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Revisiting the alerting effect of light; a systematic review

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Alerting effect of light

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Summary

Light plays an essential role in maintaining alertness levels. Like other non-image-forming responses, the alerting effect of light is influenced by its spectral wavelength, duration and intensity. Alertness levels are also dependent on circadian rhythm (Process C) and homeostatic sleep pressure (Process S), consistent with the classic two-process model of sleep regulation. Over the last decade, there has been increasing recognition of an additional process (referred to as the third process) in sleep regulation. This third process seems to receive sensory inputs from body systems such as digestion, and is usually synchronised with Process C and Process S. Previous studies on the alerting effect of light have been mostly conducted in laboratories. Although these studies are helpful in delineating the impact of Process C and Process S, their ability to assist in understanding the third process is limited. This systematic review investigated the factors that influence the alerting effect of light by examining randomized controlled trials and randomized or counterbalanced crossover studies. Factors that influence light's alerting effect were examined with reference to the three-process model. The post-illuminance alerting effect was examined separately due to its potential to offer flexible workplace-based light interventions to increase or maintain employees' alertness.

Keywords

Short wavelength light; intensity; sleepiness; alertness; circadian system, post-illuminance; three-process model

Abbreviation list

- EEG** Electroencephalogram
- ipRGC** Intrinsically photosensitive retinal ganglion cells
- KSS** Karolinska sleepiness scale
- KGS** Kwansai Gakuin sleepiness scale
- MSLT** Multiple sleep latency test
- MWT** Maintenance of wakefulness test

NIF	Non-image-forming
PSG	Polysomnography
RCT	Randomized controlled trial
SCN	Suprachiasmatic nucleus
SEM	Slow eye movements
SSS	Stanford sleepiness scale
VAS	Visual analogue scale

Introduction

As one of the most powerful environmental stimuli, light's impact on humans extends beyond its classic visual function to other brain functions. These other brain functions are referred to as non-image-forming (NIF) responses to separate them from the classic visual responses to light. Examples of NIF responses include circadian rhythm phase shifting [1, 2], pupillary reflexes [3], mood changes [4], acute melatonin suppression [5, 6], improved cognitive function [7, 8] and the promotion of alertness levels [7, 9, 10]. Over the last decade [7, 11, 12], there has been growing interest in understanding the neurophysiological pathways via which light influences alertness levels, partly due to its potential to be applied in real world settings as a countermeasure for sleepiness.

Central to the physiology of light's NIF responses, including light's alerting effect, are the intrinsically photosensitive retinal ganglion cells (ipRGC) located in the retina. Although these ipRGCs only account for 1-5% of the total ganglion cells [13], their role in light's NIF responses is fundamental and is independent of the classic visual system. For example, in completely blind participants, light is able to modulate electroencephalogram (EEG) activity and impact the subcortical areas that regulate alertness levels when participants are engaged in cognitive tasks [14]. ipRGCs primarily receive input from melanopsin, an ipRGC expressed photoreceptor [15], but also receive input from rod-cone networks [13]. Rods and cones are most sensitive to medium and long wavelength light, whereas

melanopsin photoreceptors have a maximum sensitivity to short wavelength light of 480nm (blue light) [13]. Predictably, blue light has been found to have a greater influence on the thalamus and the frontal and parietal cortical areas than green and violet light [8, 16]. In addition to wavelength, the alerting effect of light is also associated with the duration and intensity of light exposure. For instance, a dose-response relationship between light intensity and its alerting effect has been observed during biological night (11pm-7am for normal chronotypes) [17]. Furthermore, a longer duration of white intense light is predictive of larger brain activation [18]. Collectively, previous studies have clearly demonstrated the importance of light's physical properties in promoting alertness levels; however, light's alerting effect must also be considered within a broad sleep regulation framework.

The earliest and most tested model of sleep regulation is the two-process model, which comprises two separate processes [19]. Process C, representing the circadian rhythm, is usually high during the day to facilitate activity and low during biological night to facilitate sleep. Process S, representing sleep debt, increases during wakefulness and decreases during sleep. In this original model, these two processes interact only at discrete time points. The authors of the two-process model acknowledge that this model does not incorporate some of the complexities that have been discovered since its conception [19]. One complexity is the continuous and non-linear interaction between Process C and Process S, which allows immediate reciprocal feedback between these two processes. The other complexity is the non-Suprachiasmatic nucleus (SCN) oscillator that is linked to metabolic rate, which is further influenced by factors such as food intake and energy consumption. This non-SCN oscillator is usually synchronised with the central SCN clock, but can be desynchronised under certain conditions [19]. This continuous interaction between Process C and Process S was also recognised by another group of researchers led by Hubbard [11], who postulated a three-process conceptual framework of sleep regulation – that is, Process C, Process S and a direct effect – following their review of studies on transgenic mice. The direct effect in Hubbard et al.'s model refers to the direct effect of light on sleep that is independent of, but interacts with, circadian rhythm. The

idea of an additional process to Process C and S in regulating sleep was also proposed by Johns [20], who developed a similar conceptual framework. In Johns' framework, this additional process is expressed as Process A, which works with Process C and Process S in regulating sleepiness. Process A represents an afferent process, integrating sensory inputs from body systems e.g. postural muscles [20]. Although different terms have been used by these researchers, all three groups suggest a new and independent process to Process C and Process S in regulating sleep. This new process seems to encompass a range of endogenous (e.g. chronotype) and exogenous (e.g. physical activity, food intake) factors that are often eliminated or controlled in laboratory studies for the purpose of disentangling the role of Process C and Process S in sleep regulation. However, to enable the application of light intervention as a sleepiness countermeasure in the real world, understanding how this third process impacts light's alerting effect is vital.

The purpose of this review is to describe light intervention studies in reference to the three-process conceptual framework and considering the physical properties of light. While previous reviews aimed to clarify the underlying neurophysiological pathways via which light affects alertness levels, this current review aims to broadly document factors that influence the alerting effect of light in their most complete form, and search for patterns amongst both effective and non-effective light interventions. The results of this review will be briefly discussed in relation to the underlying physiological mechanisms as well as the methodological quality of the studies. The findings are particularly relevant to industries where alertness levels are crucial to the safety of clients, such as health care professionals and rail workers [21, 22], where poor decision-making has major consequences (e.g. death).

Methods

Eligibility criteria

Study design

Eligible studies were restricted to randomized controlled trials (RCT) and randomized or counterbalanced crossover studies. A counterbalanced crossover design was considered appropriate for testing the alerting effect of light, because the alerting effect of light is short-lived [23] and in people without significant sleep disorders, levels of alertness are generally stable. This criterion requires studies to explicitly state that participants were randomly allocated to different treatment conditions, or to order of treatment, or to state that the order of treatment was counterbalanced. To this end, studies using methods of non-random allocation to treatment (e.g. by participants' office floor [24]) were excluded. Studies that failed to report the method for allocation to treatment were excluded without contacting authors for further details.

Study participants

Adults without medical conditions known to influence their alertness levels were included. Healthy employees or volunteers were both considered eligible. On the other hand, studies examining 1) people aged 55 years and above, or 2) a clinical population, such as patients with a diagnosis of Parkinson's disease, depression, brain injury or dementia were excluded. Older people were excluded because there is evidence that the regulation of circadian rhythm weakens as people age [25], which might result in an attenuated alerting response to light intervention.

Types of interventions

Studies using light alone or with other interventions were selected. To enable the elucidation of the impact of intensity and spectral wavelength on the alerting effect of light, studies were required to report both aspects across treatment conditions to allow the differences in spectral distribution and illuminance level between intervention and controls to be determined. Light source (e.g. fluorescent, incandescent, daylight) was used as a proxy of spectral power distribution when the spectral power distribution or correlated colour temperature was not available. On the other hand, studies that failed to report intensity and/or spectral distribution for any treatment conditions were excluded.

For studies that used light and other forms of intervention (e.g. fixed sleep schedule), these studies were only included when light's alerting effect could be ascertained.

Outcome measures

The outcome of interest for this review was alertness/sleepiness. Both subjective and objective alertness measurements were considered. Validated instruments for the measurement of subjective alertness included the Karolinska sleepiness scale (KSS)[26], Stanford sleepiness scale (SSS) [27], visual analogue scales (VAS) and other self-reported scales such as the Kwansai Gakuin sleepiness scale (KGS) [28].

Objective measures of alertness/sleepiness comprised EEG correlates which included alpha (8-12Hz), theta (4-8Hz) and delta power density (1-4Hz). Increased homeostatic sleep pressure has been found to result in increased frontal low EEG (theta/delta; 1-7Hz) activity [29]. Moreover, subjectively measured sleepiness has been found to be negatively associated with global alpha power density and positively associated with frontal theta power density (4-8Hz) [30]. Incidences of slow eye movements (SEMs) that occur before sleep onset are highly correlated with subjective sleepiness and EEG low frequency activity, although this relationship is almost exclusive to an eye closed condition [31] among sleep deprived participants. Also, the maintenance of wakefulness test (MWT) [32] and multiple sleep latency test (MSLT) were considered in this review. Behavioural alertness/sleepiness measures, such as cognitive performance tests were excluded as they vary in task difficulty, which is a factor that influences alertness [33].

Electronic databases

PubMed, EMBASE, PsycINFO and Scopus databases were searched until December 2016. A list of keywords and keyword combinations used is provided in Appendix 1.

Study selection

Study selection was completed using a three-step process. At Step 1, the titles and abstracts of returned citations were read by both authors. Studies that were clearly irrelevant to the topic or did not meet inclusion criteria were excluded. At Step 2, inspection of the full texts of the remaining studies was conducted by the two authors regarding their eligibility. At Step 3, key information from the remaining articles was extracted independently by the two authors, resulting in some studies being further excluded.

Data extraction

Data on study design, sample, light treatment profile and alerting effect were extracted. Study sample was described in terms of 1) occupation 2) sample size, 3) average age, 4) percentage of females, and 5) eligibility criteria to participate. Light treatment profiles included the 1) intensity and spectral wavelength of the light, 2) timing of light intervention, 3) duration of a single light intervention session, 4) the number of light treatment sessions within one 24-hour cycle, and 5) the number of 24-hour cycles. Participants' sleep history in the 48 hours prior to light intervention was examined by documenting the sleep wake schedule and length of sustained wakefulness for the two nights prior to the light intervention. Prior light exposure immediately before intervention was also assessed. Lastly, the effectiveness of light treatment in improving alertness levels during and after light exposure was documented, respectively. A meta-analysis of the effect size of the alerting effect was planned; however, it was not possible because of the limited usable data and the heterogeneity of the studies.

Risk of bias assessment

Risk of bias assessment was undertaken using the guidelines for intervention studies from the Cochrane's handbook [23]. For RCTs, the risk of selection bias, performance bias, detection bias, bias due to incomplete data and reporting bias were evaluated. For studies with a crossover design, the examination of possible carryover effects, the availability of a complete data set and the use of

paired analysis was examined. Risk of bias was evaluated by two authors. Disagreements were resolved through discussion.

Results

A flowchart of the literature screening process is presented in Figure 1. In total, 28 studies were included, with 24 studies examining the alerting effect of light during illuminance (see Table 1) and 14 investigating the post-illuminance effect (see Table 2). Of the 28 studies, 10 studies examined alertness levels both during and post-illuminance. Note, in presenting the results, the alertness level measured immediately after the completion of light intervention was classified as being during illuminance.

Light interventions for promoting alertness DURING illuminance (N =24)

Among the 24 studies that examined the alerting effect of light during illuminance, 11 studies were undertaken in the daytime, and 13 were conducted at night (see Table 1). Regarding study design, six of the 24 studies used a RCT design [9, 10, 33-36], and the remaining studies used a crossover design. Participants were all healthy volunteers, usually aged between 20 to 25 years, who underwent extensive screening before being recruited to the study. The sample sizes ranged from 8 [28, 37, 38] to 64 [39], and was generally around 10 to 20 participants.

a. Daytime studies (N =11)

Of the 11 daytime light studies, three studies [10, 39, 40] found a significant *during illuminance* alerting effect, six studies reported a non-significant alerting effect [33, 35, 37, 41-43] and two studies reported mixed results regarding the alerting effect of light where light had an alerting effect on an objective but not a subjective measure [34, 44]. The details of these studies are outlined below.

i. **Studies with significant alerting effect (N=3)**

The three studies [10, 39, 40] that observed a significant alerting effect all used a 1000lux fluorescent light as the intervention. Comparison light conditions differed slightly. One study [10] compared the intervention with a 3lux incandescent light and the other two studies [39, 40] compared their intervention with a 200lux fluorescent light of the identical colour temperature to their intervention light. Two studies delivered intervention light in an intermittent pattern [39, 40], and one study administered the intervention light in a continuous manner [10], with a total duration of light exposure ranging from 4 to 6hrs. A sleep restriction protocol was implemented in the study by Phipps-Nelson et al. [10], but not in the other two studies [39, 40]. In the study by Phipps-Nelson et al., participants were allowed to sleep 5hrs per night for the 2 nights prior. In terms of the prior light exposure, Smolders et al. [40] had participants undergo a 30-min adaption session under 200lux light (same as their control light condition), Phipps-Nelson et al. [10] had their participants exposed to dim light (<5lux) for about 6hrs, and Huiberts et al. [39] implemented a 25min adaption period using 100lux light. Smolders et al. [40] and Huiberts et al. [39] measured subjective sleepiness by KSS (average score), and Phipps-Nelson et al. [10] measured subjective sleepiness by KSS (average score) and objective sleepiness using SEMs.

ii. Studies with non-significant alerting effect (N=6)

The six studies that found non-significant results can be grouped according to the type of intervention light used. Two studies – one conducted by Munch & Jaeggies [41] and the other by Weisgerber et al. [42] – used broadband light of increased illuminance as the intervention. Four studies, conducted by Sahin & Figueiro [43], Okamoto & Nakagawa [37], Segal et al. [35] and Alkozei et al. [33] respectively, used monochromatic blue light as the intervention. The characteristics of these studies are provided below with reference to the three studies that reported a significant alerting effect where applicable.

