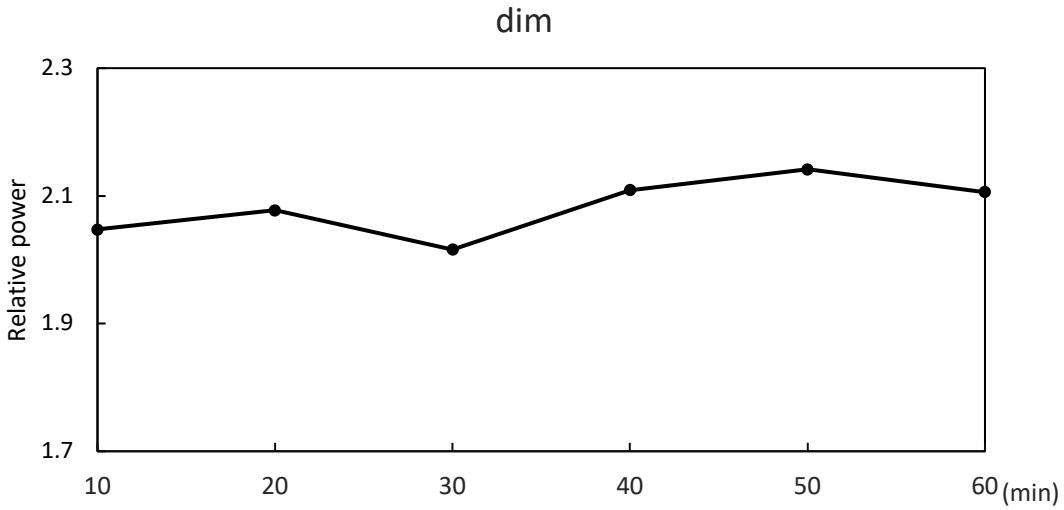
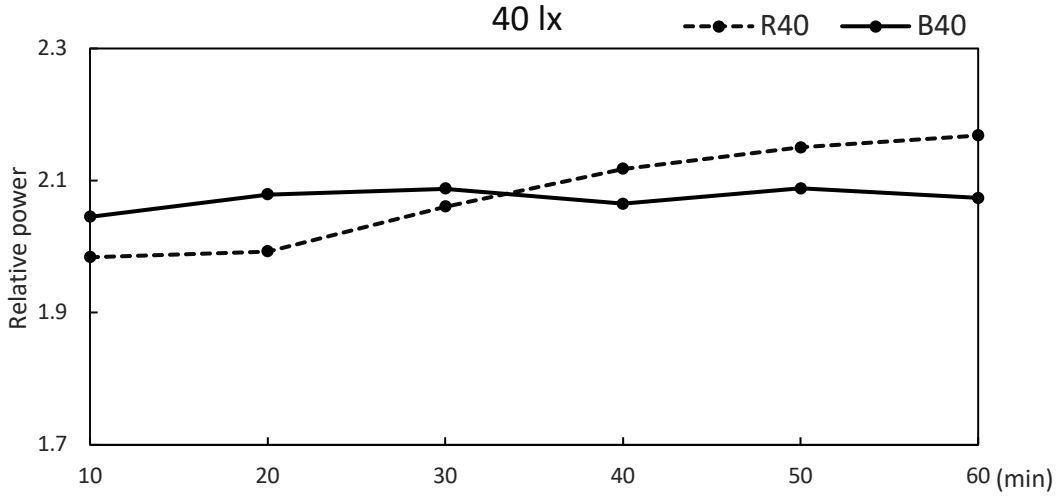
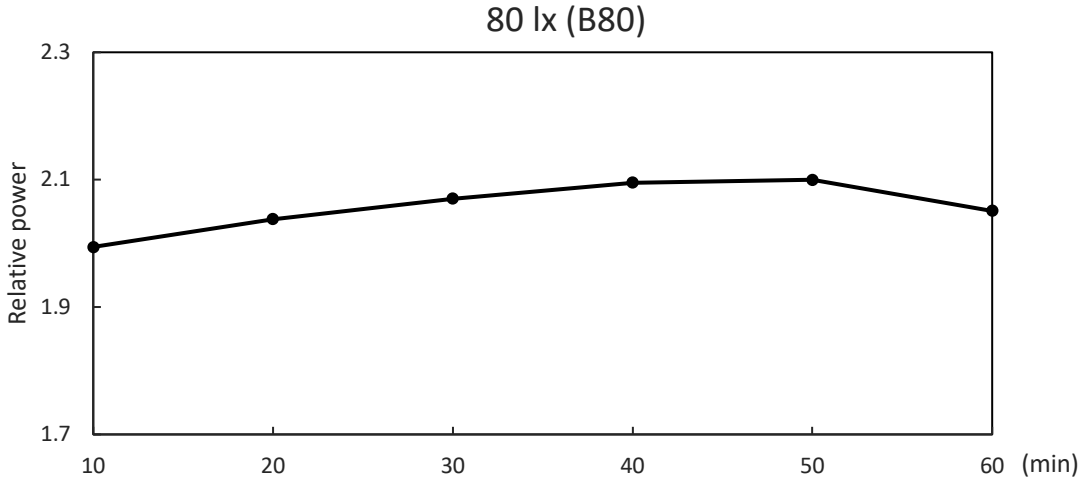


Figure 6.3.2: Beta power change pooled over all 8 participants shown at 5-minute intervals


dim
Relative power
2.3
2.1
1.9
1.7
10
20
30
40
50
60
(min)


40 lx
R40
B40
Relative power
2.3
2.1
1.9
1.7
10
20
30
40
50
60
(min)


80 lx (B80)
Relative power
2.3
2.1
1.9
1.7
10
20
30
40
50
60
(min)

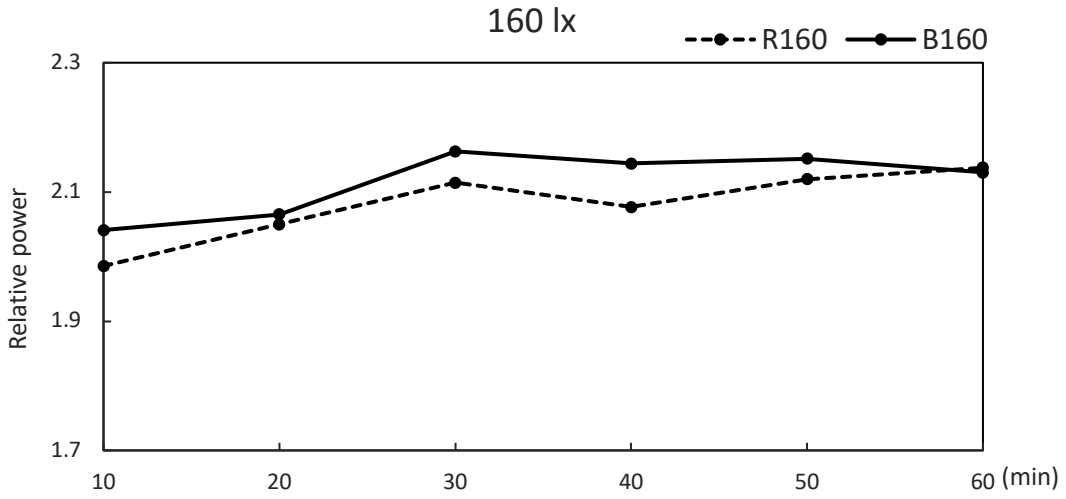


Figure 6.3.3: Beta power change pooled over all 8 participants shown at 10-minute intervals

Figures 6.3.1-6.3.3 show that the beta power over the dim period was approximately stable. The figures also show that beta power for both the red and blue light conditions rises gradually over the 40-minute time period. And with the increasing light level this trend has become more noticeable. This suggests that the effect of coloured light on beta power has little latency and that at the end of the 40-minute period the beta power is still rising.

However, it is not easy to carry out statistical analyses on the raw or moving average data. Instead, normalised data were used. In each frequency range, EEG power averaged over the 40 minutes under coloured lighting was divided by the average over the initial 20 minutes of the dim light period. This was done for each participant and all eight participants were averaged together to get overall results.

The results of two red lights were compared with the Dim light condition (where participants were under dim light for 60 minutes, CCT 2000 K, <1 lx) and the other three Blue light conditions from the previous study, on the basis that the same eight participants took part in both studies. Note that in the Dim light condition the result over the last 40 minutes were also normalised to the initial 20 minutes. One-way ANOVA was performed using the normalised power in each of the frequency ranges studied. When necessary, post-hoc t-tests (with Bonferroni corrections) were used to further compare the statistical significance between lighting conditions.

One-way ANOVA revealed a significant main effect of lighting condition in theta-alpha ($F(5,42)=2.490$; $p=0.046$) and beta ($F(5,42)=4.894$; $p=0.001$). No significant difference was observed in alpha ($F(5,42)=0.983$; $p=0.439$). As beta showed the most significant result, post-hoc pairwise comparisons were done for beta. Significant differences were found between Dim and B160, B40 and B160 in beta range. These results are listed in Table 6.3.1.

Table 6.3.1 Post-hoc pairwise comparisons for EEG beta power

Pairs	Significance*
Dim-B160	0.004*
B40-B160	0.025*
Dim-R40	0.055

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

Figure 6.3.4 shows the results of normalised power for six lighting conditions in three frequency ranges studied (where *indicates statistical significance). Note that the results of dim, 40 lx, 80 lx and 160 lx Blue light from the previous study are added in the figure to give a better comparison. The results showed that EEG beta power is significantly higher after exposure to 160 lx Blue light than remaining in Dim light ($p<0.05$). Exposure to 40 lx Red light has also increased beta power although this did not reach statistical significance ($p=0.055$).

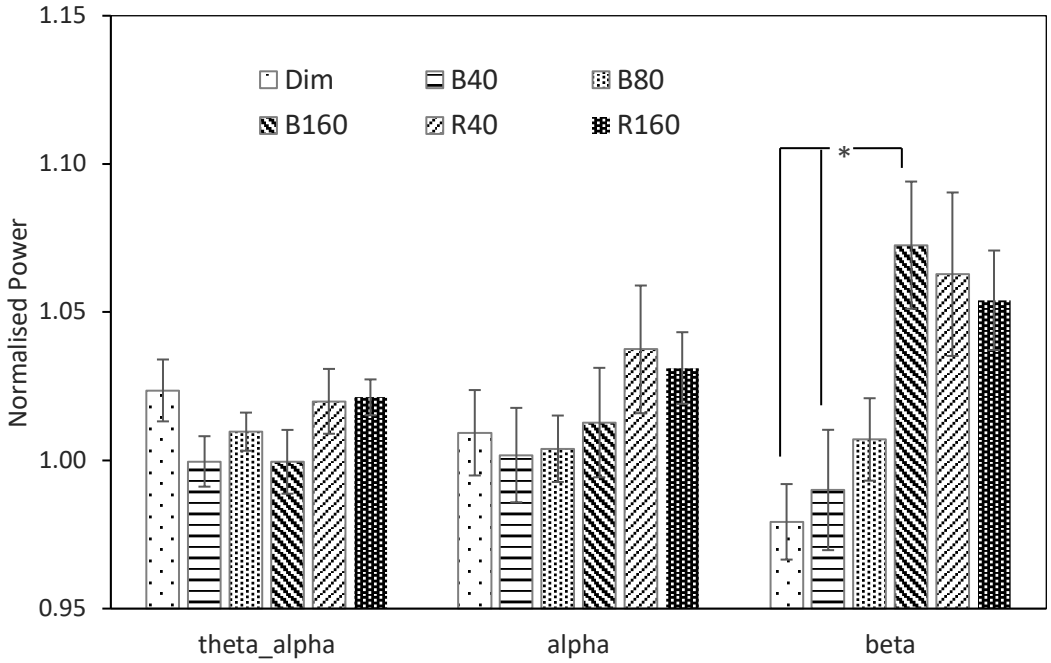


Figure 6.3.4: Mean ± standard error of the mean normalised EEG power for three frequencies

Individual normalised EEG beta power of eight participants under two red light conditions and dim light were shown in Figure 6.3.5.

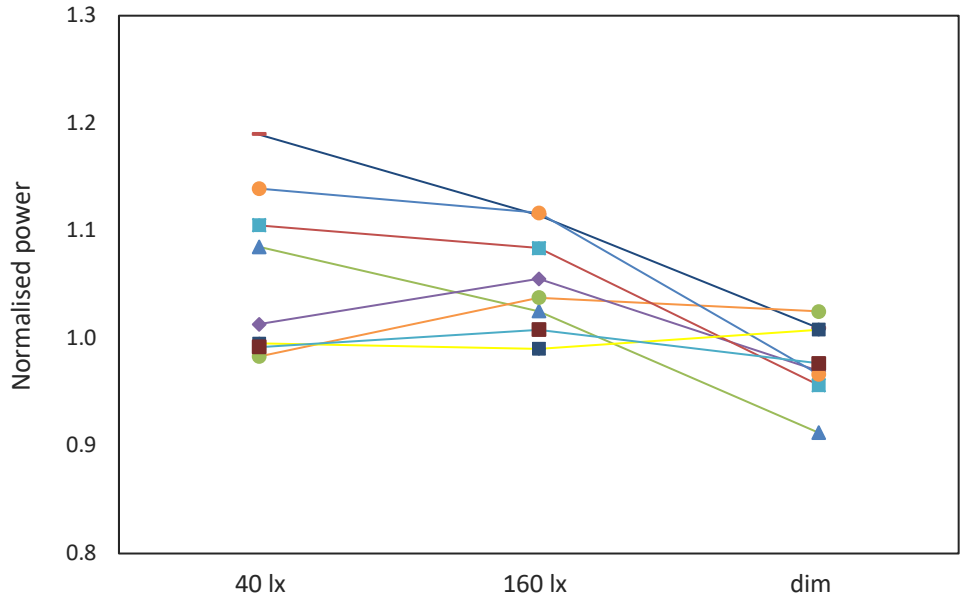


Figure 6.3.5: Individual EEG power values in beta range (the same colour symbol connected in a line indicates the values obtained from the same participant)

Furthermore, alpha power was split into lower alpha and higher alpha. Result was shown in Figure 6.3.6, along with results in theta-alpha and beta frequencies. The previous study compared lower and higher alpha and found that two parts have different patterns. The assumption is that lower and higher alpha are closed to theta and beta respectively, which are likely to behave differently. In this study again, lower alpha result looks similar to theta-alpha power, and higher alpha result is similar to beta.

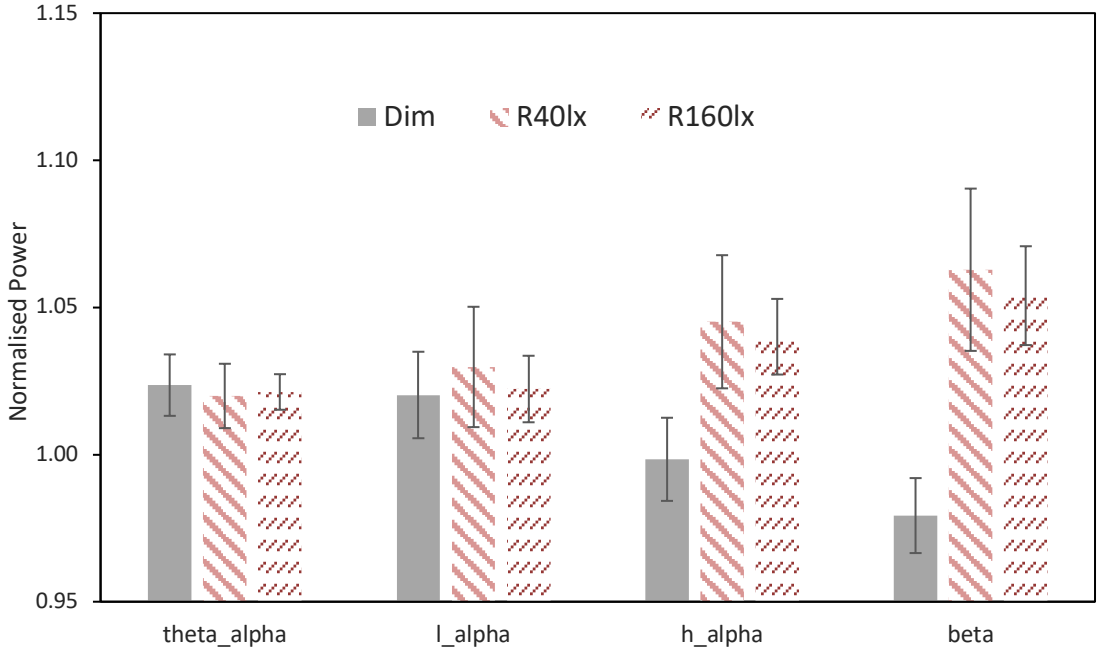


Figure 6.3.6: Normalised EEG power for four frequencies

This might enable some new insights. As EEG frequency is a continuous spectrum, its properties might be continuous as well. In other words, instead of dividing brainwaves into various bins and expecting each of them to behave discretely, we should keep in mind that they are a whole and their behaviour might not be seen separately. For example, for a specific brain state, different frequency bins might behave differently but those waves with frequencies just around the edge of each bins might not necessarily behave in a distinct way.

Figures 6.3.1-6.3.3 also showed that beta power increased gradually over the 40-minute light period. Therefore, EEG beta power averages over the preceding three minutes at each of the following time points were calculated - after 20 minutes (t20, at the end of the dim period), after 40 minutes (t40, halfway through the lighting period) and after 60 minutes (t60, at the end of

experiment). Power values at t40 and t60 were then normalised to t20 and a lighting conditions (6) x time (3) ANOVA was performed. Results showed a significant main effect of time. No significant main effect of lighting conditions was found. There was also no significant interaction (Table 6.3.2).

Table 6.3.2 Lighting conditions (6) x time (3) ANOVA results for EEG beta power

Main effect	df	F	Significance*
Lighting conditions	5	0.093	0.993
Time	2	3.785	0.027*
Interactions	10	0.317	0.975

Subjective sleepiness (KSS)

Mean KSS scores over the 40-minute exposure were normalised to the initial 20-minute dim light and then compared to the other light conditions. One-way ANOVA was performed and post-hoc t-tests (with Bonferroni corrections) were used to further compare the significance between lighting conditions. Significant results are listed in Table 6.3.3.

Table 6.3.3 Pairwise comparisons for KSS scores

Pairs	Significance*
Dim-B160	0.041*
Dim-R40	0. 024*
Dim-R160	0.034*

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

One-way ANOVA revealed a significant main effect of lighting condition ($F(5,42)=3.422$; $p=0.011$). Post-hoc pairwise comparisons found a significant difference between Dim and B160, R40 and R160 conditions. Figure 6.3.7

shows the results for the normalised KSS scores under six lighting conditions (where *indicates statistical significance). Mean scores in B160, R40 and R160 conditions are significantly lower than the score in the Dim condition (recall that a lower KSS score indicates greater alertness).

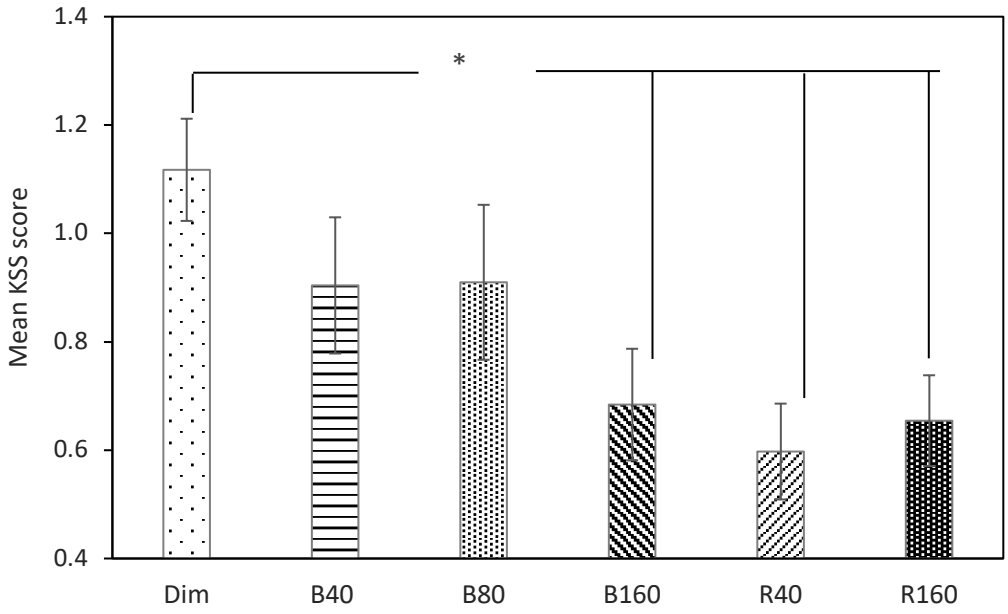


Figure 6.3.7: Mean ± standard error of the mean normalised KSS scores (lower scores indicate greater alertness)

Individual scores of eight participants under two red light conditions and dim light were shown in figure 6.3.8.