Munch & Jaeggie's [41] study is comparable to the three studies that found a significant alerting effect regarding the timing of the light intervention and sleep history (see Table 1). Noticeable

differences between Munch & Jaeggie's study and the three studies with a significant finding include the absence of a controlled adaption period before the light intervention, and that participants in this study were allowed to talk, read, write and listen to music during the intervention (Table 1). The intervention light used by Weisgerber et al. [42] had a much higher illuminance than that used in the three studies with significant results (5600lux vs. 1000lux). However, participants also had longer wakefulness (22hrs vs. 4-5hrs) before being exposed to the intervention light resulting in higher sleep pressure, and were exposed to a shorter intervention light session (48mins vs. 5-6hrs) compared to the three studies reporting a significant alerting effect. Furthermore, during light exposure, participants in Weisgerber et al.'s study were allowed to read and talk to the research assistant. Both of the studies measured subjective sleepiness only, using the KSS.

The irradiance/illuminance level of monochromatic blue light used was 40lux in Sahin & Figueiro's study [43], 10lux in Okamoto & Nakagawa' study [37], $2.8-8.4 \times 10^{13}$ photons/cm²/s in Segal et al.'s study [35], and 214lux in Alkozei et al.'s study [33]. The comparison light in these studies was 40lux red light [43], 10lux green and red light [37], $2.8-8.4 \times 10^{13}$ photons/cm²/s green light [35], and 188lux amber light [33], respectively. All four studies administered the light intervention over a single session, with the duration of the session ranging from 28mins [37] to 3hrs [35]. A sleep restriction protocol was implemented in the study by Segal et al. [35], where participants were allowed 8hrs sleep within the 48-hour period prior to the intervention. Participants' regular sleep and wake schedule was used in the other three studies [33, 37, 43]. The duration of the dark/dim light adaption period varied among these studies, which were 10mins [37], 30mins [33], 42mins [43], and 3hrs [35], respectively. Sahin & Figueiro [43] and Segal et al. [35] measured both subjective sleepiness using the KSS and objective sleepiness using EEG correlates. Okamoto & Nakagawa [37] and Alkozei et al. [33] measured subjective sleepiness using the KSS and SSS.

iii. Studies with mixed results for alerting effect (N =2)

Rahman et al. [34] and Sahin et al. [44] found a significant alerting effect of light for objective sleepiness measured by EEG correlates, but no difference for subjective alertness. Rahman et al. [34] compared a 6.5hr blue monochromatic light of 2.8×10^{13} photons/cm²/s with green monochromatic light of the same photon density from 4.75hrs after participants' individual wake times. Participants restricted their total sleep time to 8hrs over the 2 nights before light intervention. Also, a 4.75hr dim light (<3lux) adaption was implemented. Results of this study indicated no difference in the KSS, but a significant reduction of theta-alpha power density (less sleepiness) in the blue light group. The study by Sahin et al. [44] included two experiments. One compared white light of 361lux and 2568K with ambient white light of <5lux and 3500K, and the other compared red light of 213lux with ambient white light of <5lux and 3500K. Both of the experiments followed same protocol in that the participants maintained their regular sleep and wake schedule and underwent a dim light adaption period before the light intervention. Participants were exposed to a single 2hr light exposure session at one of three times (0700-0900; 1100-1300; 1500-1700). Neither intervention light influenced subjective alertness, but a reduction in alpha and theta-alpha power waves in the afternoon sessions, indicating an increased level of alertness, was found.

To summarise, it seems that fluorescent light of an illuminance of 1000lux of more than 2hrs duration is effective in promoting alertness levels during the daytime. In contrast, monochromatic blue light of low irradiance does not appear to be as effective in increasing alertness level during the daytime.

b. Night time studies (N =13)

Out of the 13 night time studies, five found a significant alerting effect of the intervention light [5, 6, 9, 45, 46], four studies found no alerting effect of intervention light [36, 47-49], and the remaining four studies reported mixed results on the alerting effect depending on the measurement of alertness [28, 38, 50, 51].

i. ***Studies with significant alerting effect (N=5)***

All five studies used blue light of low irradiance; two studies used the monochromatic form [9, 45], and the other three studies used the broadband form (blue light enriched with white light) [5, 6, 46].

In the two studies that used blue monochromatic light as the intervention, green monochromatic light of the same photon density (2.8×10^{13} photons/cm²/s) was the control [9, 45]. In the study led by Lockley [9], the duration of light intervention was 6.5hrs for 1 session and for 1 night, and in the study by Cajochen et al. [45], the light duration was 2hrs for 1 session and for 1 night. Dim light adaption was about 5hrs in both studies. A notable difference is that Lockley et al. restricted participants' sleep time to 8hrs over the 2 nights before the intervention [9], whereas Cajochen et al. asked their participants to follow their usual sleep and wake schedule [45]. Lockley et al. found a reduction in KSS scores, a decrease in delta-theta power densities, and an increase in the high range alpha waves. Cajochen et al. measured subjective sleepiness only, using the KSS; lower sleepiness was reported by the intervention group.

Of the three studies that used broadband blue light, the irradiance of the intervention light was about 40lux [5, 6, 46], and that of control light varied from 1lux [46] to 40lux [5]. The duration of light intervention was 2hrs for 1 night in Chellappa et al.'s study [5], 5hrs for 1 night in Cajochen et al.'s study [6], and 4hrs/night for 5 nights in Chang et al.'s study [46]. Participants in all three studies followed their usual sleep and wake cycle prior to the intervention light, and those in Chellappa et al. [5] and Cajochen et al.'s [6] studies went through a dim light adaption period. In all of the studies, the KSS was used to measure level of sleepiness, and a reduction in KSS score was found. In the study by Cajochen et al. [6], objective sleepiness was further measured by SEMs, and a reduced incidences of SEMs were also confirmed.

ii. Studies with non-significant alerting effect (N = 4)

Four night time studies [36, 47-49] failed to observe a significant alerting effect of the intervention light. Rangtell et al. [47] compared reading on an electronic device (102lux, 7718K) with reading a physical book under ambient room light (67.3lux, 2674K). The light exposure session was 2hrs for 1

night. This study was comparable to the three night time studies [5, 6, 46] that found a significant result regarding alerting effect of light, except for the adaption period. The light condition for their adaption period was 500lux and of 6.5hr duration [47], instead of dim or dark adaption reported in the three significant studies [5, 6, 46].

In the other three studies with non-significant results, short to medium wavelength filtered white light was compared with full spectrum white light of different illuminance levels [36, 48, 49]. Van der Werken et al. [48] compared <530nm filtered white light (193lux) with full spectrum white light (256lux); Rahman et al.[49] compared <480nm filtered (439lux) and <460nm filtered white light (459lux) with full spectrum white light (513lux), and Sasseville et al. [36] compared <530nm filtered white light with full spectrum white light (approx. 1200lux). In these studies, the intervention light contained less short wavelength (e.g. blue) light as well as having a lower illuminance level compared to their respective control light conditions. The duration of the light exposure was 8hrs for 2 nights in the study by van der Werken et al. [48], 12hrs for 1 night in the study by Rahman et al. [49], and 30mins for 1 night in the study by Sasseville et al. [36]. Using subjective sleepiness as the outcome measure, none of these studies found a significant difference across conditions.

Description of intervention light for studies with mixed results on alerting effect (N=4)

The four studies with mixed results for the alerting effect of light varied in terms of the physical properties of the intervention light.

Van der Lely et al. [51] used a similar approach to the two studies discussed earlier [48, 49], in that the authors compared filtered white light exposure to full spectrum white light. In this study [51], the light intervention was achieved by asking participants to wear blue blocker glasses from 1800hrs until bed time for 1 week at home, then 1 night in the laboratory. Those in the control group were exposed to the full spectrum of white light by wearing normal glasses. The illuminance level was 106lux for the intervention, and 103lux for the control condition. Measurements of both subjective and objective sleepiness were only assessed on the laboratory night, thus the results might reflect an

accumulative alerting effect. The authors found a higher level of subjective sleepiness (KSS) in the intervention group, but no difference for any EEG correlates.

In the study by Phipps-Nelson et al. [38], low irradiance monochromatic light (1.12-1.15lux) for 6hrs for 1 night was compared with low irradiance white light (0.02-0.2lux). Participants underwent an 8hr dim light adaption, and followed their usual sleep and wake schedule the night before the intervention. Using this protocol, the authors found no difference in subjective sleepiness as measured by KSS, but a significant reduction in theta and delta wave activities as well as SEMs incidences, suggesting a reduced level of sleepiness.

Lastly, two studies compared white light of moderate illuminance (2500-3000lux) with red light of low illuminance (4-24lux) [21] and white light (120lux) [31], respectively. In the study by Yokoi et al. [28], the duration of the light intervention was 7.5hrs for 1 night. In the study by Lavoie et al. [50], the duration of the light intervention was 4hrs for 1 night. Participants in both of the studies went through several hours of dim light adaption and followed their regular sleep and wake schedule before their light intervention. Yokoi et al. [28] reported no difference in the mean subjective sleepiness measured by KGS, but an increase in alpha wave activity at rest, which is an indicator of reduced sleepiness. Lavoie et al. [50] also failed to find a difference in subjective sleepiness using a VAS, but they reported a reduction in beta wave activity.

Taken together, blue light of low irradiance appears to be an effective measure in promoting alertness levels at night time in both monochromatic and broadband form. In contrast, white light of moderate illuminance was only effective in modulating objectively measured alertness levels. It appears that effective light treatment profiles differ diurnally. More importantly, subjective sleepiness measure seems to be less sensitive than objective sleepiness.

Alerting effect of light POST illuminance: day & night time studies (N=14)

Among the 14 studies that examined the post-illuminance alerting effect of light, five studies were RCTs [10, 33, 35, 52, 53], and the other nine studies used a crossover design. Participants were

mostly young and healthy adults, aged between 20 to 30yrs, except in one study, where some participants were aged in their 40s [38]. Sample size varied between 8 [38] and 90 [54], with many samples comprising 10 to 20 participants.

Studies investigating the alerting effect of light post-illumination can generally be classified into three groups based on the time point when measurement of alertness occurs. The first group measured post-illumination alertness within 24hrs after the light intervention before a sleep episode; the second group measured alertness within 24hrs after experimental light exposure, but after a sleep episode; and the third group measured alertness beyond 24hrs post-light intervention.

a. Post illumination alertness within 24hrs before a sleep episode (N=10)

Of the 10 studies in this group, six were undertaken during the daytime [10, 33, 35, 41, 42, 55], and four were carried out at night [38, 45, 50, 54]. The six daytime studies are detailed first, followed by the four night time studies.

i. Daytime studies (N=6)

Of the six daytime studies, post-illumination alertness was measured 2mins [55], 44mins [42], 2hrs [33, 41], 3hrs [35] and 4hrs [10] after the completion of the light intervention. The three studies that measured alertness at 2 to 3hrs post-illumination observed no alerting effect of light [33, 35, 41], yet it should be noted that these studies observed no *during illumination* alerting effect in the first instance. In the study by Phipps-Nelson et al. [10], the significant *during illumination* alerting effect disappeared at the 4-hr post-intervention timepoint. In the study by Weisgerber et al. [42], no *during illumination* alerting effect was found, but a significant alerting effect was recorded at 44mins after the completion of light intervention. Finally, a significant reduction of sleepiness was demonstrated 2mins after the light exposure by Leichtfried et al. [55].

The two studies reporting a significant post-illumination alerting effect used moderate to high illumination (1000lux and 5000lux) polychromatic light as the intervention [42, 55], and low

illuminance white light as the comparison (400lux and <50lux). Leichtfried et al. [55] exposed participants to 5000lux fluorescent light from 0740 to 0810 for 1 day, and Weisgerber et al. [42] exposed participants to 48mins of 5600lux for 1 day after 22hrs of wakefulness. Participants in Weisgerber et al.'s study were allowed to talk and watch a movie during the light intervention, but then these activities were discouraged during the 44min driving test [42].

The characteristics of the four studies with a non-significant post-illuminance alerting effect of light have been discussed earlier. To reiterate briefly, two studies used monochromatic blue light as the intervention [33, 35], one study used daylight as the intervention [41], and the other study used high illuminance white light as the intervention [10]. The light exposure duration was 30mins for 1 day in the study by Alkozei et al. [33], 3hrs for 1 day in the study by Segal et al. [35], 6hrs for 1 day in the study by Munch & Jaeggie [41], and 5hrs for 1 day in the study by Phipps-Nelson et al. [10]. The post-illuminance alerting effect was measured under <2lux light in Segal et al.'s study [35], < 6lux light in Munch & Jaeggie's study [41], <5lux light in Phipps-Nelson et al.'s study [10] and not reported by Alkozei et al. [33].

ii. Night time studies (N=4)

Of the four night time studies, the post-illuminance alertness level was measured at 45mins [54], 90mins [45], 1hr [50] and 2.5hrs [38] after the completion of light exposure. A significant post-illuminance alerting effect was reported by Karchani et al. [54] and Phipps-Nelson et al. [38]. The remaining two studies reported no post-illuminance alerting effect.

In the study by Karchani et al. [54], participants were exposed to 2500-3000lux fluorescent light during 15min work breaks with 4 breaks per night over 2 night shifts. The post-illuminance alerting effect was measured by the KSS 45mins after the light intervention under normal room light. No alerting effect during illuminance was obtained. Phipps-Nelson et al. [38] measured the *during illuminance* alerting effect of light both subjectively and objectively. They used blue light of a very low irradiance level as the intervention. Compared with white light of lower irradiance, a reduction in

SEM incidences and theta waves was recorded during illuminance, and sustained over the 2.5hrs post-illuminance in a similar light condition to their control.