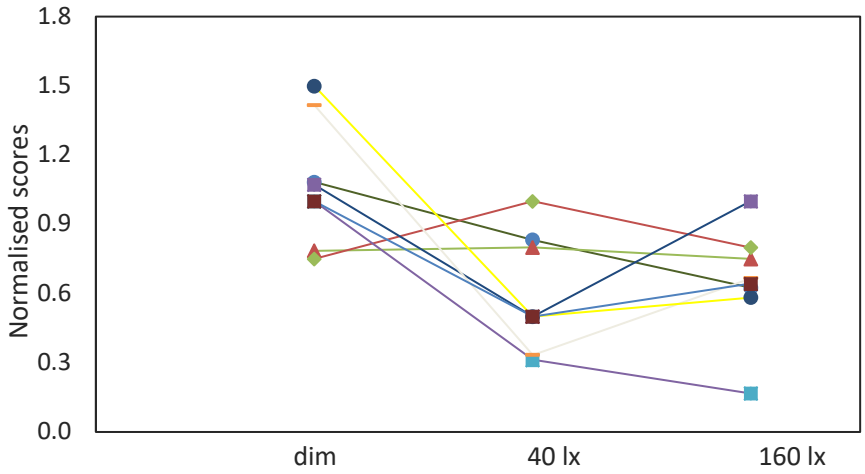


Figure 6.3.8: Individual KSS scores (the same symbol connected in a line indicates the values obtained from the same participant)

Brightness score

In addition to KSS, participants were asked to score the brightness of the light. The question being 'how bright the light do you feel' and the score ranges from 1 ('dim') to 10 ('extremely bright).

Along with KSS, brightness was rated three times (at the 20th, 40th, and 60th minute) during each session. Mean scores over the experimental condition were normalised to the initial dim exposure. 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 6.3.4.

Table 6.3.4 Pairwise comparisons for brightness scores

Pairs	Sig.*
Dim-40 lx	0.019*
Dim-160 lx	0.005*
40 lx-160 lx	1.000

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

ANOVA revealed a significant difference between Dim and 40 lx conditions; and between Dim and 160 lx conditions. Figure 6.3.9 shows the results for the normalised brightness scores under three lighting conditions (where *indicates significance). Mean score in both 40 lx and 160 lx condition were significantly higher than score in Dim condition (a higher score means the light was perceived brighter). Mean scores under 40 lx and 160 lx conditions were not significantly different ($p>0.05$).

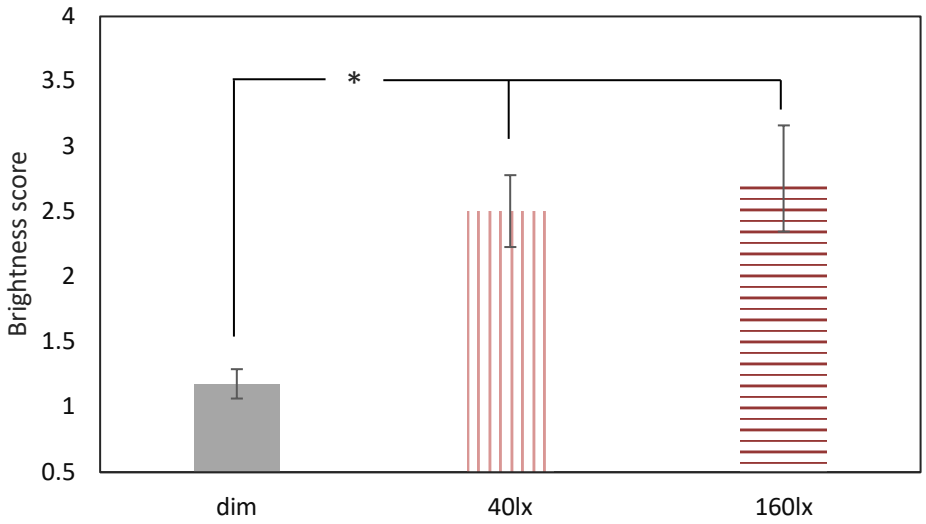


Figure 6.3.9: Mean ± standard error of the mean normalised brightness scores

Individual scores of the eight participants under three light conditions are also shown in Figure 6.3.10.

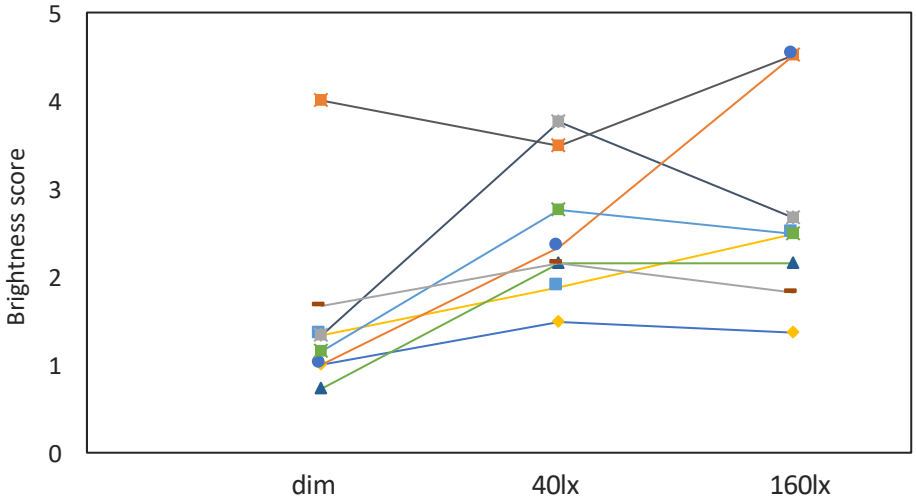


Figure 6.3.10: Individual brightness scores (the same colour connected in a line indicates scores from the same participant)

6.4 Discussion

A previous study compared short-wavelength lights at three levels (40 lx, 80 lx and 160 lx) and it was observed that exposure to 160 lx light significantly increased EEG beta power compared to remaining in the Dim condition.

Since the increase in EEG beta power indicates greater alertness, combined with other statistical results of EEG and KSS, it was concluded that 160 lx light significantly increased alertness compared to the Dim, 40 lx, and 80 lx conditions, whereas the 40 lx and 80 lx lights did not show a statistically significant effect.

This study investigated how exposures to long-wavelength lights of two different levels (40 lx and 160 lx) affect objective (EEG) and subjective (KSS) alertness during the night time. The results are then compared with the result of Dim condition in the previous study. A significant effect of light levels on EEG beta (13-30Hz) power was observed. Exposure to both 40 lx and 160 lx long-wavelength lights increased beta power compared to the Dim condition. Both exposures also increased EEG high alpha power, although this did not reach statistical significance. The effect on theta-alpha and lower alpha power are not noticeable. Furthermore, no significant difference between 40 lx and 160 lx long-wavelength lights is observed.

The results of subjective alertness (KSS) scoring is consistent with the EEG results. Participants rated themselves as more alert under both 40 lx and 160 lx lights. Both lighting conditions have lower scores than that under the Dim condition (where lower scores indicate higher alertness), this again shows a significant alerting effect of two lights compared to Dim light. There is no statistically significant difference between the KSS scoring of the two lights. As in the previous study, participants were asked to report significant changes on their bed time and any other unusual feelings (including sleep problem) on the second day after experiment. There was no report of unusual bed time shifts or sleep difficulties.

The results for brightness score are consistent with the actual light levels to some extent. 40 lx and 160 lx red light was perceived as significantly brighter than dim light. However, 40 lx and 160 lx lights were not perceived to be much different.

So far very few studies have compared the effect of light levels of short-wavelength and long-wavelength light on alertness. In the related study that looked into this topic, usually only two levels (10 lx and 40 lx) are investigated. This study extends the research on the effect of light levels on light-induced alertness. The findings suggested several interesting points.

Firstly, the results have shown again that melatonin suppression is not needed for a light-induced alerting effect. The α-opic irradiance (the specified human photoreceptor response due to its opsin-based photopigment) for each lighting was calculated according to CIE S 026 /E:2018 that describes the ability of optical radiation to stimulate each of the five photoreceptor types that can contribute to retina-mediated non-visual effects of light in humans [195].

The long-wavelength lights tested in this study have very low S-cone-opic, rhodopic and melanopic irradiance values, as showed in Table 6.4.1, compared to the Blue light previously tested. However, they are as effective as the Blue light in promoting alertness. This clearly suggests that if a long-wavelength light that is ineffective for stimulating the melatonin change had an impact on alertness, it would have to occur via a different pathway (other than the circadian system). Several studies have shown that the lack of the blue portion in the light spectrum resulted in significantly reduced melatonin suppression [196,197]. However, short-wavelength attenuated or filtered white light which hardly suppress salivary melatonin concentrations showed no adverse effect on alertness or performance as compared with bright light [198,199]. There is also indirect evidences that melatonin suppression is not necessary for us to observe an alerting effect of light.

Table 6.4.1 α-opic irradiances (mW/m^2) for six lights

α-opic irradiance for	S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic	Melanopic
B40	157.98	131.44	80.48	277.64	324.25
B80	340.38	273.25	167.00	580.18	678.81
B160	716.54	557.33	340.56	1187.21	1389.97
R40	6.51	35.97	70.46	19.89	14.59
R160	24.48	140.14	283.06	74.31	53.80

Secondly, in the previous study only 160 lx blue light significantly increased alertness. 40 lx and 80 lx blue lights seemed to have an effect, though it is not statistically significant. The two long-wavelength lights tested in this study, however, both showed statistically significant effects. It was previously concluded that a certain level of light is needed to induce alertness. The results in this study suggested that this threshold level is not the same for light of different spectral composition, as 40 lx long-wavelength light has already significantly increased alertness. It seems that for short-wavelength light, a higher level of light is needed to produce a significant effect on EEG measures and KSS.

Traditionally, a ‘cool colour’ (such as blue) is associated with the feeling of calmness, which seems to be contradictory to the idea that blue light promotes alertness. One argument for this could be that short-wavelength light impact alertness mainly through the change of melatonin level (although this might not be the only pathway), which presumably will have to take a certain period of time. Therefore, short-wavelength light, compared to long-wavelength, might take a longer duration before showing a noticeable alerting effect. Blue light also has a much higher melanopic irradiance, as listed in Table 6.4.1, than long-wavelength of the same light level, which indicates that blue light triggers ipRGC (melanopic) response much more strongly. This again showed that one of the important ways through which blue light affects alertness is circadian system, whereas long-wavelength light has achieved this mainly through other pathways.