Unlike the study by Phipps-Nelson et al. [38], the positive alerting effect found during illuminance in the studies by Cajochen et al.[45] and Lavoie et al. [50] both disappeared after the completion of light exposure. Cajochen et al. compared monochromatic blue light with green light (2.8×10^{13} photons/cm²/s), and Lavoie et al. compared white light of increased illuminance (2300-4700lux) with red light of low illuminance (4-24lux).

b. Post-illuminance alertness within 24hrs, but after a sleep episode (N=2)

Two studies investigated the alerting effect of light after one night's sleep. Both studies compared reading from an electronic device with reading a physical book [46, 47]. Results are mixed in terms of the alerting effect post-illuminance. In the study by Chang et al. [46], participants who read using an electronic device had less polysomnography (PSG) measured SEMs, prolonged sleep latency and reduced theta/alpha waves before sleep onset, and a higher level of sleepiness upon waking.

Likewise, Rangtell et al. [47] assessed PSG measured sleep latency and EEG correlates after sleep onset, and subjective sleepiness via the KSS upon waking, but the authors did not find a statistically significant difference in any of these aspects. Rangtell et al.'s [47] study differed from Chang et al.'s study in several ways; using a shorter duration of light exposure (2hrs vs 4hrs), less nights of light exposure (1 night vs. 4 nights), and a higher illuminance light condition for the adaption period (500lux vs. not reported).

c. Post-illuminance alertness beyond 24hrs (N=2)

Mixed results were found regarding the alerting effect of light beyond 24hrs. In the study by Horowitz et al. [53], participants were exposed to 2500lux fluorescent light for 6hrs over 3 nights, and a significant reduction in subjective sleepiness measured by a VAS on day 1 and day 2 after illuminance was revealed. Thessings et al. [52] reported two experiments with an identical protocol

except for the duration of the light exposure. Participants in one experiment were exposed to a very high illuminance light (8000-9000lux) for 2hrs for 1 night, and those in the other experiment were exposed to the same light intervention for 4hrs for 1 night. Post-illuminance alertness were measured by VAS and MSLT on the following night. The 2hr light exposure did not affect subjective or objective sleepiness. The 4hr light exposure shortened the sleep latency at one time point, but was not effective in reducing mean subjective sleepiness.

To summarise, the acute alerting effect of light does not seem to be sustained after the light intervention, but it is possible to alter one's alertness level by phase shifting their circadian rhythm.

Discussion

The current systematic review identified a diurnal pattern in what constitutes an effective light intervention for reducing sleepiness. Blue light of low irradiance is clearly effective in reducing sleepiness during biological night, but its influence on alertness during the day is much less evident. In contrast, white light of moderate illuminance intensity is effective in reducing subjective sleepiness during the day. However, it is not effective in reducing subjective sleepiness at night, although an alerting effect was observed when an objective measure of alertness, such as EEG, was used. Most studies included in this review were conducted under controlled laboratory conditions, where environmental stimuli are minimised; thus limiting the generalisability of the findings to industry settings.

Modulation of circadian rhythm, sleep homeostatic pressure and light intensity

Among healthy, rested and room light adapted volunteers, a 1000lux white light was shown to be more effective in reducing subjective sleepiness than 150-200lux white light during the daytime [39, 40], except for the study by Munch et al. [41]. The two studies that reported a superior alerting effect had either the same correlated colour temperature between intervention and control groups (4000K) [39], or lower colour temperature in the intervention (4000K) than the control (6500K) [40].

In the study by Munch et al. [41], the intervention light source used was daylight and/or fluorescent light to generate an intensity of 1000lux depending on the time of the day. Therefore, it is reasonable to assume that the colour temperature of the intervention light would be cooler than that of the control light source (3700K). Had participants not been exposed to daylight on the commute to the laboratory, an alerting effect might have been observed in the intervention group. In contrast to daytime studies, a 2800lux white light made no difference to subjective sleepiness compared to a 120lux white light during biological night among similar participants [28]. In this study, although both control and intervention lights were generated by fluorescent light tubes, it was not stated whether the same type of fluorescent tube was used for both conditions. Regardless, the available evidence seems to suggest that the minimum light intensity required to stimulate a subjective feeling of alertness is much higher during the day due to low sleep pressure and a rising circadian drive. At night, sleep pressure has accumulated, which in combination with a decreasing circadian drive results in a lower alertness level, which means people may be more sensitive to light intervention. The differing threshold in light intensity seems to fit well with the two-process sleep model [56]. As indicated by the results of an earlier study on the dose-response relationship of white light on alertness at biological night, although a 230lux white light was superior to 23lux white light, a further increase to 3190lux did not result in a further reduction in either subjective or objective sleepiness [17]. In contrast to our results, Ruge et al. found that a 5000lux white light was effective in reducing subjective sleepiness both during the day and at night compared to a <10lux white light [57]. Yet, it should be noted that participants in their study went through a dim light adaption, and more importantly, a much lower intensity control light condition. Prior light exposure or darkness exposure, as discussed later in detail, does impact the effectiveness of light intervention on alertness. Although a dose-response relationship has been demonstrated during biological night, this relationship has not been examined during the daytime. Further, how this dose-response relationship varies according to wavelength is unknown.

Modulation of circadian rhythm, sleep homeostatic pressure and light wavelength

The present review clearly shows that low irradiance blue light was more powerful in reducing subjective sleepiness than monochromatic green light of the same photon density during biological night in both rested [45] and sleep deprived participants [9]. This observation is consistent with the findings of a rodent study carried out by Pilorz et al. [58], where high intensity blue light produced a greater arousing effect in mice as manifested by delayed sleep onset, behavioural aversion and high corticosterone levels in nocturnal mice compared to green light of the same photon density during night time. Different to the night time studies presented in this review, low irradiance blue light was not more alerting than green light of the same photon density when applied during the daytime [35, 37]. This diurnal difference in relation to the alerting effect of different spectrums can be explained by the three-process model of sleep regulation developed by Hubbard and colleagues [11, 59]. Light is alerting in humans, and according to this model, at night, blue light stimulates the melanopsin receptor that plays a dominant or sole role in activating the circadian rhythm, sleep pressure and direct effect processes, whereas green light only makes a small contribution to the alerting effect of light via the direct effect process and circadian rhythm mediated by rods and cones. During the daytime, green light takes a major role in increasing alertness level via rods and cones via the direct effect pathway. The alerting effect produced by green light may be equivalent to the alerting effect produced by blue light through melanopsin via the circadian rhythm. This might explain the non-significant differences seen between blue and green light during the day.

Other influencing factors for alertness

Most of the included studies examined healthy participants with non-extreme chronotypes, except for the study by van der Ley [51], where participants were adolescents with moderate to extreme evening chronotypes. Chronotype has been identified as a personal trait that modulates the alerting effect of light. As summarised by Gaggioni et al. [60] in relation to cognitive function, during biological night, blue light is less beneficial for participants with an evening chronotype than participants with a morning chronotype, because participants with evening types have a stronger

compensation mechanism to oppose the adverse effect of a combination of a low circadian drive and high sleep pressure than participants with morning types. The inclusion of participants with a moderate to extreme evening chronotype in van der Ley's [51] study might explain why no differences in EEG data were observed between the filtered blue light and full spectrum white light conditions. However, it is hard to explain why a significant reduction in subjective sleepiness was observed in the filtered blue light condition.

During the assessment of sleepiness, most of the included studies required that participants simultaneously completed monotonous activities. For three studies [28, 41, 42], participants were allowed to speak with each other or a research assistant. Talking to other people is known to promote greater alertness compared to sitting alone [61], because during an executive task, thalamus, a key brain structure linking alertness and cognition [8] is consistently recruited. This might explain the findings of Weisgerber et al. where no difference in alertness was found during the light intervention when participants were allowed talk; and yet a significant alerting effect was seen 45 minutes after the light exposure [42].

Waking EEG correlates in relation to Process C and Process S

Among studies where EEG correlates were used as an objective measurement for sleepiness, alpha, theta and delta bands were measured. In the studies included in this review, the definitions used for these wave bands were very similar to those proposed by Cajochen and colleagues [29], with alpha defined as 8-12Hz, theta as 4-8Hz, and delta as 1-4Hz. Some combined wave bands of alpha and theta were also used [34, 43, 44, 50], and in two studies, specific wave activity was not differentiated due to an overall non-significant finding [35, 51]. Both subjective and objective measures of sleepiness (e.g. EEG correlates) measure a state of drowsiness [20]. These measures demonstrate high agreement. When the presence of an alerting effect of light differs according to the measurement type, it is usually the case that the objective measurement, but not subjective measures, demonstrates an alerting effect [34, 38, 44]. This pattern seems to indicate that subjective

measures are less sensitive to changes in alertness compared to objective measures. In the current review, the only exception to this pattern is van der Ley's [51] study where a difference in subjective alertness was observed when no effect on EEG was found.

Prior light exposure/sustained alerting effect of light

Some preliminary conclusions about the post-illuminance alerting effect of light can be drawn from this review. First, prior light exposure does seem to attenuate the alerting effect of the light intervention. For example, in the study by Rangtall et al. [47], 102lux light of a colour temperature of 7718K failed to elicit an alerting effect compared to a 67.3lux light of 2674K, whereas other similar studies [6, 46] observed a significant alerting effect. This is likely to be associated with the 6.5hr of 500lux prior light exposure. Prior daylight exposure is also likely to be explanation for the non-significant alerting effect of the intervention light observed in Munch & Jaeggie's study [41]. A similar effect has also been demonstrated in rodent models, where the effect of the light/dark cycle extends for several hours [62]. Second, the time of day that the alerting effect was measured is likely to have moderated the post-illuminance alerting effect of light. In the daytime study by Phipps-Nelson et al. [10], the non-significant post-illuminance alerting effect was measured at 2100hrs when the circadian drive for alertness was at its highest (for participants without extreme chronotypes [56]), which might have masked the post-illuminance effect. In their night time study [38], the post-illuminance alerting effect was measured at 0930 in almost complete darkness, and the reduction of delta, theta waves and SEMs observed during blue light condition persisted. Together, these results lend support to the notion that an alerting effect of light can be sustained beyond the immediate light exposure (see also Hubbard et al. [11]). To date, many of the studies that examined the post-illuminance alerting effect of light have measured this effect under a dim light condition, where the alerting effect of light dissipates quickly. However, these conditions do not mimic those of industry and such dim lighting are rarely seen in some workplaces such as hospitals. Therefore, future research should also investigate the optimal light intervention for the purpose of producing an

adequate post-illuminance alerting effect of light under room light conditions. This question is meaningful for the health industry in particular, where staff and patients require different light/darkness exposure, especially at night. Tanaka et al. [63] reported that a 10min bright white light exposure was effective in reducing subjective sleepiness at 3hrs post-illuminance under room light conditions when completing normal work activities, but this study was not included in this review because the light properties of the intervention were not reported.

Risk of bias assessment results

Overall, the studies included in this review demonstrated high internal validity. As indicated in Figures 2 & 3, it is common for studies to not report information that allows for the assessment of the risk of bias associated with random sequence generation, allocation concealment and outcome assessment. However, we stress the difference between reporting and executing, and therefore, our assessment of bias may overestimate the risk of bias. With regard to the crossover trials, the proportion of studies reporting the results of an assessment of possible carryover effects was low. Furthermore, paired analysis was used in all but two studies [49, 55]. Yet, the use of unpaired analysis is likely to result in an underestimation of the true effect size. Therefore, it may be that light intervention is more effective than indicated here.

Conclusion

Blue light of low irradiance is probably an effective light intervention for increasing alertness levels at night, but is less effective during the daytime. Moderate bright light is likely to be effective in reducing sleepiness during the daytime, but might be less effective at night. Environmental factors (including prior light exposure) and individual factors (including chronotype and the activities undertaken during the measurement of sleepiness) influence the alerting effect of a light intervention. The development of light therapy as a sleepiness prevention strategy requires researchers not only to report the most complete form of the light's physical properties [13], but also to report other detailed information in relation to the third process that may contribute to sleep

regulation in addition to Process C and Process S. Investigation of the dose-response relationship between specific light interventions and the alerting effect during the daytime and how this is influenced by spectral wavelength is also recommended. Knowledge gained from such research will eventually assist in the development and use of suitable light infrastructure and light interventions for various workplaces.

Practice points

1. The minimum light intensity required to induce an alerting effect is higher during the day than at night, and this minimum light intensity is likely to vary with the spectral distribution of light.
2. Light's alerting effect is not only modulated by Process C and Process S, but also by the third process, which has been referred to as Process A, or the direct effect of light.
3. The alerting effect of light is likely to be sustained beyond the light intervention, but its impact will be highly dependent on other factors.

Research agenda

1. Investigate the dose-response relationship between various light properties and its alerting effect during the day to determine the minimum intensity required in relation to spectral wavelength distribution.
2. Investigate the post-illuminance alerting effect of light, considering the circadian rhythm (Process C), sleep homeostasis (Process S) and other environmental stimuli and personal traits (the third process).
3. Explore the use of brief light interventions at the beginning of a work shift as a method to increase alertness during the work period.

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Table 1 Studies examining the alerting effect of light *DURING illuminance* (n =24).