Comparing the EEG and KSS results under each lighting condition with their corresponding α-opic values, alertness seems to increase as the increasing α-opic irradiance for the blue lights. However, this does not seem to apply to the red lights. This again showed the first point we made that red light might impact alertness mainly through other paths (apart from the circadian system). For blue lights there seems to be a dose-response relationship between alerting effects and their α-opic metrics. This would require further study to find out more.

It is also noticeable that two levels of lights (40 lx and 160 lx) tested in this study are not significantly different from each other in promoting alertness. It seems clear that the relations between light levels and alertness change is not linear. The first question raised from this is whether red (long-wavelength)

light is actually more effective than blue in terms of acute alertness change? Additionally, 10 lx of red light is also found to significantly affect the EEG measures compared to preceding dark conditions [11]. It remains unknown whether there is an optimum light level of red light for alertness, and these results definitely demand further study.

In summary, study 3 expanded the previous work of study 2 on the effect of light levels of short-wavelength on alertness. Two light levels of long-wavelength lights were investigated with the same experimental methodology and the results have shown that long-wavelength is as effective as blue light in promoting acute alertness. This study is also a validation of the notion that melatonin is not the only pathway regulating alertness and long-wavelength light impacts alertness through another mechanism. This study also provides some evidence that the relation between long-wavelength light and alertness change is not linear and further study is required to explore on this issue.

Chapter 7
Discussion

7.1 Summary of Research

This research includes three studies that aim to evaluate and compare alerting abilities between a blue light and a green light, between three short-wavelength lights, and between two long-wavelength lights respectively.

The first study compared EEG measures for nine participants under two light exposures. A narrowband wavelength blue light that peaks at 460-480 nm and a broadband wavelength green (across the spectrum from 500 nm to 680 nm) with equal intensity were tested. Nine participants underwent a two-night within-subject protocol, where they were under tested light for 20 minutes after 15 minutes adaption in dim environment. Normalised EEG measures showed that participants had greater power in high alpha and beta frequencies under blue light than under green light exposure. The subsequent pilot experiment further compared between two short-wavelength lights. Although these results did not reach statistical significance, they reflect the current findings on the alerting effect of short-wavelength light. The methodology used in this study provided a good example for the next two studies.

The second study consisted of two experiments. The first experiment aimed to investigate how EEG as well as other measures change over a relatively long exposure duration, so as to evaluate an effective exposure duration for the main experiment. This experiment involved four subjects and three short-wavelength lights. Subjects were exposed for 120 minutes, with the first 20 minutes under a dim environment and then 100 minutes under a short-wavelength light. Subjective sleepiness (which was assessed using the KSS) and the perception on the light brightness were rated every 20 minutes by the participants. EEG power was measured continuously over 120 minutes. Results for three frequency bins: theta (3-7 Hz), alpha (8-13 Hz) and beta (13-30 Hz) at three light levels (40, 80 and 160 lx) for four participants were plotted at 10-minute interval. The plots showed that EEG power change in the first hour of light exposure was consistent with that in the second hour.

This has given some evidence that exposure time of an hour might be sufficient for the effect to be observed and prolong it to any longer does not seem to be necessary. Therefore, exposure duration of experiment 2 was decided to be 60 minutes. Part of the results in this study (EEG, KSS and brightness scores in the first hour) was also included in experiment 2 for overall analysis.

Experiment 2 is the main experiment of study 2, which aimed to evaluate and compare the alerting effects of four light conditions (dim, 40 lx, 80 lx and 160 lx). Together with the four participants in experiment 1, eight participants produced valid date for experiment 2. EEG power (theta, alpha and beta waves) change during the 60-minute exposure for four light conditions (dim, 40 lx, 80 lx and 160 lx) were plotted. One-way ANOVA was performed using the normalised EEG power in each of the frequency ranges studied. The results showed power in beta range was significantly higher after exposure to 160 lx blue lights than after exposure to the other three lighting conditions. Some results have also been observed in other frequency ranges, although these did not reach statistically significance. In the subjective alertness (KSS) questionnaire participants rated themselves significantly more alert under 160 lx blue light than under dim condition. In the brightness perception rating, participants find it least bright under dim light condition and significantly brighter under 160 lx light condition. These results have given us a picture that in terms of the measurements taken in this study, brighter blue light has made participants both subjectively and objectively more alert.

In experiment 2 it was observed that the relationship between light levels and alerting effects is definitely not a simple linear one. In addition, there are many factors that can limit the study e.g. sample size and subject control. However, some significant results were still obtained, and the experimental settings used in this study provides an example for subsequent study and further research.

Study 3 aimed to extend study 2 to investigate how exposure to two long-wavelength lights (40 lx and 160 lx) affect objective (EEG) and subjective (KSS) alertness during the night time. To give comparable results, the same eight participants who finished study 2 were invited for this study. The same methodology was adopted and two light conditions were tested. Participants were exposed to red light for 40 minutes, preceded by 20 minutes in dim

condition. EEG, KSS and brightness score were collected over the experiment. EEG beta power change over time was plotted by every minute, every 5 minutes and every 10 minutes for all lighting conditions including dim light, three blue lights from previous experiment and two red lights. The results of two red lights were compared with the dim condition (where participants were under dim light for 60 minutes) from the previous study. Results showed that compared to remaining in a dim condition, exposure to both red lights increased beta power. Participants rated themselves to be subjectively more alert under red lights. And both red lights were perceived as significantly brighter than dim condition.

Study 3 gave new insights on EEG. For example, results again showed that lower alpha looks similar to theta-alpha power, and higher alpha behaves similar to beta. This reminded us that the behaviours of different frequency bins are related to one another. More importantly, this experiment supports the notion that melatonin is not the only pathway regulating alertness. Long-wavelength lights might impact alertness through other mechanism.

7.2 EEG and Alertness

This research mainly used EEG as the technique to evaluate alertness and some observations about EEG and alertness are now made.

EEG noise and control

EEG is noisy as a technique. The activity of the human cortex is complex and not only brain activities are recorded in EEG. Essentially EEG measures the electrical activities on the scalp and more than brain activities can contribute to this. Many other activities such as eye blinks, coughs, yawns, and head/face movements can also affect the measures. Some of these result in typical patterns in the EEG waves and these are ‘decontaminated’ later in the signal processing. However, not all noise can be removed this way. In this research, data were accumulated over a long period of time e.g. the mean values over 5 or 10 minutes of recording. From this point of view, it would of course be ideal to measure EEG for as long as possible. It might also help to repeat experiments with each participant. However, it is not practical to do so. The work here that demonstrated that 60 minutes exposure duration is effective was important. Repeating experiments also

does not seem to be realistic in this research as it is too time consuming for participants. However, these are things (increasing sample size, repeating experiment) that should be considered in future work.

What is alertness

The alertness referred to in this research can be interpreted as mental activities. For example, when participants change from feeling ‘sleepy’ to ‘less sleepy’ or ‘more awake’, it is concluded that they feel ‘more alert’. In this situation. alertness can be seen as being associated with sleepiness/wakefulness.

In another case when participant is not feeling sleepy but rather wakeful e.g. when they are reading a book. Now they have become even more concentrated for some reason. Here we can also say they are ‘more alert’. In this situation alertness is associated with activity or concentration.

EEG gives a large amount of data. However, they are unprocessed and raw. EEG could not tell straightforward ‘participant is very focus now’ or ‘participant is falling asleep’, instead it gives figures that need to be interpreted. This large database is open for researcher to explain. It is important how we understand what EEG is measuring and how we comprehend its relationship with alertness.

What is EEG measuring

As long as brain activities exist (even when we are asleep brain is still functioning), brain waves can be recorded in EEG. It is well known that different waves are associated with different mental states. Therefore, when we try to interpret EEG, we need to know what state participant is in, so to look at the right wavebands. Here we might as well summarise three most relevant cases:

People are asleep – look at waves lower that alpha (3-8 Hz);
People are awaked/having light to focus brain activities – look at beta (13-30Hz);
People are in between being awake and falling asleep – look at alpha (8-12Hz).

This partly explained the slightly confusing situation that some of the previous studies found their most significant results in different waves. As research was carried out in various conditions and the participants were in different state, it could show a different picture in EEG results.

In this research, specifically, the context is ‘people doing reading in the evening’. It turned out we found most significant results in beta power. Although we tried to put experiment later at night, it was still quite a while before people’s bedtime. And more importantly, they were doing reading throughout the experiment. Now it is not difficult to understand why beta is the best one to look at. Beta power is likely to be the most relevant in this condition.

Instead alpha power can be vague. Alpha is special because it is in between theta and beta who might show different power change trend. That is why we also tried splitting alpha into lower and higher parts to figure out something more.

What EEG cannot tell us about alertness

The impact of colour and light on alertness is controversial partly because of the confusion between three domains: physical, physiological and psychological. Light reaching the retina might affect brain in multiple ways and it is difficult to determine the underlying mechanisms. However, it needs to be clarified that these - physical, physiological and psychological - are the pathways that contribute to light-induce alertness. Alertness fluctuation recorded by EEG could be caused via any of these pathways. EEG is not able to tell us about these underlying mechanisms, instead it only shows us the ultimate outcome - alertness change.

7.3 Further Work

Studies have suggested that light could affect alertness without affecting melatonin. If we are to associate the alerting effect with affecting sleep – especially circadian rhythm, melatonin is the marker to look at. Results in this research showed that lights have an impact on alertness. This however should not be related to sleep interruption, as we did not measure melatonin.

Further work could be done to explore the relations between alertness change and sleep interruption. Melatonin measurement along with performance tests can be used besides EEG evaluation.

Another question is on threshold light levels that required to produce alerting effect. In this research we also tried to explore on this matter. There are actually many aspects related to this question, including timing, illuminance levels, exposure duration and wavelength distribution of lights. With the aim to better understand the relations between these parameters and alerting responses of human, further work can be done to explore how these factors affect light-induced alerting effects.

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Appendix A

Munich ChronoType Questionnaire (MCTQ)

Instructions:
In this questionnaire, you report on your typical sleep behaviour over the past 4 weeks. We ask about work days and work-free days separately. Please respond to the questions according to your perception of a standard week that includes your usual work days and work-free days.