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
Daytime-high intensity white light										
Phipps-Nelson et al. 2003 [10]	<ul style="list-style-type: none"> • RCT • Random allocation reported • Lab – modified constant routine 	<ul style="list-style-type: none"> • Volunteers • N =16 • Mean age: 25.3 yrs • 62.5% female • Non-smokers • Consume <300mg caffeine/day • Consume <5 standard units of alcohol/wk • Good physical and psychological health • No poor sleep quality • No shift work and across time zone travelling in the last 3mths • No extreme chronotypes 	Dim light of <5lux from awakening to 1200hrs	<p>Sleep restriction protocol applied: 5hrs/night for 2 nights before light intervention</p> <p>Participants were awake for 6hrs before light intervention</p>	<p>DAYTIME (1200-1700)</p> <p>5hrs/session</p> <p>1 day</p>	<p>White light</p> <p>1056lux</p> <p>Fluorescent tubes + the background dim light of < 5lux from incandescent globes</p> <p>Thorn 2L 36W fluorescent tubes.</p>	<p>White light</p> <p>3.3lux</p> <p>Incandescent globes</p> <p>Standard incandescent globes, indicating a warm light source</p>	<p>KSS</p> <p>Yes, intervention light significantly reduced subjective sleepiness (a lower KSS score) compared to the control light.</p>	<p>SEM incidents</p> <p>Yes, intervention light significantly reduced objective sleepiness (reduced SEM incidences) than dim light</p>	<p>PVT + sleepiness measure every 30mins + KDT + saliva sample</p> <p>Wore EEG electrodes, and ate in a modified constant routine</p>
Smolders et al. 2012 [40]	<ul style="list-style-type: none"> • Crossover • WP unclear • Order of light treatment counterbalanced • Lab -simulated office room 	<ul style="list-style-type: none"> • Student volunteers • N =32 • Mean age: 22.0 yrs • 41.0% female • No complaint of general health • No cross-time zone travelling in past 2 wks • No extreme chronotypes 	<p>200lux (4000K) for 30 minutes prior to experiment</p> <p>Daylight exposure before the adaption period</p> <p>Evidence: Participants were allowed to go outside before the sessions. Participants in the afternoon</p>	<p>Nil sleep restriction</p> <p>Participants followed their usual sleep-wake schedule.</p> <p>Participants attending the afternoon session had a longer sleep period than those attending the morning session.</p>	<p>DAYTIME</p> <p>Morning session: 0900-1000 OR 1100-1200</p> <p>Afternoon session: 1300-1400 OR 1500-1600</p> <p>1hr/session</p> <p>1 day</p>	<p>White light</p> <p>1000lux at eye level</p> <p>Fluorescent 2700K (TL5-28W/827) on the wall + 6500K (TL5-28W/865)</p> <p>CCT 4000K</p> <p>Peak wavelength = 612nm as per Figure 1</p>	<p>White light</p> <p>200lux at eye level</p> <p>Fluorescent 6500 K (TL5-28W/865) fluorescent tubes</p> <p>CCT 6500K</p>	<p>KSS</p> <p>Yes, intervention light significantly reduced sleepiness compared to the control light.</p>	<p>N/A</p>	<p>In Block 1, 2 & 3:</p> <p>EEG (eye open and closed) + auditory PVT + LDST + Questionnaire</p> <p>In baseline & Block 4:</p> <p>EEG (eye open and closed) + auditory PVT + NC + Questionnaire</p>

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
					# of 24hr cycles			Outcome of light intervention	Outcome of light intervention	
Munch et al. 2012 [41]	<ul style="list-style-type: none"> Crossover WP = 16 hours Randomisation of order reported Lab 	<ul style="list-style-type: none"> Volunteers N = 29 Mean age: 23.6 yrs 41.4% female Non-smokers Moderate consumption of caffeine and alcohol generally; refrain from caffeine and alcohol on the study day No current regular medication No medical or psychiatric disorders No shift work or cross time zone travelling in past 2 mths 28 normal chronotype, 1 morning type 	<p>Daylight exposure on the commute from home to the lab is likely</p> <p>Evidence: morning light exposure was not controlled</p>	<p>Nil sleep restriction</p> <p>Participants kept regular sleep and wake schedule</p> <p>Participants were awake for 4-5hrs prior to light intervention</p>	<p>DAYTIME (1200-1800)</p> <p>6hrs/session</p> <p>1 day</p>	<p>White light</p> <p>1000lux at eye level</p> <p>Daylight ± fluorescent light of 1000lux to maintain above 1000lux</p> <p>CCT 6504K</p>	<p>White light</p> <p>176lux at eye level</p> <p>Fluorescent tubes</p> <p>CCT 3700K</p>	<p>KSS</p> <p>No, daylight was not effective in reducing during light exposure sleepiness than office light (no difference)</p>	<p>N/A</p>	<p>Participants allowed to read, write, listen to music and talk (no laptops)</p> <p>Completed KSS, subjective wellbeing questionnaire every 30mins</p>
Huiberts et al. 2015 [39]	<ul style="list-style-type: none"> Crossover WP ≥ 2 days Random allocation to lighting conditions reported Lab 	<ul style="list-style-type: none"> Volunteers N = 64 Mean age: 21.4 yrs 50.0% female No extreme chronotypes 	<p>100lux (4000K) for 25mins prior to experiment</p>	<p>Nil sleep restriction</p> <p>Participants kept their usual sleep and wake schedule</p> <p>Participants attending the afternoon session differed to those</p>	<p>DAYTIME</p> <p>Morning sessions: 0900-1030 OR 1045-1215 OR</p> <p>Afternoon sessions: 1215-1345 OR 1345-1515 OR 1545-1715 OR</p> <p>1hr/session</p>	<p>White light</p> <p>1000lux at eye level</p> <p>Photon density 8.09×10^{14} photons $S^{-1} cm^2$</p> <p>Irradiance $304 \mu W/cm^2$</p> <p>Fluorescent</p>	<p>White light</p> <p>200lux at eye level</p> <p>Photon density 1.63×10^{14} photons $S^{-1} cm^2$</p> <p>Irradiance $61 \mu W/cm^2$</p> <p>Fluorescent</p>	<p>KSS</p> <p>Yes, intervention light was effective in reducing sleepiness than RL in the morning</p> <p>No, intervention light was not effective in reducing sleepiness than RL in the afternoon (no difference)</p>	<p>N/A</p>	<p>n-back task + Forward Digit-Span Task + Backward Digit-Span task + subjective assessment of performance, mood, tension, vitality and sleepiness</p>

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
						# of 24hr cycles	Outcome of light intervention	Outcome of light intervention		
Weisgerber et al. 2017 [42]	<ul style="list-style-type: none"> • Crossover balanced design • WP ≥ 1wk • Lab – simulated driving session 	<ul style="list-style-type: none"> • Volunteers • N = 19 • Mean age: 22.8 yrs • 31.6% female • No sleep disorder • No use of sleep medications • No use of NSAID • Healthy • No shift work and travelling across time zones in the past 3mths • No extreme chronotype 	<p>Sleep deprivation group: 35lux (incandescent) for 6hrs starting from participants' usual bed time</p> <p>Rested group: Various daylight (dawn light) for 45mins from usual wake up time to arrival at the lab</p>	<p>attending the morning session in terms of time awake</p> <p>Sleep deprivation group: Sleep restriction protocol applied: no sleep was allowed the night before light treatment.</p> <p>Participants were awake for 22hrs before light treatment</p> <p>Rested group: Nil sleep restriction.</p> <p>Participants were awake for 45mins before light treatment</p>	<p>1 day</p> <p>Sleep deprivation group DAYTIME (0600-0800)</p> <p>45mins/session</p> <p>1 day</p> <p>Rested group DAYTIME (from awakening)</p> <p>45mins/session</p> <p>1 day</p>	<p>CCT 4000K</p> <p>White light</p> <p>5600lux at eye level</p> <p>Fluorescent</p> <p>5000K Sunbox K10 model, sunbox, USA + 4100 K SAdelite lamp Northern Lights Canada</p> <p>CCT 4100-5000K</p>	<p>CCT 4000K</p> <p>White light</p> <p><50lux at eye level</p> <p>Incandescent</p> <p>No further information available</p>	<p>KSS</p> <p>No, intervention light was not effective in reducing sleepiness than control light (KSS measured immediately after light exposure)</p>	<p>N/A</p>	<p>Oral temperature + PVT every 30mins</p> <p>Participants were allowed to read, do homework, watch a pre-screened movie and chat with the research assistant between PVT assessments</p>
Daytime-low intensity blue light										
Sahin & Figueiro 2013 [43]	<ul style="list-style-type: none"> • Crossover • WP = 1 wk • Presentation order counterbalanced • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 13 • Mean age: 20.5 yrs for males, and 21 yrs for females • 38.5% female 	<p>< 2lux light for 30mins preparation (1400-1430hrs)</p> <p>Dark adaption</p>	<p>Nil sleep restriction.</p> <p>Participants slept from 2300-0700 for</p>	<p>DAYTIME (1442-1530)</p> <p>48mins/session</p> <p>1 day</p>	<p>Blue light = 460nm</p> <p>40lux</p> <p>Irradiance:</p>	<p>Red light = 630nm</p> <p>40lux</p> <p>Irradiance: 18.9</p>	<p>KSS, measured 4 times during light exposure</p> <p>No, blue light was not effective in</p>	<p>Alpha (8-12Hz) Theta (4-8Hz) alpha-theta (5-9Hz)</p> <p>EEG at F, P, T, O 10-20system</p>	<p>EEG electrodes attached + KSS 4 times</p> <p>Participants were seated and asked to</p>

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
					# of 24hr cycles			Outcome of light intervention	Outcome of light intervention	
		<ul style="list-style-type: none"> No alcohol or caffeine intake within 12hrs before experiment No physical and mental health problems No colour blindness No shift work or cross time zone travelling in the past 3mths No extreme chronotype 	for 12mins	the night before light treatment		40.2 μ W/cm ²	μ W/cm ²	reducing subjective sleepiness than red light (no differences)	EEG when awake No, blue light was not effective in reducing objectively measured sleepiness than red light (no difference)	stare at the light source. No eating, drinking, and talking allowed.
Rahman et al. 2014 [34]	<ul style="list-style-type: none"> RCT Random allocation to light treatment reported Lab 	<ul style="list-style-type: none"> Volunteers N = 16 Mean age: 24.8 yrs 0% female No use of caffeine, alcohol, smoking, over the counter and recreational drugs within 3wks before light exposure No physical, psychological, and ophthalmic conditions Maintained a self-selected 8hr sleep-wake schedule for 3wks before the light intervention No report of chronotypes 	< 3lux fluorescent light for the 4.75hrs from awakening	<p>Sleep restriction applied: No sleep for the 1st night, and 8hrs/night for the 2nd night before light treatment</p> <p>Participants were awake for 4.75hrs prior to light intervention</p>	<p>DAYTIME (~4.75hr after individual's wake time)</p> <p>6.5hrs/session</p> <p>1 day</p>	Monochromatic blue light of 460nm	Monochromatic green light of 555nm	<p>KSS, measured 7 times, every hour</p> <p>No, blue light is not effective in reducing subjective sleepiness at any point during light exposure than green light (no difference)</p>	<p>Theta/low range alpha waves (7.5-8.5Hz)</p> <p>Awake 10-20 system</p> <p>Yes, blue light is effective in reducing objective sleepiness (less theta/low range alpha waves) than green light</p>	Seated and gazed at the light source, completed auditory PVT and KSS tasks every 60mins
Okamoto & Nakagawa 2015 [37]	<ul style="list-style-type: none"> Crossover WP not reported Order of light treatment counterbalanced Lab 	<ul style="list-style-type: none"> Volunteers N = 8 Mean age: 22.9 yrs 0% female Non-smokers No caffeine and alcohol within the 12hrs 	<p>Dark adaption for 10 mins</p> <p>Daylight exposure was likely on the commute from</p>	<p>Nil sleep restriction.</p> <p>Mean sleep duration is 7.5 hrs, waking at 0830</p>	<p>DAYTIME (1200-1600)</p> <p>28mins/session for 1 session</p>	<p>Monochromatic short wavelength light 470nm</p> <p>10lux</p>	<p>1.Monochromatic medium wavelength light 530nm</p> <p>10lux</p>	<p>KSS, measured 6 times during light exposure</p> <p>No, short wavelength light was not effective in</p>	N/A	EEG electrodes were attached, Auditory PVT + oddball task

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle # of 24hr cycles	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement Outcome of light intervention	Objective sleepiness measurement Outcome of light intervention	Participants' activities during sleepiness assessment
		before light treatment • No report of chronotypes	home to the lab	Participants were awake for at least 4hrs (note, exact time for starting light treatment was not reported)	1 day	Photo density: 33.9×10^{12} photons/cm ² /s Irradiance: 14.4μW/cm ² Half peak bandwidth 22nm	Photon density: 4.9×10^{12} photons/cm ² /s Irradiance: 1.8μW/cm ² Half peak bandwidth 27nm 2. Monochroma tic long wavelength light 620nm 10lux Photon density: 14.9×10^{12} photons/cm ² /s Irradiance: 4.7μW/cm ² Half peak bandwidth 16nm	reducing subjective sleepiness compared to medium and long wavelength light.		
Segal et al. 2016 [35]	• RCT • Random allocation reported • Lab	• Volunteers • N = 60 • Age range: 18-31 yrs • 52.7% female • Non-smokers or no drug user in the past 12mths • Caffeine consumption < 300mg/day in the past 12mths	< 3lux ambient fluorescent light for 3.25hrs from awakening.	Sleep restriction applied: 5hrs/night for night 1, and 3hrs/night for night 2 before light treatment Participants	DAYTIME (3.25hrs from waking) 3hrs/session for 1 session 1 day	Monochromatic blue light Melbourne 458 nm, Boston 480nm Photon density = 2.8×10^{13} photons/cm ² /s	Monochromatic green light Melbourne 551 nm; Boston 555nm Photon density = 2.8×10^{13} photons/cm ² /s at Melbourne	KSS, measured 4 times No , blue light is not effective in reducing subjective sleepiness than green light (no difference)	EEG correlates No definition of specific wave frequency Awake No , as there was no difference in any EEG bins between blue and green light	From awakening to 9.25hrs after awake, participants did PVT, KSS, KDT tests every 30 to 60mins Participants performed the Stroop task and 2-