Personal Data

Date: _____

Name: _____

eMail: _____

Age: _____ years

Sex: female ☐ male ☐

Height: _____ cm

Weight: _____ kg

Country: _____

City: _____

Postal Code: _____

Participant ID:

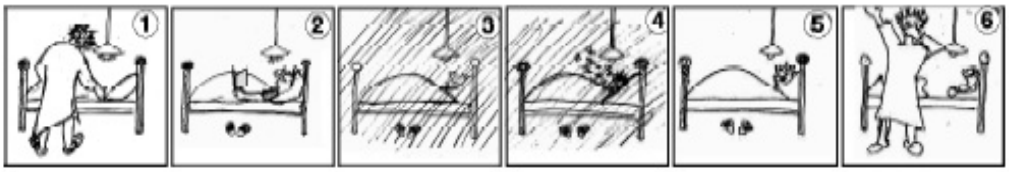
MCTQ

I have a regular work schedule (this includes being, for example, a housewife or househusband):

Yes ☐ I work on 1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ day(s) per week.

No ☐

Is your answer "*Yes, on 7 days*" or "*No*", please consider if your sleep times may nonetheless differ between regular 'workdays' and 'weekend days' and fill out the MCTQ in this respect.



Please use 24-hour time scale (e.g. 23:00 instead of 11:00 pm)!

Workdays

Image 1: I go to bed at _____ o'clock.

Image 2: Note that some people stay awake for some time when in bed!

Image 3: I actually get ready to fall asleep at _____ o'clock.

Image 4: I need _____ minutes to fall asleep.

Image 5: I wake up at _____ o'clock.

Image 6: After _____ minutes I get up.

I use an alarm clock on workdays: Yes ☐ No ☐

If "Yes": I regularly wake up BEFORE the alarm rings: Yes ☐ No ☐

Free Days

Image 1: I go to bed at _____ o'clock.

Image 2: Note that some people stay awake for some time when in bed!

Image 3: I actually get ready to fall asleep at _____ o'clock.

Image 4: I need _____ minutes to fall asleep.

Image 5: I wake up at _____ o'clock.

Image 6: After _____ minutes I get up.

My wake-up time (Image 5) is due to the use of an alarm clock: Yes ☐ No ☐

There are particular reasons why I cannot freely choose my sleep times on free days:

Yes ☐ If "Yes": Child(ren)/pet(s) ☐ Hobbies ☐ Others ☐, for example:_____

No ☐

Participant ID:

Work Details

In the last 3 months, I worked as a shift worker.

No ☐ Yes ☐ (please continue with "*My work schedules are ...*").

My usual work schedule …

… starts at _____ o´clock.

… ends at _____ o´clock.

My work schedules are …

… very flexible ☐ … a little flexible ☐ … rather inflexible ☐ … very inflexible ☐

I travel to work …

… within an enclosed vehicle (e.g. car, bus, underground). ☐

… not within an enclosed vehicle (e.g. on foot, by bike). ☐

I work at home. ☐

For the commute to work, I need ___ hours and ___ minutes.

For the commute from work, I need ___ hours and ___ minutes.

Time Spent Outdoors

On average, I spend the following amount of time outdoors in daylight (without a roof above my head):

on workdays: _____ hours _____ minutes

on free days: _____ hours _____ minutes

Stimulants

Please give approximate/average amounts!

		per →	day	/ week	/ month
I smoke	_____ cigarettes ...		☐	☐	☐
I drink	_____ glasses of beer ...		☐	☐	☐
I drink	_____ glasses of wine ...		☐	☐	☐
I drink	_____ glasses of liquor/whiskey/gin etc. ...		☐	☐	☐
I drink	_____ cups of coffee ...		☐	☐	☐
I drink	_____ cups of black tea ...		☐	☐	☐
I drink	_____ cans of caffeinated drinks (soft-drinks) ...		☐	☐	☐
I take sleep medication _____ times ...			☐	☐	☐

Appendix B

Participant Information & Questionnaire

Name _____

Age _____

Sex female □ male □

Bed time : I recently go to bed at around ____ pm.

Rise time: I recently wake up at around ____ am.

	per day/ week/ month
I smoke _____ cigarettes	□ □ □
I drink _____ glasses of beer/wine	□ □ □
I drink _____ cups of coffee	□ □ □

*Please give approximate/average amounts.

Participant ID:

Appendix C

1. Karolinska Sleepiness Scale (KSS)

Please write down the number of the description that best indicate your sleepiness right now:

1 extremely alert

2 very alert

3 alert

4 rather alert

5 neither alert nor sleepy

6 some signs of sleepiness

7 sleepy, but no effort to keep awake

8 sleepy, some effort to keep awake

9 very sleepy, great effort to keep awake, fighting sleep

2. How bright the light do you feel?

Please score the brightness of the light as below:

Dim 1 2 3 4 5 6 7 8 9 10 Extremely bright

Appendix D

Evaluation of the Alertness Effect of Light on Humans

Date 30/3/2017

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

- This study aims to evaluate how different lights affect people's alertness. Around 5 participants with normal colour vision will take part in the research.

- It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time without it affecting any benefits that you are entitled to in any way. You do not have to give a reason.

- You will be asked to do this experiment twice at about the same time slot in the day. Each experiment will take around an hour. You are asked not to take alcohol or caffeine from three hours prior to the experiment.
In each experiment you will be spending 35 minutes reading a book in the lighting room. You will be wearing an EEG device through out the session (this will record your brain activity and can inform us how tired or alert you are) and the use of phone/tablet or any other self-luminous electronic devices is strictly not allowed.

- All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any reports or publications.
- At request, you will be given a copy of the information sheet to keep. Further information please E-mail Jing Lin at cm14jl@leeds.ac.uk. Thank you for taking the time to read through the information.

Evaluation of the Alertness Effect of Blue Light on Humans

Date 11/9/2018

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will

involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

- This study aims to evaluate how blue lights of different intensities affect people's alertness. Around 10 participants with normal colour vision will take part in the research.

- You will be asked to do this experiment three times at about the same time slot in the evening. Each experimental session will take around 70 minutes. You are asked not to take alcohol or caffeine from three hours prior to the experiment.
In each session you will be spending the whole time reading books in the lighting room. You will be wearing an EEG device throughout the session (to record your brain activity) and the use of phone/tablet or any other self-luminous electronic devices is strictly not allowed. Every 20 minutes you will be asked to fill a questionnaire. You are allowed to drink water during the session but not any other liquid or food. You will be allowed to go to toilet when in need.

- It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time without it affecting any benefits that you are entitled to in any way. You do not have to give a reason. All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any reports or publications. At request, you will be given a copy of the information sheet to keep. Further information please E-mail Jing Lin at cm14jl@leeds.ac.uk. Thank you for taking the time to read through the information.

Evaluation of the Alertness Effect of Red Light on Humans

Date 28/8/2019

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

- This study aims to evaluate how red lights of different intensities affect people's alertness. Around 8 participants with normal colour vision will take part in the research.

- You will be asked to do this experiment twice at about the same time slot in the evening. Each experimental session will take around 60 minutes. You are asked not to take alcohol or caffeine from three hours prior to the experiment.
In each session you will be spending the whole time reading books in the lighting room. You will be wearing an EEG device throughout the session (to record your brain activity) and the use of phone/tablet or any other self-luminous electronic devices is strictly not allowed. Every 20 minutes you will be asked to fill a questionnaire. You are allowed to drink water during the session but not any other liquid or food. You will be allowed to go to toilet when in need.

- It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time without it affecting any benefits that you are entitled to in any way. You do not have to give a reason. All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any reports or publications. At request, you will be given a copy of the information sheet to keep. Further information please E-mail Jing Lin at cm14jl@leeds.ac.uk. Thank you for taking the time to read through the information.

Appendix E

Consent to take part in:

Evaluation of the Alertness Effect of Red Light on Humans

	Add your initials next to the statements you agree with
I confirm that I have read and understand the information sheet dated 28/8/2019 explaining the above research project and I have had the opportunity to ask questions about the project.	
I agree for the data collected from me to be stored and used in relevant future research in an anonymised form.	
I understand that relevant sections of the data collected during the study, may be looked at by auditors from the University of Leeds or from regulatory authorities where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	
I agree to take part in the above research project and will inform the lead researcher should my contact details change during the project and, if necessary, afterwards.	

Name of participant	
Participant's signature	
Date	
Name of lead researcher	Jing Lin
Signature	
Date*	

*To be signed and dated in the presence of the participant.

Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the letter/ pre-written script/ information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be kept with the project's main documents which must be kept in a secure location.

Faculty of Arts, Humanities and Cultures Research Ethics Committee
University of Leeds

21 April 2017

Dear Jing

Title of study Evaluation of the Alertness Effect of Light on Human
Ethics reference LTDESN-068

I am pleased to inform you that the above research application has been reviewed by the Faculty of Arts, Humanities and Cultures Research Ethics Committee and I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	*Version*	*Date*
LTDESN-068 Consent-Jing.pdf	1	31/03/2017
LTDESN-068 Information Sheet-Jing.pdf	1	31/03/2017
LTDESN-068 LightTouchEthicsForm - jing.doc	1	31/03/2017

Please notify the committee if you intend to make any amendments to the information in your ethics application as submitted at date of this approval as all changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation and other documents relating to the study, including any risk assessments. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Victoria Butterworth
Research Ethics Administrator, Research & Innovation Service
On behalf of Dr Kevin Macnish, Chair, PVAR FREC

CC: Student's supervisor

Arts, Humanities and Cultures Faculty Research Ethics Committee
University of Leeds

8 October 2018

Dear Jing,

Title of study: **Evaluation of the Alertness Effect of Blue Light on Humans**
Ethics reference: **LTDESN-094**

I am pleased to inform you that the above application for light touch ethical review has been reviewed by a representative of the Arts, Humanities and Cultures Faculty Research Ethics Committee and, following receipt of your response to their initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
LTDESN-094 further information requested.txt	1	27/09/2018
LTDESN-094 consent_formlowrisk.doc	2	28/09/2018
LTDESN-094 info sheet.docx	2	28/09/2018
LTDESN-094 LightTouchEthicsForm - jing.doc	2	28/09/2018

Please notify the committee if you intend to make any amendments to the original research as submitted at date of this approval, including changes to recruitment methodology. All changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation, as well as other documents relating to the study. You will be given a two week notice period if your project is to be audited, there is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Prof Robert Jones, Chair, AHC FREC
CC: Prof Stephen Westland

Arts, Humanities and Cultures Faculty Research Ethics Committee
University of Leeds

19 September 2019

Dear Jing,

Title of study: **Evaluation of the Alertness Effect of Red Light on Humans**
Ethics reference: **LTDESN-113**

I am pleased to inform you that the above application for proportionate (light touch) ethical review has been reviewed by a representative of the Arts, Humanities and Cultures Faculty Research Ethics Committee and I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
LTDESN-113 LightTouchEthicsForm - jing.doc	1	29/08/2019
LTDESN-113 info sheet.docx	1	29/08/2019
LTDESN-113 consent_formlowrisk.doc	1	29/08/2019

Please notify the committee if you intend to make any amendments to the original research as submitted at date of this approval, including changes to recruitment methodology. All changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation, as well as other documents relating to the study. You will be given a two week notice period if your project is to be audited, there is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Prof Robert Jones, Chair, AHC FREC
CC: Professor Stephen Westland

Appendix F

relative spectral power of lights in study 1

Wavelength(nm)	Blue	Green	White
380	0.0077	0.0078	0.0052
385	0.0047	0.0052	0.0040
390	0.0019	0.0029	0.0030
395	0.0015	0.0043	0.0096
400	0.0011	0.0054	0.0157
405	0.0040	0.0166	0.0482
410	0.0068	0.0279	0.0813
415	0.0273	0.0468	0.1329
420	0.0477	0.0656	0.1845
425	0.1655	0.0687	0.1716
430	0.2830	0.0718	0.1590
435	0.7049	0.0725	0.1477
440	1.1124	0.0718	0.1334
445	1.8237	0.0763	0.1356
450	2.5335	0.0808	0.1379
455	2.7888	0.0661	0.1367
460	3.0728	0.0521	0.1370
465	3.3527	0.0434	0.1684
470	3.6484	0.0348	0.2007
475	3.4089	0.0395	0.2052
480	3.1637	0.0440	0.2094
485	2.3256	0.0744	0.1661
490	1.5309	0.1063	0.1260
495	1.0766	0.1975	0.1173
500	0.6179	0.2888	0.1084
505	0.4256	0.4444	0.1314
510	0.2339	0.5995	0.1542
515	0.1628	0.7644	0.1786
520	0.0885	0.9151	0.1997
525	0.0613	0.9824	0.1994
530	0.0340	1.0500	0.1991
535	0.0243	1.0341	0.1889
540	0.0147	1.0211	0.1794
545	0.0112	1.0047	0.1723
550	0.0077	0.9861	0.1647
555	0.0062	0.9686	0.1601
560	0.0048	0.9623	0.1574
565	0.0039	0.9486	0.1559

570	0.0029	0.9236	0.1526
575	0.0032	0.9250	0.1581
580	0.0034	0.9194	0.1625
585	0.0034	0.9119	0.1705
590	0.0033	0.8986	0.1773
595	0.0030	0.8550	0.1658
600	0.0026	0.8105	0.1540
605	0.0036	0.7602	0.1410
610	0.0047	0.7225	0.1302
615	0.0047	0.7032	0.1262
620	0.0048	0.6867	0.1226
625	0.0041	0.7119	0.1253
630	0.0035	0.7359	0.1277
635	0.0039	0.7220	0.1386
640	0.0043	0.7130	0.1506
645	0.0047	0.7141	0.1862
650	0.0052	0.7235	0.2238
655	0.0062	0.6730	0.2144
660	0.0069	0.6103	0.2011
665	0.0072	0.4488	0.1379
670	0.0076	0.2924	0.0764
675	0.0096	0.2402	0.0601
680	0.0116	0.1863	0.0434
685	0.0111	0.1647	0.0383
690	0.0102	0.1364	0.0316
695	0.0101	0.1238	0.0290
700	0.0097	0.1061	0.0252
705	0.0093	0.0919	0.0220
710	0.0091	0.0808	0.0195
715	0.0069	0.0714	0.0161
720	0.0048	0.0636	0.0129
725	0.0051	0.0590	0.0113
730	0.0054	0.0536	0.0095

relative spectral power of lights in study 2

wavelength(nm)	40 lx	80 lx	160 lx	dim
380	0.0026	0.0039	0.0091	0.0043
385	0.0025	0.0028	0.0075	0.0031
390	0.0026	0.0019	0.0063	0.0022
395	0.0029	0.0023	0.0050	0.0028
400	0.0031	0.0026	0.0036	0.0032
405	0.0026	0.0024	0.0037	0.0030

410	0.0022	0.0022	0.0039	0.0027
415	0.0021	0.0028	0.0062	0.0027
420	0.0020	0.0034	0.0085	0.0028
425	0.0044	0.0099	0.0288	0.0032
430	0.0068	0.0164	0.0490	0.0037
435	0.0266	0.0663	0.1799	0.0046
440	0.0459	0.1148	0.3070	0.0055
445	0.1518	0.3667	0.9173	0.0071
450	0.2575	0.6181	1.5263	0.0087
455	0.7300	1.6956	3.8781	0.0081
460	1.2100	2.7907	6.2701	0.0075
465	2.3515	5.1559	10.8999	0.0068
470	3.5022	7.5416	15.5737	0.0061
475	3.6825	7.7032	15.5898	0.0048
480	3.8547	7.8489	15.5752	0.0035
485	2.8861	5.8601	11.6558	0.0037
490	1.9715	3.9811	7.9549	0.0040
495	1.3901	2.8133	5.6469	0.0054
500	0.8032	1.6343	3.3165	0.0067
505	0.5521	1.1269	2.2977	0.0075
510	0.3018	0.6210	1.2821	0.0084
515	0.2096	0.4321	0.8945	0.0093
520	0.1133	0.2348	0.4893	0.0100
525	0.0777	0.1617	0.3382	0.0102
530	0.0421	0.0885	0.1870	0.0105
535	0.0298	0.0625	0.1321	0.0112
540	0.0177	0.0368	0.0780	0.0118
545	0.0130	0.0272	0.0574	0.0126
550	0.0083	0.0175	0.0366	0.0133
555	0.0061	0.0134	0.0282	0.0137
560	0.0040	0.0094	0.0200	0.0143
565	0.0034	0.0079	0.0163	0.0154
570	0.0028	0.0064	0.0123	0.0163
575	0.0029	0.0060	0.0113	0.0185
580	0.0029	0.0055	0.0101	0.0207
585	0.0028	0.0052	0.0095	0.0237
590	0.0026	0.0049	0.0088	0.0264
595	0.0027	0.0043	0.0089	0.0262
600	0.0028	0.0037	0.0089	0.0259
605	0.0027	0.0039	0.0083	0.0256
610	0.0025	0.0042	0.0079	0.0258
615	0.0020	0.0032	0.0077	0.0271
620	0.0014	0.0022	0.0075	0.0285
625	0.0018	0.0027	0.0077	0.0336
630	0.0023	0.0032	0.0079	0.0386
635	0.0019	0.0036	0.0081	0.0427

640	0.0016	0.0042	0.0084	0.0472
645	0.0023	0.0049	0.0093	0.0594
650	0.0030	0.0057	0.0103	0.0723
655	0.0028	0.0056	0.0121	0.0697
660	0.0026	0.0053	0.0137	0.0659
665	0.0036	0.0074	0.0159	0.0442
670	0.0046	0.0097	0.0182	0.0230
675	0.0054	0.0115	0.0216	0.0169
680	0.0062	0.0132	0.0247	0.0108
685	0.0074	0.0144	0.0284	0.0097
690	0.0083	0.0150	0.0309	0.0082
695	0.0077	0.0131	0.0292	0.0084
700	0.0067	0.0106	0.0263	0.0083
705	0.0045	0.0077	0.0232	0.0068
710	0.0025	0.0051	0.0209	0.0054
715	0.0038	0.0054	0.0213	0.0059
720	0.0051	0.0058	0.0222	0.0066
725	0.0040	0.0067	0.0218	0.0059
730	0.0029	0.0075	0.0211	0.0051

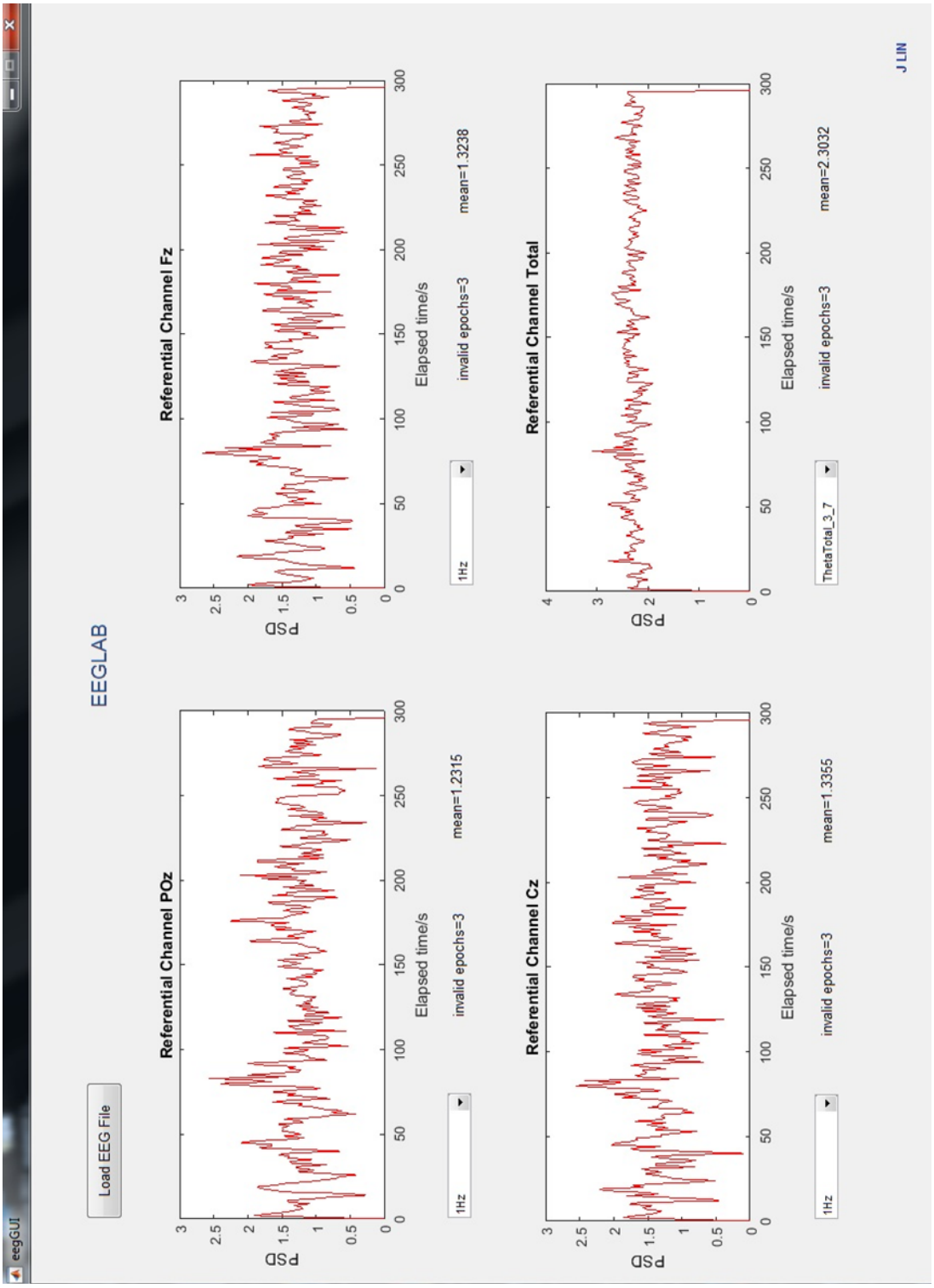
relative spectral power of lights in study 3

wavelength(nm)	40 lx	160 lx
380	0.0012	0.0022
385	0.0011	0.0019
390	0.0010	0.0017
395	0.0009	0.0027
400	0.0009	0.0037
405	0.0027	0.0122
410	0.0046	0.0208
415	0.0162	0.0665
420	0.0277	0.1121
425	0.0536	0.2172
430	0.0795	0.3222
435	0.1156	0.4527
440	0.1518	0.5831
445	0.1724	0.6299
450	0.1930	0.6767
455	0.1576	0.5416
460	0.1222	0.4064
465	0.1005	0.3351
470	0.0789	0.2638
475	0.0789	0.2679