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
# of 24hr cycles						Outcome of light intervention	Outcome of light intervention			
		<ul style="list-style-type: none"> Alcohol consumption < 14U/wk in the past 12mths No psychiatric or chronic illness Not on regular medications No colour blindness No sleep disorder No shift work in the past 2yrs No travelling across time zones for no more than 2 times in the last 3mths No extreme chronotypes 		were awake for 3.25hrs prior to light treatment		at Melbourne site, 8.4×10^{13} at Boston site	site, 8.4×10^{13} at Boston site		groups	back task
		<ul style="list-style-type: none"> Volunteers N = 35 Mean age: 22yrs 51.4% female Right handed primary English speaking free from psychiatric, neurological, and substance use disorder Regular sleep and wake habits, which could have included extreme chronotypes 				Irradiance: $13.24\mu\text{W}/\text{cm}^2$ Melbourne; $34.06\mu\text{W}/\text{cm}^2$ Boston pupils dilated	Irradiance: $10.99\mu\text{W}/\text{cm}^2$ Melbourne; $28.75\mu\text{W}/\text{cm}^2$ Boston pupils dilated	SEMs with eye open No , blue light is not effective in reducing SEM incidences than green light		
Alkozei et al. 2016 [33]	<ul style="list-style-type: none"> RCT Random allocation to light treatment reported Lab 		Amber light exposure for 30mins (0945-1015) in a darkened room	Nil sleep restriction Followed usual sleep-wake schedule Participants were awake for at least 1hr prior to light intervention	DAYTIME (1015-1045) 30min/session 1 day	Blue light = 469nm 214lux	Amber light = 578nm 188lux	SSS, measured at the end of light exposure No , blue light is not effective in reducing subjective sleepiness than amber light	N/A	In a seated position, gaze at the light source, completed n-back practice
Daytime-others										
Sahin et al. 2014 [44] experiment 1	<ul style="list-style-type: none"> Crossover WP = 1 wk Order of light treatment counterbalanced Lab 	<ul style="list-style-type: none"> Volunteers N = 13 Mean age: 23.0 yrs 43.8% female No smoking No major health issues 	< 5lux fluorescent light (3500K) from awakening (at 6hrs) until light treatment	Nil sleep restriction Regular sleep and wake schedule 2230-0600	DAYTIME 0700-0900 OR 1100-1300 OR 1500-1700 2hrs/session	White light (380nm-730nm) 361lux $1.1\text{w}/\text{m}^2$ Luxeon M3-	Ambient white light < 5lux Fluorescent	KSS, measured 4 times No , white light was not effective in reducing subjective sleepiness than	Alpha (8-12Hz), alpha-theta (5-9Hz) Awake Yes , white bright light is effective in reducing alpha &	Saliva sample+ KSS+EEG + GONOGO + MAT

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
						# of 24hr cycles	Outcome of light intervention	Outcome of light intervention		
		<ul style="list-style-type: none"> No use of prescription medication No colour blindness No travel across more than two time zones during the last mth Chronotype = 3.5 ±1.9, which could have included extreme types 		Participants were awake for 1 hr before the 1 st session	1 day	PW71 white light emitting LEDs	CCT 2568K	ambient white light (no difference)	alpha-theta waves at session 2 and 3 Theta (5-7Hz) Beta (13-30Hz)	
						CCT 3500K			Awake No , white bright light is not effective in reducing theta and beta activities than ambient white light	
Sahin et al. 2014 [44] experiment 2	<ul style="list-style-type: none"> Crossover WP = 1 wk Order of light treatment counterbalanced Lab 	<ul style="list-style-type: none"> Volunteers N = 13 Mean age: 23.0 yrs 43.8% female Non-smokers No major health issues No use of prescription medication No colour blindness No travel across more than two time zones during the last mth prior to the study Chronotype = 3.5 ±1.9, which could have included extreme types 	Arrived at the lab the night before, and woke at 0600, and then were kept under dim light < 5lux condition	<p>Nil sleep restriction</p> <p>Regular sleep and wake schedule 2230-0600</p> <p>Have been awake for 1 hr before the 1st session</p>	<p>DAYTIME</p> <p>0700-0900 OR 1100-1300 OR 1500-1700</p> <p>2hrs/session</p> <p>1 day</p>	<p>Red light of 631nm</p> <p>213lux;/ 1.1w/m2</p> <p>Luxeon LUXM2-PD01-0050 red LEDs</p> <p>Half peak band width 16nm</p>	<p>Ambient white light</p> <p><5lux</p> <p>Fluorescent light</p> <p>CCT 3500K</p>	<p>KSS, measured 4 times</p> <p>No, red light was not effective in reducing subjective sleepiness than ambient white light (no difference)</p>	<p>Alpha (8-12Hz)</p> <p>Awake</p> <p>Yes, red light is effective in reducing alpha waves in Session 3</p> <p>Alpha-theta (5-9Hz) Beta (13-30Hz) Theta (5-7Hz)</p> <p>Awake</p> <p>No, red bright light is not effective in reducing alpha, alpha-theta, beta and theta wave activities.</p>	Saliva sample+ KSS+EEG + GONOGO + MAT
Night time-low intensity monochromatic blue light										
Cajochen et al. 2005 [45]	<ul style="list-style-type: none"> Crossover WP = 1wk Order of light treatment 	<ul style="list-style-type: none"> Volunteers N = 10 Mean age: 25.9 yrs 0% female 	2 lux dim light for 1.5hrs starting from 1800	Sleep time for the night before light treatment is	<p>NIGHTTIME</p> <p>(2130-2330)</p> <p>2hrs/session</p>	Monochromatic blue light = 460nm	Monochromatic green light = 555nm	<p>KSS, measured 5 times every 30mins</p> <p>Yes, blue light is</p>	N/A	Skin conductor and rectal probe were used to collect temperature, heart

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle # of 24hr cycles	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement Outcome of light intervention	Objective sleepiness measurement Outcome of light intervention	Participants' activities during sleepiness assessment
	counterbalanced • Lab	<ul style="list-style-type: none"> • Non-smokers • No caffeine or alcohol within 1 week before the study • No medical, psychiatric, and sleep disorders • No eye conditions Maintained a self-selected sleep-wake cycle, which could have included extreme chronotypes	2hrs dark adaption (1930-2130)	not reported, but participants' usual sleep-wake cycle is stated Participants were wake for 13.5hrs before light treatment	1night	photon density = 2.8×10^{13} photons/cm ² /s Irradiance: 12.1μW/cm² half peak band width: 10nm	photon density = 2.8×10^{13} photons/cm ² /s Irradiance: 10.05μW/cm² half peak band width: 10nm	effective in reducing subjective sleepiness than green light		rate, KSS and saliva
Lockley et al. 2006 [9]	<ul style="list-style-type: none"> • RCT • Random allocation to light treatment reported • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 16 • Mean age: 23.3 yrs • 50.0% female • No use of medications, supplements, recreational drugs, caffeine, alcohol or nicotine • No physical, psychological and ophthalmologic exams • No eye conditions • Maintained a self-selected constant 8 hr sleep/dark schedule for 3wks before the study • No mention of chronotypes 	< 3lux dim fluorescent light for 4.75hrs from 9.25hrs prior to the participant's usual wake time	Sleep restriction applied: No sleep for the 1st night, and 8hrs/night for the 2nd night before light treatment Participants were awake for 4.75hrs prior to light intervention	NIGHTTIME (~9.25hrs before individuals' wake time) 6.5hrs/session 1night	Monochromatic blue light of 460nm photon density 2.8×10^{13} photons/cm ² /s Irradiance: 12.1μW/cm² pupils dilated	Monochromatic green light of 555nm photon density 2.8×10^{13} photons/cm ² /s Irradiance: 10.0μW/cm² pupils dilated	KSS, measured every hour for 7 times Yes , blue light was effective in reducing subjective sleepiness than green light	Delta-theta (0.5-5.5Hz) High frequency alpha (9.5-11Hz) Awake Yes , blue light is effective in reducing sleepiness (a reduction in delta-theta range & an increase in high alpha range) than green light	EEG+EOG+ KSS + PVT every hour Indwelling catheter for plasma sample
Phipps-Nelson et al. 2009 [38]	<ul style="list-style-type: none"> • Crossover • WP = at least 4 wks • Order of light treatment 	<ul style="list-style-type: none"> • Volunteers • N = 8 • Mean age: 32.1 yrs • 37.5% female • Low to moderate 	< 5lux, then < 1 lux from 1200-2030 in the lab	Nil sleep restriction Regular sleep wake cycle	NIGHT TIME (2330-0530) 6hrs/session	Blue light 460nm 1.12-1.15lux	Ambient white light 0.02-0.2 lux	KSS, measured twice No , blue light was not effective in	Delta (1-4.5Hz) Theta (4.5-8Hz) Awake Yes , blue light	Simulated driving test, PVT, KSS and saliva sample tests

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
					# of 24hr cycles			Outcome of light intervention	Outcome of light intervention	
	counterbalanced • Lab	caffeine and alcohol use • No eye disease • No sleep disorder • No extreme chronotypes		(2300-0700) Participants were awake for 17.5 hrs prior to light intervention	1 day	Irradiance: 2.05 to 2.07 μ W/cm ² , Photon density: 5x10 ¹² photons/cm ² /s half peak band width: 25nm	Irradiance: 0.05 to 0.17 μ W/cm ² peak wavelength of 430 & 620nm	reducing subjective sleepiness than ambient white light (no difference)	reduced delta & theta wave activities than ambient white light Alpha (8-12.5Hz) Awake No, blue light was not effective on alpha activities than ambient white light SEM incidences Yes, blue light reduced SEM incidences than ambient white light	
Night time-low intensity blue enhanced white light										
Chellappa et al. 2011 [5]	• Crossover • WP =1 wk • Order of light treatment counterbalanced • Lab	• Volunteers • N = 16 • Mean age: 24.3 yrs • 0% female • Non-smokers • No medical, psychiatric and sleep disorders, • No use of medications, and drug abuse • No excessive alcohol, caffeine use, • No shift work and trans meridian flights in the past 1 mth • No extreme chronotypes • No poor sleep quality	< 8lux dim light from 1800-1930 Darkness adaption from 1930-2130	Nil sleep restriction Usual sleep and wake schedule Participants were awake for 13.5hrs prior to light intervention	NIGHTTIME (2130-2330hrs) 2hrs/session 1 night	Blue enriched white light 40lux at eye level Fluorescent light CCT 6500K Peak wavelength: 435 nm Greater input from 420-520nm band than the control as per Figure 2	White light 40lux at eye level Fluorescent light CCT 2500K Peak wavelength: 435nm	KSS, measured 3 times Yes, 6500K light is effective in reducing subjective sleepiness than 2500K light	N/A	VAS + KSS + saliva sample & cognitive test. Participants remained seated and gazed at the wall

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment	Outcome of light intervention	Outcome of light intervention
											# of 24hr cycles	
Cajochen et al. 2011 [6]	<ul style="list-style-type: none"> • Crossover • WP = 1 wk • Order of light treatment was counterbalanced • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 13 • Mean age: 23.8 yrs • 0% female • No use of tobacco, medication, other drugs • No visual impairment • Reasonable sleep quality & general health • No shift work within the last 3mths and trans-meridian flights. • No extreme chronotypes 	30mins dark adaption plus 4hrs dim light of <4lux red light prior to their usual bed time (around 2300hrs)	<p>Sleep time for the night before light treatment was not reported, but was the same as their usual sleep wake time</p> <p>Participants are likely to be awake for about 10hrs before light treatment</p>	<p>NIGHTTIME (2000-0100)</p> <p>5hrs/session</p> <p>1 night</p> <p>Participants received 10 mins break each hour</p>	<p>LED illuminated HP LP2480zx screen</p> <p>Similar spectral distribution from 500nm to 78nm ranges to the fluorescent lamp</p> <p>Greater output within the range of 410-500nm</p> <p>Photo flux: 2.1 x 10¹³ photons/cm2/s for the 454-474nm range</p> <p>CCT 6953K</p>	<p>Fluorescent lamp illuminated HP LP2475w screen</p> <p>Similar spectral distribution from 500nm to 780nm to the LED illuminated screen.</p> <p>Less output within the range of 410nm to 500nm</p> <p>Photo flux: 0.7 x 10¹³ photons/cm2/s for the 454-474nm range</p> <p>CCT 4775K</p>	<p>KSS, measured every 30mins</p> <p>Yes, blue enhanced screen is effective in reducing subjective sleepiness than non-LED screen ONLY during the 20 movie watching (snowy scenes)</p>	<p>SEM incidents</p> <p>Yes, blue enhanced screen is effective in reducing sleepiness (reduced SEM incidences)</p> <p>Low frequency bins</p> <p>Yes, blue enhanced screen is effective in reducing sleepiness (reduced low frequency bins)</p>	<p>An hr before and after movie, GO/NOGO task, time estimation task, word pair task and visual comfort scales were completed</p> <p>Saliva collection, 3-min KDT every hour</p>		
Chang AM et al. 2015 [46]	<ul style="list-style-type: none"> • Crossover • WP not reported • Order of light treatment randomised • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 12 • Mean age: 25 yrs • 50.0% female • No use of drugs, alcohol, nicotine and caffeine within 3wks • No use of medications • No chronic medical or psychological conditions, or sleep disorders 	Not reported	<p>Nil sleep restriction</p> <p>Participants were likely to have been awake for 10hrs prior to light intervention</p>	<p>NIGHTTIME (1800-2200)</p> <p>4hrs/session</p> <p>5 nights</p>	<p>Blue intense light + ambient room light</p> <p>31.73lux</p> <p>Fluorescent</p> <p>Peak</p>	<p>Ambient room light</p> <p>0.91lux</p> <p>Fluorescent</p> <p>Peak</p>	<p>KSS, measured 1hr before bed time every night (once/night)</p> <p>Yes, reading ebooks was effective in reducing subjective sleepiness than reading a physical book</p>	N/A	<p>For the first 3hrs reading, participants were seated to read. Then, participants had a 15mins break, where they could walk around and prepare for bed, before returning to read in bed</p>		

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle # of 24hr cycles	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement Outcome of light intervention	Objective sleepiness measurement Outcome of light intervention	Participants' activities during sleepiness assessment
		<ul style="list-style-type: none"> No impaired vision. No shift work in the last 3yrs or travelled time zone in the last 3mths. Maintained a fixed 8hr (10pm-6am) within 3wks before the study No report of chronotypes 				wavelength = 452nm as per Figure 4	wavelength = 612nm as per Figure 4	Note: pre light treatment KSS was not reported for every night		Both used pleasant leisure reading materials
Rangtall et al. 2016 [47]	<ul style="list-style-type: none"> Crossover WP = 6 days Randomisation of light treatment order reported Lab 	<ul style="list-style-type: none"> Volunteers N = 14 Age: not reported % female unknown Normal weight, right handed No use of drugs, nicotine, and travelling of time zone within the month before No psychiatric, neurologic, hormonal, metabolic, sleep disorders No eye conditions Chronotype = 16.8 ± 2.8 could have included extremes 	500lux for 6.5hrs before light treatment	<p>Nil sleep restriction</p> <p>Participants were likely to have been awake for 13hrs prior to light intervention</p>	<p>NIGHTTIME (2100-2300)</p> <p>2hrs/session</p> <p>1 night</p>	<p>Reading on an electronic device – magician</p> <p>102lux</p> <p>Peak wavelength: 458nm as per Figure 3</p> <p>Has twice more intensity of 466-477nm than the control</p> <p>CCT 7718K</p>	<p>Physical book reading – magician</p> <p>67.3lux</p> <p>Peak wavelength: 611nm as per Figure 3</p> <p>CCT 2674K</p>	<p>KSS, measured every 30mins for 5 times</p> <p>No, reading an ebook does not reduce subjective sleepiness (no difference)</p>	N/A	“Magician” was the ebook
Night time-high intensity blue filtered white light										
Rahman et al. 2011 [49]	<ul style="list-style-type: none"> Crossover WP = likely to be 1 wk, Random allocation to light treatment order 	<ul style="list-style-type: none"> Volunteers N = 12 Mean age: 25.8 yrs 42.0% female No medication except contraceptives 	Maintained in the same room for 1hr before light treatment to mimic real shift work	<p>Nil sleep restriction</p> <p>Participants were asked to maintain a</p>	<p>NIGHTTIME (2000-0800)</p> <p>12hrs/session</p> <p>1 night</p>	<p>1.<480nm filtered fluorescent of 439.43lux</p> <p>No outputs in</p>	<p>Full spectrum fluorescent of 513lux</p> <p>Had more outputs in the</p>	<p>SSS, measured every 2hrs for 6 times</p> <p>No, full spectrum white light was not effective in reducing</p>	N/A	Objective and subjective neuro-psychometric tests + saliva sample collection, buccal swab cell collection.

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
					# of 24hr cycles			Outcome of light intervention	Outcome of light intervention	
	reported • Lab	<ul style="list-style-type: none"> No sleep disorder No visual impairment No depression No prior history of shift work No mention of chronotypes 		regular sleep/wake schedule pre and during experiments Participants were awake for 12hrs prior to light intervention		the 420-470nm More outputs in the 540-700nm range than the control 2.<460nm filtered fluorescent of 459.67lux Very little outputs in the 420-470nm More outputs in the 540-700nm range than the control	420-470nm. Less outputs in the 540-700nm range than the intervention	subjective sleepiness than short-wave length filtered white lights		Played board games as a group when not completing tests
Van der Werken et al. 2013 [48]	<ul style="list-style-type: none"> Crossover WP = at least 1wk random allocation to order of treatment reported Lab 	<ul style="list-style-type: none"> Volunteers N = 33 Mean age: 22.6yrs 0% female Non-smokers No excessive use of alcohol, caffeine No use of medications No sleep disorders No somatic diseases No depression No chronic disease No visual impairment No night shifts within the last 3mths No travelling across time zones within the 1mth 	< 5lux for 2hrs before light treatment	Not reported	NIGHTTIME (2300-0700) 8hrs/session 2 nights	<530nm filtered fluorescent white light from Phillips TL-D 36W/830 193lux Irradiance for 420-530nm = 0W/m ² Peak wavelength from 530nm above = 545nm & 610nm, similar to the	Full spectrum fluorescent white light from Phillips TL-D 36W/830 256 lux Irradiance for 420-530nm = 0.14W/m ² Peak wavelength from 530nm above: 545nm & 610nm, similar to the	KSS, measured 8 times No , short-wavelength attenuated white light is not effective in reducing subjective sleepiness than full spectrum white light (no difference)	N/A	Saliva, urine sample, and skin temperature, KSS measurements

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement	Objective sleepiness measurement	Participants' activities during sleepiness assessment
						# of 24hr cycles	Outcome of light intervention	Outcome of light intervention		
		<ul style="list-style-type: none"> No extreme chronotypes 				control	intervention			
Sasseville et al. 2015 [36]	<ul style="list-style-type: none"> RCT Random allocation to light treatment reported Lab 	<ul style="list-style-type: none"> Volunteers N = 20 Mean age: 25.9 yrs 55% female No mental and physical illness No use of medication except contraceptives No report of chronotypes 	< 5lux	<ul style="list-style-type: none"> Nil sleep restriction Regular sleep and wake schedule 	NIGHTTIME (0300-0330) 30mins/session 1 night	<ul style="list-style-type: none"> < 540nm filtered white light 1150lux Irradiance for <540 nm: 0 Irradiance for the whole spectrum = 500uW/cm² at eye level 	<ul style="list-style-type: none"> Full spectrum White light 1420 lux Irradiance for < 540 not reported, peak wavelength for this range: 475nm Irradiance for the whole spectrum = 500uW/cm² at eye level 	<ul style="list-style-type: none"> VAS-alertness KSS-sleepiness, measured upon light turned off (once only) No, <540nm filtered white light is not effective in reducing sleepiness than normal white light (no difference) 	N/A	<ul style="list-style-type: none"> Alertness, energy, mood and sleepiness +Conner's objective performance test
Night time-high intensity white light										
Lavoie et al. 2003 [50]	<ul style="list-style-type: none"> Crossover WP = 7-10 days Order of light treatment counterbalanced Lab 	<ul style="list-style-type: none"> Volunteers N = 14 Mean age: 26.1 yrs 57.1% female Non-smokers No use of drugs and medications No caffeine during and on the day before experiment In good physical and mental health No sleep disorder No history of psychiatric and neurological disorders. No shift work or across 	< 15lux from 1900 to 0030	<ul style="list-style-type: none"> Nil sleep restriction Regular sleep wake schedule from 2300-0100 to 0700-0900 Participants were awake for 15.5 to 17.5hrs prior to light intervention 	NIGHTTIME (0030-0430) 4hrs/session 1 night	<ul style="list-style-type: none"> White light 2300 to 4700lux Fluorescent No further information available 	<ul style="list-style-type: none"> Red light 4-24lux No further information available 	<ul style="list-style-type: none"> VAS, measured twice No, white bright light was not effective in reducing subjective sleepiness than red light (no difference) 	<ul style="list-style-type: none"> Beta 1 (16-24Hz) measured twice Awake Yes, white bright light was effective in reducing Beta-1 activities Theta-alpha (5-9Hz) Awake No, white bright light was not effective in reducing theta-alpha wave activities 	<ul style="list-style-type: none"> Cognitive tasks, EEG, KSS, KDTs and skin temperature measurements

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle # of 24hr cycles	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement Outcome of light intervention	Objective sleepiness measurement Outcome of light intervention	Participants' activities during sleepiness assessment
Yokoi et al. 2003 [28]	<ul style="list-style-type: none"> • Crossover • WP = at least 1wk • Random order of treatment reported • Lab 	<p>time zone in the last month</p> <ul style="list-style-type: none"> • Habitual sleep time from 2300 to 0100hrs, could have included extreme chronotypes <ul style="list-style-type: none"> • Volunteers • N = 8 • Mean age: 22 yrs • 0% female • Habitual bedtime at 0153hrs • No caffeine or alcohol within 24hr of the studies • No pain medication within 24hrs of the studies • No report of chronotypes 	< 150lux for the 2 hours before light exposure (1930 to 2110)	<p>Nil sleep restriction</p> <p>Regular sleep and wake schedule</p> <p>Participants were awake for 13hrs prior to light intervention</p>	<p>NIGHTTIME (2110-0430)</p> <p>7.5hrs/session</p> <p>1 night</p>	<p>White light</p> <p>2800lux</p> <p>Fluorescent</p> <p>No further information available</p>	<p>White light</p> <p>120lux</p> <p>fluorescent</p> <p>No further information available</p>	<p>Kwansei Gakuin sleepiness scale (KGS), measured 4 times, every 2hrs</p> <p>No, the intervention light was not effective in reducing average subjective sleepiness at rest and working conditions, but the sleep onset was earlier in the control group.</p>	<p>Alpha (8.0566-13.183Hz)</p> <p>Theta (4.1504-8.0566Hz), measured every 2hrs, 4 times</p> <p>Awake</p> <p>Yes, at rest: intervention light significantly reduced objective sleepiness than dim light because alpha waves were higher in BL condition than DL condition, Fig 1 & 2, indicating less sleepiness</p> <p>No, during mental task, there was no difference in theta or alpha wave activities between intervention and control light</p>	KGS, EEG, mental tasks
Night time-others										
Van der Lely et al. 2015 [51]	<ul style="list-style-type: none"> • Crossover • ambulatory phase is 1wk + 	<ul style="list-style-type: none"> • Volunteers • N = 13 • Mean age: 17.0 yrs 	<8lux dim light adaption for 2hrs followed	Nil sleep restriction	<p>Ambulatory phase:</p> <p>1800 to one's</p>	Wear blue blocker (BB) glasses, so	Wear clear lenses, so exposed to full-	KSS, measured 6 times	EEG correlates Frequency bands not reported, only	Participants completed psychomotor

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Time of intervention delivery within one 24hr cycle # of 24hr cycles	Intensity (lux) of intervention	Intensity (lux) of control	Subjective sleepiness measurement Outcome of light intervention	Objective sleepiness measurement Outcome of light intervention	Participants' activities during sleepiness assessment
	laboratory phase 1 day • WP =1 wk • Order of light treatment counterbalanced • Home followed with lab	<ul style="list-style-type: none"> • 0% female • Good somatic and mental health • Average use of 2.5hrs per evening in front of media screen • No somatic and psychogenic origin • No sleep disorder • No drug or alcohol dependency • No transmeridian travel in past month (detailed in the supplementary material) • Moderate to extreme evening types 	by dark adaption for 0.5hr before experimental light exposure	Regular sleep wake schedule maintained 3 days before the lab Light exposure in the lab started 3 hrs before one's habitual bed time, so participants were awake for 13hrs prior to intervention	bedtime for 1 wk Laboratory phase: 3hrs before one's habitual bed time for 1 night	exposed to blue light filtered screen 106 lux 98.3% of < 480nm was filtered similar wavelength distribution at > 620nm to the control	spectrum blue light enriched screen 103lux 8.2% of < 480nm was filtered similar wavelength distribution at > 620nm to the intervention	Yes , BB is effective in promoting subjective sleepiness during light exposure than full spectrum screen Note: this during light exposure effect might reflect an accumulative effect of BB from the ambulatory phase	reported Asleep No , BB was not effective in promoting sleepiness during light exposure than wearing control glass	vigilance tests, KSS tests during this 5.5hrs light exposure

Captions: BB = Blue blocker; CCT = Correlated colour temperature; EEG = Electroencephalography; EOG = Electrooculogram; KDT = Karolinska drowsiness test; KGS = Kwansei Gakuin sleepiness KSS = Karolinska sleepiness scale; LDST = Letter digit substitution test; MAT= Multi-attribute task; NC = Necker cube pattern control task; NSAID = Nonsteroidal anti-inflammatory drug; PVT = Performance vigilance test; SEM = Slow eye movement; VAS = visual analogue scale; WP = Washout period

Table 2 Studies examining the POST illuminance alerting effect of light (N = 14)

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
Daytime post-illuminance alertness within 24hrs, before a sleep episode												
Lavoie et al. 2003 [50]	<ul style="list-style-type: none"> • Crossover • WP = 7-10 days • Order of light treatment counterbalanced • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 14 • Mean age: 26.1 yrs • 57.1% female • Non-smokers • No use of drugs and medications • No caffeine during and on the day before experiment • In good physical and mental health • No sleep disorder • No history of psychiatric and neurological disorders. • No shift work or across time zone in the last month • Habitual sleep time from 2300 to 0100hrs, could have included extreme chronotypes 	< 15lux from 1900 to 0030	<p>Nil sleep restriction</p> <p>Regular sleep wake schedule from 2300-0100 to 0700-0900</p> <p>Participants were awake for 15.5 to 17.5hrs prior to light intervention</p>	< 15lux	N/A	<p>NIGHTTIME (0030-0430)</p> <p>4hrs/session</p> <p>1 night</p>	<p>White light</p> <p>2300 to 4700lux</p> <p>Fluorescent</p> <p>No further information available</p>	<p>Red light</p> <p>4-24lux</p> <p>No further information available</p>	<p>VAS, at 1hr after illuminance (once only)</p> <p>No, white bright light was not effective in reducing subjective sleepiness compared to red light</p> <p>Note: during light exposure alertness effect was not significant</p>	<p>Theta-alpha (5-9Hz)</p> <p>Beta 1 (16-24Hz)</p> <p>Awake (at 1hr post, once only) & MWT (at 30 mins, 2hr post, twice)</p> <p>No, white bright light was not effective in reducing MWT, beta-1 or theta-alpha activities compared to red dim light</p>	<p>Cognitive tasks, EEG, KSS, KDT and skin temperature measurements</p>
Phipps-Nelson et al. 2003 [10]	<ul style="list-style-type: none"> • RCT • Random allocation reported • Lab – modified constant routine 	<ul style="list-style-type: none"> • Volunteers • N =16 • Mean age: 25.3 yrs • 62.5% female • Non-smokers • Consume <300mg caffeine/day 	dim light of <5lux from awakening to 1200hrs	<p>Sleep restriction protocol applied: 5hrs/night for 2 nights before light intervention</p>	Not directly reported, likely to be dim light of <5lux	N/A	<p>DAYTIME (1200-1700)</p> <p>5hrs per session</p> <p>1 day</p>	<p>White light</p> <p>1056lux</p> <p>Fluorescent + incandescent globes</p>	<p>White light</p> <p>3.3lux</p> <p>Standard Incandescent globes, indicating a</p>	<p>KSS, 4hrs after illuminance</p> <p>No, intervention light was not effective in reducing subjective sleepiness</p>	<p>SEMs, 4hrs after illuminance</p> <p>No, intervention light was not effective in reducing objective sleepiness</p>	