480	0.0788	0.2719
485	0.0952	0.3307
490	0.1116	0.3896
495	0.1340	0.4700
500	0.1564	0.5504
505	0.1766	0.6214
510	0.1968	0.6925
515	0.2115	0.7461
520	0.2263	0.7997
525	0.2410	0.8519
530	0.2556	0.9041
535	0.2734	0.9670
540	0.2911	1.0298
545	0.3119	1.1030
550	0.3326	1.1762
555	0.3554	1.2628
560	0.3782	1.3495
565	0.4042	1.4675
570	0.4302	1.5855
575	0.4598	1.7861
580	0.4894	1.9867
585	0.5264	2.2896
590	0.5634	2.5924
595	0.6242	2.6922
600	0.6850	2.7919
605	0.8195	3.1448
610	0.9541	3.4976
615	1.2763	4.5372
620	1.5986	5.5767
625	2.2334	7.6011
630	2.8682	9.6254
635	2.6625	10.5655
640	2.4569	11.5056
645	1.7048	8.7633
650	0.9527	6.0209
655	0.7026	4.2123
660	0.4525	2.4036
665	0.3744	1.8117
670	0.2963	1.2197
675	0.2580	1.0119
680	0.2196	0.8042
685	0.1922	0.6940
690	0.1648	0.5839
695	0.1439	0.5099
700	0.1229	0.4359
705	0.1079	0.3824

710	0.0929	0.3290
715	0.0816	0.2879
720	0.0704	0.2467
725	0.0616	0.2200
730	0.0528	0.1933

Appendix G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Referential Channel Fz
Referential Channel Cz
Referential Channel Total
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Elapsed time/s
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1Hz
ThetaTotal_3_7
J LIN

Appendix H

relative spectral power of Blue 2

Wavelength(nm)	Blue 2
380	0.0068
385	0.0150
390	0.0240
395	0.1801
400	0.3235
405	1.2447
410	2.1833
420	4.8036
425	3.9452
430	3.0958
435	2.4434
440	1.7430
445	1.8937
450	2.0445
455	1.8307
460	1.6358
465	1.1420
470	0.6546
475	0.4453
480	0.2361
485	0.1793
490	0.1258
495	0.1494
500	0.1728
505	0.2226
510	0.2722
515	0.2620
520	0.2469
525	0.1953
530	0.1437
540	0.0742
545	0.0562
550	0.0379
555	0.0288
560	0.0200
565	0.0153
570	0.0105
575	0.0088
580	0.0070
585	0.0059
590	0.0047
595	0.0045
600	0.0043
605	0.0041
610	0.0039

615	0.0042
620	0.0044
625	0.0056
630	0.0069
635	0.0074
640	0.0079
645	0.0066
650	0.0054
660	0.0040
665	0.0041
670	0.0043
675	0.0063
680	0.0082
685	0.0071
690	0.0057
695	0.0053
700	0.0046
705	0.0056
710	0.0068
715	0.0075
720	0.0084
725	0.0094
730	0.0101

Appendix I

Results for three frequency bins at three intensities for each of four participants

Participant 1

	40 lx			80 lx			160 lx		
time(min)	theta	alpha	beta	theta	alpha	beta	theta	alpha	beta
10	2.39	1.97	1.72	2.40	1.96	1.72	2.46	1.94	1.59
20	2.33	1.93	1.68	2.34	1.99	1.79	2.47	1.95	1.63
30	2.23	1.98	1.78	2.46	2.08	1.81	2.44	2.00	1.66
40	2.24	2.00	1.83	2.44	2.05	1.80	2.41	2.01	1.77
50	2.26	2.06	1.93	2.34	1.99	1.81	2.34	2.21	2.00
60	2.26	2.08	1.98	2.37	2.06	1.93	2.34	2.18	2.01
70	2.30	2.11	1.95	2.33	2.07	1.97	2.32	2.13	1.96
80	2.33	2.15	2.01	2.37	2.13	2.00	2.35	2.05	1.85
90	2.29	2.04	1.88	2.36	2.05	1.96	2.34	2.20	2.06
100	2.22	2.13	2.10	2.38	2.15	2.06	2.32	2.08	1.90
110	2.29	2.08	1.91	2.32	2.09	2.02	2.30	1.99	1.79
120	2.29	2.08	1.95	2.35	1.98	1.81	2.26	1.99	1.79

Participant 2

	40 lx			80 lx			160 lx		
time(min)	theta	alpha	beta	theta	alpha	beta	theta	alpha	beta
10	2.35	2.07	1.65	2.21	1.97	1.62	2.27	2.02	1.69
20	2.32	2.06	1.67	2.19	1.94	1.61	2.29	2.05	1.72
30	2.32	2.04	1.65	2.22	1.97	1.67	2.34	2.07	1.72
40	2.34	2.04	1.66	2.29	2.04	1.73	2.36	2.09	1.77
50	2.31	2.03	1.65	2.22	1.96	1.68	2.33	2.09	1.76
60	2.35	2.09	1.72	2.25	2.00	1.71	2.37	2.15	1.80
70	2.32	2.07	1.68	2.27	1.98	1.69	2.31	2.06	1.70
80	2.35	2.09	1.71	2.25	1.97	1.68	2.34	2.13	1.80
90	2.34	2.12	1.77	2.21	2.07	1.60	2.35	2.11	1.76
100	2.36	2.10	1.76	2.19	1.97	1.66	2.34	2.08	1.72
110	2.34	2.07	1.72	2.25	2.00	1.67	2.38	2.10	1.76
120	2.33	2.13	1.76	2.24	2.03	1.71	2.35	2.10	1.74

Participant 3

40 lx	80 lx	160 lx

time(min)	theta	alpha	beta	theta	alpha	beta	theta	alpha	beta
10	2.46	2.48	1.98	2.41	2.19	1.82	2.28	2.17	1.81
20	2.69	2.34	1.74	2.39	2.23	1.90	2.29	2.32	2.02
30	2.37	2.34	1.98	2.36	2.22	1.87	2.29	2.17	1.76
40	2.35	2.30	1.95	2.35	2.14	1.81	2.31	2.33	2.01
50	2.33	2.24	1.85	2.30	2.11	1.74	2.27	2.26	1.91
60	2.37	2.30	1.86	2.32	2.16	1.81	2.31	2.29	1.89
70	2.34	2.19	1.77	2.34	2.18	1.82	2.29	2.18	1.79
80	2.36	2.38	2.05	2.32	2.26	2.00	2.29	2.22	1.87
90	2.32	2.43	2.10	2.30	2.18	1.84	2.27	2.28	1.86
100	2.36	2.45	2.14	2.30	2.11	1.73	2.32	2.31	2.01
110	2.37	2.44	2.11	2.27	2.05	1.59	2.32	2.15	1.78
120	2.31	2.27	1.83	2.24	2.05	1.60	2.37	2.17	1.83

Participant 4

	40 lx			80 lx			160 lx		
time(min)	theta	alpha	beta	theta	alpha	beta	theta	alpha	beta
10	2.39	2.34	2.11	2.50	2.43	2.17	2.53	2.56	2.25
20	2.34	2.34	2.06	2.56	2.47	2.22	2.50	2.48	2.21
30	2.47	2.42	2.17	2.56	2.55	2.31	2.47	2.54	2.28
40	2.55	2.46	2.18	2.56	2.57	2.32	2.43	2.50	2.24
50	2.57	2.62	2.37	2.62	2.60	2.31	2.40	2.55	2.25
60	2.54	2.61	2.36	2.58	2.63	2.32	2.44	2.54	2.33
70	2.54	2.59	2.36	2.57	2.56	2.27	2.45	2.56	2.30
80	2.56	2.63	2.42	2.57	2.62	2.42	2.42	2.54	2.34
90	2.50	2.53	2.24	2.53	2.55	2.31	2.34	2.50	2.25
100	2.64	2.69	2.45	2.42	2.53	2.18	2.38	2.52	2.29
110	2.63	2.73	2.51	2.50	2.57	2.32	2.42	2.59	2.35
120	2.63	2.73	2.51	2.50	2.55	2.23	2.47	2.68	2.56

Results for three frequency bins at each light condition

	40 lx			80 lx			160 lx		
time(min)	theta	alpha	beta	theta	alpha	beta	theta	alpha	beta
10	2.40	2.22	1.86	2.38	2.14	1.83	2.38	2.17	1.84
20	2.42	2.17	1.79	2.37	2.16	1.88	2.39	2.20	1.90
30	2.35	2.19	1.89	2.40	2.21	1.91	2.39	2.19	1.85
40	2.37	2.20	1.91	2.41	2.20	1.92	2.37	2.23	1.95
50	2.37	2.24	1.95	2.37	2.16	1.88	2.34	2.28	1.98
60	2.38	2.27	1.98	2.38	2.21	1.94	2.36	2.29	2.01

70	2.38	2.24	1.94	2.38	2.20	1.94	2.34	2.23	1.94
80	2.40	2.31	2.04	2.38	2.25	2.03	2.35	2.24	1.97
90	2.36	2.28	2.00	2.35	2.21	1.93	2.32	2.27	1.98
100	2.39	2.34	2.11	2.32	2.19	1.91	2.34	2.25	1.98
110	2.41	2.33	2.06	2.34	2.18	1.90	2.36	2.21	1.92
120	2.39	2.30	2.01	2.33	2.15	1.84	2.36	2.24	1.98