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention on 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
		<ul style="list-style-type: none"> Consume <5 standard units of alcohol/wk Good physical and psychological health No poor sleep quality No shift work and across time zone travelling in the last 3mths No extreme chronotypes 		Participants were awake for 6hrs before light intervention				Only mentioned Thorn 2L 36W fluorescent tubes	warm light source	compared to control light (no difference in mean)	compared to control light (no difference in mean)	
Munch et al. 2012 [41]	<ul style="list-style-type: none"> Crossover WP = 16 hours Randomisation of order reported Lab 	<ul style="list-style-type: none"> Volunteers N=29 Mean age: 23.6 yrs 41.4% female Non-smokers Moderate consumption of caffeine and alcohol generally; refrain from caffeine and alcohol on the study day No current regular medication No medical or psychiatric disorders No shift work or cross time zone travelling in past 2 mths 28 normal chronotype, 1 morning type 	Daylight exposure on the communal from home to the lab is likely	<p>Nil sleep restriction</p> <p>Participants kept regular sleep and wake schedule</p> <p>Participants were awake for 4-5hrs prior to light intervention</p>	< 6lux dim light	N/A	<p>DAYTIME (1200-1800)</p> <p>6hrs/session</p> <p>1 day</p>	<p>White light</p> <p>1000lux at eye level</p> <p>Daylight ±fluorescent light to maintain illuminance at above 1000lux</p> <p>CCT 6504K on estimation</p>	<p>White light</p> <p>176lux at eye level</p> <p>Fluorescent</p> <p>CCT 3700K</p>	<p>KSS, 2hrs after illuminance</p> <p>No, daylight was not effective in reducing sleepiness compared to office light (no difference in the mean sleepiness score)</p> <p>Note: participants in the office light group had earlier onset of sleepiness compared to the daylight group.</p>	N/A	in a seated position under dim light and completed n-back task, produced saliva sample, and completed KSS every 30mins
Leichtf	<ul style="list-style-type: none"> Crossover 	<ul style="list-style-type: none"> Volunteers 	400lux for	Nil sleep	400lux	N/A	DAYTIME	White light	White light	VAS, 2 mins after	N/A	Under dim

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
ried et al. 2015 [55]	<ul style="list-style-type: none"> WP = 7 days Random allocation to order of treatment reported Lab 	<ul style="list-style-type: none"> N = 35 Mean age: 33.0 yrs 51.5% female No use of medications No chronic diseases No visual impairment No shift work or transmeridian travel in the last 2mths 15.2% morning type, 12.1% evening type, 72.7% moderate types 	100min from 0600-0740	restriction			(0740-0810)	5000lux	400lux	illumiance		light condition, no cognitive task involved
				Usual sleep and wake schedule			30mins/session 2 days	Fluorescent light	Fluorescent light	Yes, bright light was effective in reducing subjective sleepiness		
				Have been awake for 1hr & 40mins before light treatment				CCT 6500K	CCT 4000K			
Alkozei et al. 2016 [33]	<ul style="list-style-type: none"> RCT Random allocation to light treatment reported Lab 	<ul style="list-style-type: none"> Volunteers N = 35 Mean age: 22yrs 51.4% female Right handed primary English speaking free from psychiatric, neurological, and substance use disorder Regular sleep and wake habits, which could have included extreme chronotypes 	Amber light exposure for 30mins (0945-1015) in a darkened room	Nil sleep restriction	Not reported	N/A	DAYTIME (1015-1045hrs)	Blue light = 469nm	Amber light = 578nm	SSS, measured at 2hrs after illuminance (once)	N/A	N-back test was performed 11.25-11.35hrs, an one hour before SSS measurement
			Daylight exposure was likely on the communal from home to the lab	Followed usual sleep-wake schedule			30mins/session 1 day	214lux	188lux	No, blue light is not effective in reducing subjective sleepiness compared to amber light (no difference)		
				Participants were awake for at least 1hr prior to light intervention				Model HF3321/60; Philips Electronics, Stamford CT				
								Panel irradiance: 0.35mW/cm ²				
								Panel irradiance: 1.23mW/cm ²				
Segal et al.	<ul style="list-style-type: none"> RCT Random 	<ul style="list-style-type: none"> Volunteers N = 60 	< 3lux ambient	Sleep restriction	< 2lux ambient	N/A	DAYTIME (from 3.25hrs after	Monochromatic blue light	Monochromatic green light	KSS, over 3hrs after illuminance,	EEG correlates No definition of	From awakening to

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Participants' activities during sleepiness assessment
2016 [35]	allocation to light treatment reported • Lab	<ul style="list-style-type: none"> Age range: 18-31 yrs 52.7% female Non-smokers or no drug user in the past 12mths Caffeine consumption < 300mg/day in the past 12mths Alcohol consumption < 14U/wk in the past 12mths No psychiatric or chronic illness Not on regular medications No colour blindness No sleep disorder No shift work in the past 2yrs No travelling across time zones for no more than 2 times in the last 3mths No extreme chronotypes 	fluorescent light for 3.25hrs from waking prior to light treatment.	applied: 5hrs/night for night 1, and 3hrs/night for night 2 before light treatment Participants were awake for 3.25hrs prior to light treatment	light for the 3 hours post experimental light exposure		waking time) 3hrs/session for 1 session 1 day	Melbourne =458nm, Boston = 480nm photon density = 2.8×10^{13} photons/cm ² /s at Melbourne site, 8.4×10^{13} at Boston site Irradiance: 13.24μW/cm ² Melbourne; 34.06μW/cm ² Boston pupils dilated	Melbourne 551nm; Boston 555nm photon density = 2.8×10^{13} photons/cm ² /s at Melbourne site, 8.4×10^{13} at Boston site Irradiance: 10.99μW/cm ² Melbourne; 28.75μW/cm ² Boston pupils dilated	measured twice over this period No , blue light is not effective in reducing sleepiness compared to green light (no difference)	specific wave frequency Awake No , as there was no difference in any EEG bins between blue and green light groups	9.25hrs after awake, participants completed PVT, KSS, KDT tests every 30 to 60mins under modified CR In Melbourne, participants performed the Stroop task and 2-back task
Weisgerber et al. 2017 [42]	• Crossover • WP ≥ 1wk • Order of light treatment counterbal	<ul style="list-style-type: none"> Volunteers N = 19 Mean age: 22.8 yrs 31.6% female No sleep disorder No use of sleep 	Sleep deprivation group: 35lux (incandescents) for 6hrs	Sleep deprivation group: Sleep restriction protocol	1.5lux at when performing simulated driving test	N/A	Sleep deprivation group DAYTIME (0600-0800) 45mins/session	White light 5600lux at eye level Fluorescent	White light <50lux at eye level Incandescent	KSS, 44mins after illuminance (immediately after driving simulation) yes , light	N/A	talking was discouraged, driving simulation was monotonous

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
	anced • Lab – simulated driving session	medications • No use of NSAID • Healthy • No shift work and travelling across time zones in the past 3mths • No extreme chronotype	starting from participants' usual bed time Rested group: Various daylight (dawn light) for 45mins from usual wake up time to arrival at the lab	applied: no sleep was allowed the night before light treatment. Participants were awake for 22hrs before light treatment Rested group: Nil sleep restriction. Participants were awake for 45mins before light treatment			1 day Rested group DAYTIME (from awakening) 45mins/session 1 day	5000K Sunbox K10 model, Sunbox USA + 4100K SAdelite, Lamp Northern Lights Canada CCT 4100K-5000K	light No further information	intervention was effective in reducing subjective sleepiness Note: light intervention was not effective immediately upon the completion of light exposure		
Night time- post-illuminance alertness within 24hrs before a sleep episode												
Cajochen et al. 2005 [45]	• Crossover • WP = 1wk • Order of light treatment counterbalanced • Lab	• Volunteers • N = 10 • Mean age: 25.9 yrs • 0% female • Non-smokers • No caffeine or alcohol within 1 week before the study • No medical, psychiatric, and sleep disorders	2 lux dim light for 1.5hrs from 1800-1930 Dark adaption from 1930-2130	Sleep time for the night before light treatment is not reported, but participants' usual sleep-wake cycle is stated Participants were wake for	2lux	N/A	NIGHTTIME (2130-2330) 2hrs/session 1 night	Monochromatic blue light = 460nm Photon density = 2.8×10^{13} photons/cm ² /s Irradiance: 12.1µW/cm ²	Monochromatic green light = 555nm Photon density = 2.8×10^{13} photons/cm ² /s Irradiance: 10.05µW/cm ²	KSS, over the 1.5hrs after illuminance, measured 4 times No , blue light was not effective in reducing subjective sleepiness compared to green light Note: blue light was effective during	N/A	KSS assessment, saliva collection, continuous rectal temperature monitoring and skin surface monitoring, continuous heart rate

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
Phipps-Nelson et al. 2009 [38]	<ul style="list-style-type: none"> • Crossover • WP = at least 4 wks • Order of light treatment counterbalanced • Lab 	<ul style="list-style-type: none"> • No eye conditions • Maintained a self-selected sleep-wake cycle, which could have included extreme chronotypes • Volunteers • N = 8 • Mean age: 32.1 yrs • 37.5% female • Low to moderate caffeine and alcohol use • No eye disease • No sleep disorder • No extreme chronotypes 	<p>< 5lux, then < 1 lux from 1200-2030hrs in the lab</p>	<p>13.5hrs before light treatment</p> <p>Nil sleep restriction</p> <p>Regular sleep wake cycle (2300-0700)</p> <p>Participants were awake for 17.5 hrs prior to light intervention</p>	<p>< 1lux condition</p>	<p>N/A</p>	<p>NIGHTTIME (2330-0530)</p> <p>6hrs/session</p> <p>1 day</p>	<p>Blue light = 460nm</p> <p>1.12-1.15lux</p> <p>Irradiance: 2.05~2.07uw/cm²,</p> <p>Photon density: 5x10¹² photons/cm²/s</p> <p>Half peak band width: 25nm</p>	<p>half peak band width: 10nm</p> <p>half peak band width: 10nm</p> <p>Ambient white light</p> <p>0.02-0.2lux</p> <p>Peak wavelength = 430nm & 620nm</p> <p>Irradiance: 0.05 to 0.17uW/cm²</p>	<p>light exposure</p> <p>KSS, measured twice over the 2.5hrs after illuminance</p> <p>No, blue light was not effective in reducing subjective sleepiness compared to ambient light</p> <p>Note: no difference during light exposure either</p>	<p>Delta (1-4.5Hz) Theta (4.5-8Hz) at 3hrs after illuminance</p> <p>Awake</p> <p>Yes, blue light reduced delta & theta wave activity compared to ambient white light</p> <p>Alpha (8-12.5Hz), , at 3hrs after illuminance</p> <p>Awake</p> <p>No, blue light was not effective on alpha activities compared to ambient white light</p> <p>SEM incidences , at 3hrs after illuminance</p> <p>Yes, blue light</p>	<p>monitoring</p> <p>Simulated driving test, PVT, KSS and saliva sample tests</p>

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention on 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
Kachar ni et al. 2011 [54]	<ul style="list-style-type: none"> • Crossover • WP = 6 days • Randomisation of order reported • Field - metal production plant 	<ul style="list-style-type: none"> • Shift workers at a metal production plant • N = 90 • mean age: 30.4 yrs • 0% female Participants were free of disease and drug use 	Not reported	Participants were working on evening shifts from 1400-2200	Not reported	N/A	NIGHTTIME (2200-2215hrs) (2400-2415hrs) (0200-0215hrs) (0400-0415hrs) 15mins/session 4 sessions/night 2 nights	White light 2500-3000lux Fluorescent No further information	White light 300lux Fluorescent No further information	SSS, measured 45mins after illuminance Yes , white bright light was effective in reducing subjective sleepiness compared to normal room light	reduced SEM incidences compared to ambient white light N/A	Completing a real night shift
Night time-post- illuminance alertness within 24hrs, but after a sleep episode												
Chang et al. 2015 [46]	<ul style="list-style-type: none"> • Crossover • WP not reported • Order to light treatment randomised • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 12 • Mean age: 25 yrs • 50.0% female • No use of drugs, alcohol, nicotine and caffeine within 3wks • No use of medications • No chronic medical or psychological conditions, or sleep disorders • No impaired vision. • No shift work in the last 3yrs or travelled time zone 	Not reported	Nil sleep restriction Participants were likely to have been awake for 10hrs prior to light intervention	After light exposure & before sleep: Darkness for PSG assessment < 8lux for KSS assessment After 1 night's sleep: < 8lux for KSS assessment	N/A	NIGHTTIME (1800-2200) 4hrs/session 1 night	Blue intense light + ambient room light 31.73lux Fluorescent Peak wavelength = 452nm as per Figure 4	Ambient room light 0.91lux Fluorescent Peak wavelength = 612nm as per Figure 4	KSS, measured 5-6 times for the one hour after waking up Yes , ebook reading increased subjective sleepiness upon waking after 1 night's sleep	Delta/theta (1.0-7.5Hz), no differentiation was made between the 2 bands Awake Yes , reading ebooks was effective in reducing sleepiness (less delta/theta) compared to reading a physical book	

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention	Participants' activities during sleepiness assessment
										Outcome of light intervention	Outcome of light intervention	
		in the last 3mths • Maintained a fixed 8hr (10pm-6am) within 3wks before the study • No report of chronotypes									Sleep latency by PSG when asleep after light exposure & REM Yes , ebook reading prolonged sleep latency measured by PSG, and reduced REMs incidences. Slow oscillation (0.5-1Hz) SWA (1-4Hz) Theta (4-7Hz) Alpha (8-12Hz) Spindle (12-15Hz) Beta (15-25Hz)	
Rangtel et al. 2016 [47]	<ul style="list-style-type: none"> • Crossover • WP = 6 days • Randomisation of order of light treatment reported • Lab 	<ul style="list-style-type: none"> • Volunteers • N = 14 • Age: not reported • % female unknown • Normal weight, right handed • No use of drugs, nicotine, and travelling of time zone within the month before • No psychiatric, neurologic, hormonal, metabolic, sleep disorders • No eye conditions • Chronotype = 16.8 ± 2.8 could have included extremes 	500lux for 6.5hrs before light treatment	<p>Nil sleep restriction</p> <p>Participants were likely to have been awake for 13hrs prior to light intervention</p>	<p>After light exposure & before sleep:</p> <p>Darkness for PSG assessment (asleep)</p> <p>One night sleep post light treatment:</p> <p>Not reported</p>	N/A	<p>NIGHTTIME (2100-2300)</p> <p>2hrs/session</p> <p>1 night</p>	<p>Reading on an electronic device</p> <p>102 lux</p> <p>Peak wavelength: 458nm as per Figure 3</p> <p>Has twice more intensity of 466-477nm compared to the control</p> <p>CCT 7718K</p>	<p>Physical book reading</p> <p>67.3 lux</p> <p>Peak wavelength = 611nm as per Figure 3</p> <p>CCT 2674K</p>	<p>KSS, measured every 15mins for 5 times over the one hour after awake</p> <p>No, reading an ebook does not reduce sleepiness after one night sleep (no difference across conditions)</p>	<p>Slow oscillation (0.5-1Hz)</p> <p>Theta (4-7Hz)</p> <p>Alpha (8-12Hz)</p> <p>Spindle (12-15Hz)</p> <p>Beta (15-25Hz)</p> <p>Asleep</p> <p>No, reading an ebook does not impact on the any of the above frequencies</p> <p>Sleep latency (PSG)</p> <p>No, reading an ebook does not impact on sleep latency (no difference across the conditions)</p>	Upon awakening

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Participants' activities during sleepiness assessment
Night time-post-illuminance beyond 24hrs												
Thessing et al. 1994 [52] experiment 1	<ul style="list-style-type: none"> • RCT • Randomisation to light treatment reported • Lab-simulated assembly line task 	<ul style="list-style-type: none"> • Volunteers • N = 20 • Mean age: 21 yrs • 63.3% female • Non-smokers • Free of active medical or psychological illness or sleep complaints. • No extreme photosensitivity • No night work in the last 3mths • No extreme chronotypes 	Unknown	<p>Nil sleep restriction</p> <p>Regular sleep and wake schedule</p> <p>Participants were awake for 16hrs prior to light intervention</p>	<300 lux for 4hrs from 0400-0800 on the night of light treatment	<300 lux for the 2 nd night from 1900-2300	<p>NIGHTTIME (2400-0400)</p> <p>4hrs/session</p> <p>1 night</p>	<p>White light</p> <p>8772lux at eye level</p> <p>Fluorescent</p> <p>No further information available</p>	<p>White light</p> <p>355lux at eye level</p> <p>Fluorescent</p> <p>No further information available</p>	<p>VAS, 24hrs after illuminance, measured 5 times</p> <p>No, BL-2 was not effective in reducing objective sleepiness compared to BL-0</p>	<p>MSLT, 24hrs after illuminance, measured 5 times</p> <p>No, BL-2 was not effective in reducing objective sleepiness compared to BL-0</p>	
Thessing et al. 1994 [52] experiment 2	<ul style="list-style-type: none"> • RCT • Randomisation to light treatment reported • Lab-simulated assembly line task 	<ul style="list-style-type: none"> • Volunteers • N = 20 • Mean age: 21 yrs • 63.3% female • Non-smokers • Free of active medical or psychological illness or sleep complaints. • No extreme photosensitivity • No night work in the last 3mths • No extreme chronotypes 	Unknown	<p>Nil sleep restriction</p> <p>Regular sleep and wake schedule</p> <p>Participants were awake for 16hrs prior to light intervention</p>	<300 lux for 4hrs from 0400-0800 on the night of light treatment	<300 lux for the 2 nd night from 1900-2300	<p>NIGHTTIME (2400-0400)</p> <p>4hrs/session</p> <p>1 night</p>	<p>White light</p> <p>9258lux</p> <p>Fluorescent</p> <p>No further information available</p>	<p>White light</p> <p>355lux</p> <p>Fluorescent</p> <p>No further information available</p>	<p>VAS, 24hrs after illuminance, measured 5 times</p> <p>No, BL-4 was not effective in reducing subjective sleepiness compared to BL-0</p>	<p>MSLT, 24hrs after illuminance, measured 5 times</p> <p>No, BL-4 was not effective in reducing objective sleepiness (mean MSLT) compared to BL-0, but at 0500, participants in the BL-4 group had significantly longer MSLT compared to the BL-0 group.</p>	

Citation	Study design Setting	Sample	Light condition for the adaption period	Sleep history 24 hrs prior to intervention	Light condition after completion of intervention within 24hrs	Light condition after completion of intervention on 24hrs after	Time of delivering within one 24hr cycle # of 24hr cycle repeated	Intensity (lux) of intervention	Intensity (lux) of control	Measurement of subjective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Measurement of objective sleepiness/time period relevant to the completion of light intervention Outcome of light intervention	Participants' activities during sleepiness assessment
Horowitz et al. 2001 [53]	<ul style="list-style-type: none"> • RCT • Random allocation to light treatment reported • Lab (involving constant routine before and after) 	<ul style="list-style-type: none"> • Volunteers • N = 54 • Mean age: 27 yrs • 50.0% female • No caffeine, nicotine, alcohol, and medication use for 3wks before the study • No medical and mental illnesses • No sleep disorders • No report of chronotypes 	< 8lux dim light for 6hrs from 1700-2300	<p>Nil sleep restriction</p> <p>Usual sleep-wake schedule</p> <p>Participants were likely to have been awake for 15hrs prior to light intervention</p>	< 8lux dim light, which is the light condition for the 38 hr constant routine	N/A	<p>NIGHTTIME (2300-0500)</p> <p>6hrs/session</p> <p>3 nights</p>	<p>White light</p> <p>2500lux at the gaze</p> <p>Fluorescent</p> <p>No further information available</p>	<p>White light</p> <p>150lux at the gaze</p> <p>Fluorescent</p> <p>No further information available</p>	<p>VAS, measured at 24hrs & 48hrs after illuminance under constant routine</p> <p>Yes, the bright light was effective in reduced subjective sleepiness compared to room light</p>	N/A	Constant routine

Captions: BL = Bright light; CCT = Correlated colour temperature; EEG = Electroencephalography; KDT = Karolinska drowsiness test; KSS = Karolinska sleepiness scale; MSLT= Multiple sleep latency test; MWT= Maintenance of wakefulness test; N/A = not applicable; NSAID = Nonsteroidal anti-inflammatory drugs; PSG = Polysomnography; PVT= Performance vigilance test; REM = Rapid eye movement; SSS = Stanford sleepiness scale; SWA = Slow wave activity; VAS= Visual analogue scale

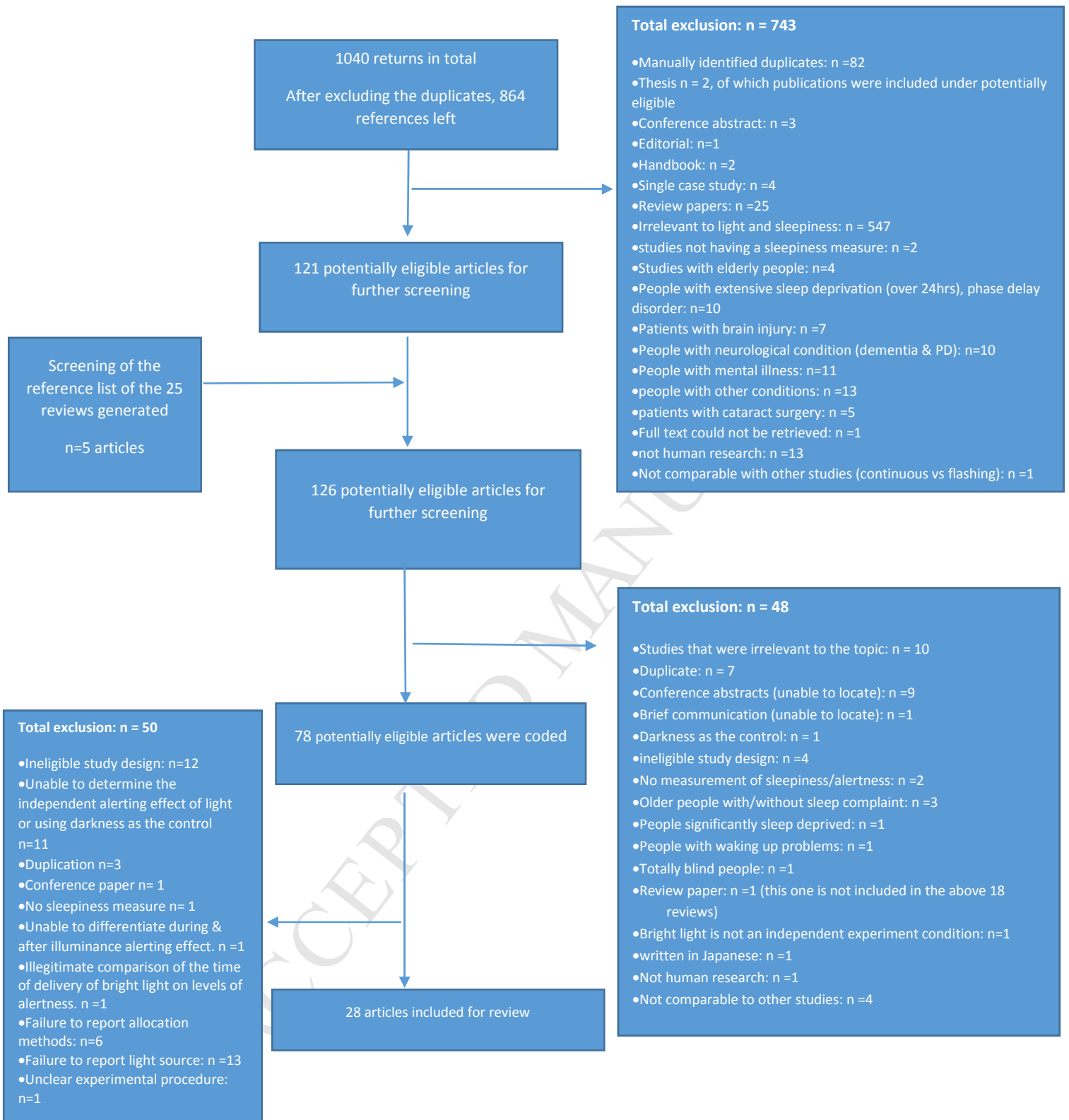
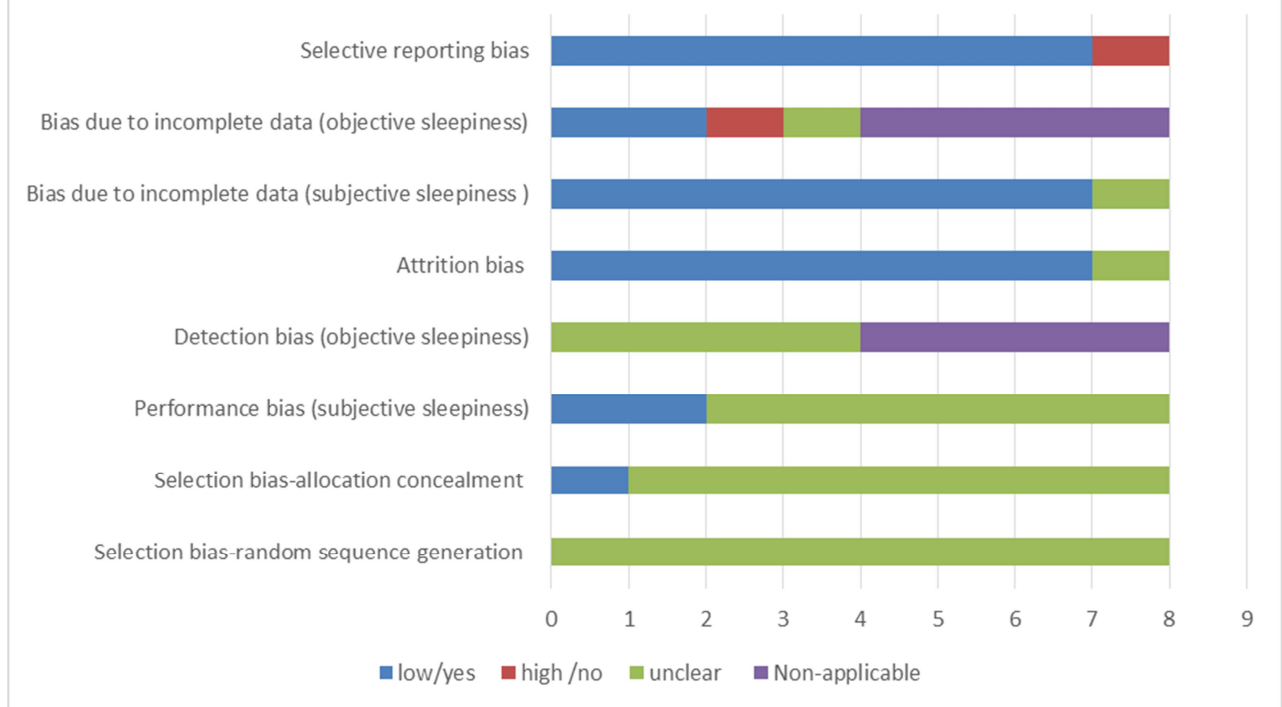


Figure 1 PRISMA flowchart for screening of literature

Figure 2 Assessment of risk of bias for RCTs (N = 8)

RCT = Randomised controlled trials