Results for three light conditions at each frequency bin

	theta			alpha			beta		
time(min)	40 lx	80 lx	160 lx	40 lx	80 lx	160 lx	40 lx	80 lx	160 lx
10	2.39	2.38	2.38	2.22	2.14	2.17	1.86	1.83	1.84
20	2.42	2.37	2.39	2.17	2.16	2.20	1.79	1.88	1.90
30	2.37	2.40	2.39	2.19	2.21	2.19	1.89	1.91	1.85
40	2.39	2.41	2.37	2.20	2.20	2.23	1.91	1.92	1.95
50	2.38	2.37	2.34	2.24	2.16	2.28	1.95	1.88	1.98
60	2.40	2.38	2.36	2.27	2.21	2.29	1.98	1.94	2.01
70	2.38	2.38	2.34	2.24	2.20	2.23	1.94	1.94	1.94
80	2.40	2.38	2.35	2.31	2.25	2.24	2.04	2.03	1.97
90	2.38	2.35	2.32	2.28	2.21	2.27	2.00	1.93	1.98
100	2.43	2.32	2.34	2.34	2.19	2.25	2.11	1.91	1.98
110	2.42	2.34	2.36	2.33	2.18	2.21	2.06	1.90	1.92
120	2.40	2.33	2.36	2.30	2.15	2.24	2.01	1.84	1.98

Mean power pooled over all participants and light intensity levels

time(min)		SEM
10	2.13	0.05
20	2.14	0.05
30	2.16	0.05
40	2.18	0.04
50	2.18	0.05
60	2.21	0.04
70	2.18	0.04
80	2.22	0.04
90	2.19	0.04
100	2.21	0.04
110	2.19	0.05
120	2.18	0.05

Mean normalised KSS scores

	Score	SEM
Dim	1.12	0.10
40 lx	0.90	0.13
80 lx	0.91	0.14
160 lx	0.68	0.10

Individual KSS scores

Participant	1	2	3	4	5	6	7	8
Dim	1.08	1.00	0.75	1.07	1.00	1.42	1.50	1.00
40 lx	1.17	0.90	0.56	0.50	0.90	0.86	0.86	1.75
80 lx	1.40	0.70	0.83	1.50	0.50	0.57	0.58	1.50
160 lx	1.17	0.30	0.71	0.75	0.50	0.63	1.00	1.00

Normalised brightness scores

		SEM
Dim	2.10	0.34
40 lx	2.33	0.52
80 lx	3.11	0.69
160 lx	1.18	0.11

Individual brightness scores

Participant	1	2	3	4	5	6	7	8
Dim	1.33	1.00	1.33	1.00	1.00	1.17	0.75	1.67
40 lx	3.00	5.50	2.75	0.90	1.75	1.83	1.50	1.38
80 lx	3.00	5.50	6.50	0.90	1.75	3.25	1.83	2.17
160 lx	2.50	4.00	1.33	0.90	2.50	2.25	1.50	1.83

Appendix J

Beta power change by minute for five conditions

time(min)	dim	R40	B40	B80	R160	B160
1	2.08	1.99	2.00	1.94	1.91	2.01
2	2.12	2.01	1.97	1.94	1.96	2.03
3	2.08	2.02	2.01	1.96	1.93	2.02
4	2.09	1.96	1.99	2.04	1.99	2.04
5	2.01	1.98	2.05	2.01	1.99	2.06
6	2.05	2.00	2.07	2.01	1.98	2.07
7	2.05	2.00	2.09	2.04	2.00	2.07
8	2.08	2.01	2.12	2.05	2.01	1.98
9	2.09	1.98	2.09	2.02	2.00	2.07
10	2.05	1.97	2.06	2.01	2.06	2.03
11	2.09	1.95	2.18	1.99	2.06	2.06
12	2.06	1.95	2.12	2.04	2.09	2.01
13	2.10	1.93	2.11	2.05	2.05	2.02
14	2.05	1.94	2.06	2.05	2.05	2.03
15	2.08	2.03	2.06	2.04	2.01	2.05
16	2.07	1.94	2.03	2.05	2.05	2.03
17	2.05	2.00	2.08	2.05	2.02	2.03
18	2.07	2.07	2.01	2.00	2.08	2.05
19	2.06	2.08	2.00	2.04	2.03	2.08
20	2.07	2.04	2.04	2.06	2.08	2.12
21	2.07	2.01	2.04	2.08	2.06	2.17
22	2.08	2.06	2.05	2.13	2.02	2.16
23	2.04	2.04	2.09	2.15	2.08	2.11
24	2.05	2.07	2.09	2.11	2.13	2.18
25	1.93	2.09	2.15	2.08	2.15	2.19
26	2.00	2.11	2.11	2.04	2.12	2.14
27	2.01	2.07	2.03	2.07	2.15	2.16
28	2.05	2.04	1.93	2.04	2.13	2.16
29	2.02	2.01	1.97	2.08	2.13	2.15
30	2.06	2.04	2.06	2.08	2.12	2.15
31	2.08	2.09	2.08	2.09	2.13	2.14
32	2.12	2.13	2.03	2.06	2.09	2.14
33	2.09	2.17	2.03	2.09	2.09	2.18
34	2.11	2.11	2.06	2.11	2.09	2.19
35	2.12	2.11	2.04	2.10	2.04	2.16

36	2.10	2.12	2.09	2.12	2.04	2.13
37	2.12	2.18	2.07	2.06	2.08	2.13
38	2.13	2.12	2.00	2.08	2.10	2.15
39	2.11	2.08	2.02	2.05	2.13	2.17
40	2.13	2.16	2.04	2.07	2.10	2.15
41	2.17	2.19	2.09	2.12	2.08	2.12
42	2.15	2.12	2.07	2.11	2.13	2.15
43	2.11	2.06	2.12	2.07	2.15	2.15
44	2.02	2.09	2.04	2.12	2.10	2.16
45	2.07	2.11	2.03	2.12	2.14	2.20
46	2.17	2.16	2.07	2.10	2.17	2.18
47	2.18	2.20	2.19	2.15	2.11	2.13
48	2.07	2.12	2.14	2.16	2.07	2.17
49	2.14	2.20	2.15	2.05	2.14	2.11
50	2.16	2.14	2.17	2.07	2.09	2.11
51	2.12	2.11	2.10	2.03	2.11	2.15
52	2.08	2.08	2.22	2.10	2.13	2.25
53	2.11	2.15	2.11	2.10	2.12	2.21
54	2.08	2.19	2.10	2.07	2.11	2.24
55	2.06	2.18	2.07	2.05	2.13	2.16
56	2.10	2.19	1.99	2.08	2.17	2.13
57	2.11	2.17	2.06	2.08	2.15	2.18
58	2.14	2.17	2.15	2.08	2.16	2.15
59	2.12	2.17	2.07	2.04	2.13	2.12
60	2.13	2.19	2.13	2.05	2.14	2.08

Beta power change by 5-minute for five conditions

time(min)	dim	R40	B40	B80	R160	B160
5	2.04	1.98	2.03	1.98	1.95	2.03
10	2.05	1.98	2.06	2.01	2.02	2.05
15	2.09	1.99	2.12	2.02	2.04	2.05
20	2.07	1.99	2.03	2.06	2.06	2.08
25	2.00	2.05	2.09	2.08	2.11	2.18
30	2.03	2.07	2.08	2.06	2.12	2.15
35	2.10	2.10	2.06	2.09	2.09	2.15
40	2.12	2.14	2.07	2.10	2.07	2.14
45	2.12	2.15	2.06	2.12	2.11	2.16
50	2.17	2.15	2.12	2.08	2.13	2.14
55	2.09	2.15	2.08	2.04	2.12	2.15
60	2.12	2.19	2.06	2.06	2.15	2.11

Beta power change by 10-minute for five conditions

time(min)	dim	R40	B40	B80	R160	B160
10	2.05	1.98	2.05	1.99	1.99	2.04
20	2.08	1.99	2.08	2.04	2.05	2.07
30	2.02	2.06	2.09	2.07	2.11	2.16
40	2.11	2.12	2.07	2.10	2.08	2.14
50	2.14	2.15	2.09	2.10	2.12	2.15
60	2.11	2.17	2.07	2.05	2.14	2.13

Normalised EEG power for three frequencies

	Dim	B40 lx	B80 lx	B160 lx	R40	R160
theta_alpha	1.02	1.00	1.01	1.00	1.02	1.02
alpha	1.01	1.00	1.00	1.01	1.04	1.03
beta	0.98	0.99	1.01	1.07	1.06	1.05

SEM	Dim	B40 lx	B80 lx	B160 lx	R40	R160
theta_alpha	0.01	0.01	0.01	0.01	0.01	0.01
alpha	0.01	0.02	0.01	0.02	0.02	0.01
beta	0.01	0.02	0.01	0.02	0.03	0.02

Individual EEG power values in beta range

participant	1	2	3	4	5	6	7	8
40 lx	1.09	1.19	0.98	1.01	1.11	1.14	1.00	0.99
160 lx	1.03	1.11	1.04	1.06	1.08	1.12	0.99	1.01
dim	0.91	1.01	1.03	0.97	0.96	0.97	1.01	0.98

Normalised EEG power for four frequencies

	theta_alpha	l_alpha	h_alpha	beta
Dim	1.02	1.02	1.00	0.98
R40 lx	1.02	1.03	1.05	1.06
R160 lx	1.02	1.02	1.04	1.05

SEM	theta_alpha	l_alpha	h_alpha	beta
dim	0.01	0.01	0.01	0.01

R40 lx	0.01	0.02	0.02	0.03
R160 lx	0.01	0.01	0.01	0.02

Mean normalised KSS scores

	score	SEM
Dim	1.12	0.09
B160 lx	0.68	0.10
R40 lx	0.60	0.09
R160 lx	0.65	0.08

Individual KSS scores

participant	dim	40 lx	160 lx
1	1.08	0.83	0.63
2	0.79	0.80	0.75
3	0.75	1.00	0.80
4	1.07	0.50	1.00
5	1.00	0.31	0.17
6	1.42	0.33	0.67
7	1.50	0.50	0.58
8	1.00	0.50	0.64

Mean normalised brightness scores

	score	SEM
Dim	1.18	0.11
40 lx	2.51	0.28
160 lx	2.76	0.41

Individual brightness scores

participants	dim	40 lx	160 lx
1	1.33	1.88	2.50
2	1.00	3.50	4.50
3	1.33	3.75	2.67
4	1.00	1.50	1.38
5	1.00	2.33	4.50

6	1.17	2.75	2.50
7	0.75	2.17	2.17
8	1.67	2.17	1.83