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Acute alerting effects of light: A systematic literature review

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ABSTRACT

Periodic, well timed exposure to light is important for our health and wellbeing. Light, in particular in the blue part of the spectrum, is thought to affect alertness both indirectly, by modifying circadian rhythms, and directly, giving rise to acute effects. We performed a systematic review of empirical studies on direct, acute effects of light on alertness to evaluate the reliability of these effects. In total, we identified 68 studies in which either light intensity, spectral distribution, or both were manipulated, and evaluated the effects on behavioral measures of alertness, either subjectively or measured in reaction time performance tasks. The results show that increasing the intensity of polychromatic white light has been found to increase subjective ratings of alertness in a majority of studies, though a substantial proportion of studies failed to find significant effects, possibly due to small sample sizes or high baseline light intensities. The effect of the color temperature of white light on subjective alertness is less clear. Some studies found increased alertness with higher color temperatures, but other studies reported no detrimental effects of filtering out the short wavelengths from the spectrum. Similarly, studies that used monochromatic light exposure showed no systematic pattern for the effects of blue light compared to longer wavelengths. Far fewer studies investigated the effects of light intensity or spectrum on alertness as measured with reaction time tasks and of those, very few reported significant effects. In general, the small sample sizes used in studies on acute alerting effects of light make it difficult to draw definitive conclusions and better powered studies are needed, especially studies that allow for the construction of dose-response curves.

1. Introduction

Light affects humans in various ways. Some of the most established effects of ocular light exposure concern changes in circadian rhythms, such as those underlying sleep/wake regulation [1,2], and in diurnal cycles of hormone levels and core body temperature [3–5]. These effects require monitoring the parameter of interest for multiple days in order to make them detectable. Others are more direct or acute, such as the suppression of melatonin levels [6–8], and occur during or right after light exposure. Along with these more physiological effects, changes in cognitive performance due to light exposure have been reported as well. These too can be more indirect, such as deterioration in cognitive performance due to sleep loss after circadian phase shifts [9,10], or acute, already occurring during light exposure [11]. Here, we focus on what may be one of the most fundamental of these acute cognitive effects of light, namely on alertness. Although performance on any task in daily life is likely to depend on several cognitive functions, a person is unlikely to do well on a task in a state of low alertness. Understanding alerting effects of light is therefore not only important from a theoretical point of view, but may also lead to practical applications to improve alertness and hence performance.

In the scientific literature, the term ‘alertness’ may refer to different constructs, depending on the context and research field it is being used in. Moreover, it is frequently used without being clearly defined [12]. A great deal of research on alerting effects of light originates from work on sleep/wake regulation and circadian rhythms. In this context, the word ‘alertness’ is commonly used to denote the opposite of ‘sleep’ and indeed seems almost synonymous with ‘wakefulness’ [13,14]. It is often

Abbreviations: CCT, correlated color temperature; ipRGC, intrinsically photosensitive retinal ganglion cell; KSS, karolinska sleepiness scale; PVT, psychomotor vigilance task; RT, reaction time; SCN, suprachiasmatic nucleus

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measured by means of various self-report questionnaires such as the Karolinska Sleepiness Scale (KSS, [15]), which measures subjective sleepiness on a 9-point scale, or the Stanford Sleepiness Scale [16], which uses a 7-point scale. Other commonly used measurement instruments are the Global Vigor & Affect Scale [17] and the General activation and deactivation-sleep components of Thayer's Activation–Deactivation Adjective Check list [18]. Some studies use one single visual analog scale to measure alertness (see [19,20] for overviews of subjective measures). The obvious advantages of self-report measures are their apparent face validity and ease of administration. However, since it is difficult to keep participants blind to light manipulations, these measures of subjective alertness are also susceptible to biases arising from expectations or associations. Moreover, they often correlate poorly with more objective measures of alertness, such as task performance or physiological measurements [21–23].

In psychological studies, the term 'alertness' is also used to denote a state of vigilance or sustained attention, in which the person is not only awake, but also able to respond adequately to sparse stimuli [12,24]. In this sense, it not just relates to the person's arousal level, but also implies the ability to achieve and maintain a certain level of cognitive performance in a given task [25]. This is the definition of alertness that we will use in this review. Correspondingly, it can be measured in simple vigilance performance tasks, such as the Psychomotor Vigilance Task (PVT, [26]). In the original, visual version of the PVT, the participant is instructed to respond as quickly as possible to a change in the visual display. Visual changes occur randomly during 10 min with an interstimulus interval of 1–10 s. To exclude possible visual effects, an auditory version of the PVT is preferred for studies on alerting effects of light, with the participant responding to randomly occurring beeps (see [27]). Higher reaction times and a higher proportion of lapses (reaction times above a certain cut off) are taken as indications of reduced alertness. Earlier studies have also used the Mackworth clock test [28], in which participants have to detect occasional jumps in the hands of a clocklike display during 30 min. A newer instrument is the Attention Network Test [29], which aims at discriminating between alerting, orienting and executive attention.

Various other cognitive tasks have been used in studies on alerting effects of light, such as the Go/NoGo reaction time task [30,11,31,32], the digit symbol substitution task [33] or letter digit substitution task [34] and the N-back task [32,35]. Although performance on these tasks will be certainly determined to some extent by the alertness state of the person, the alertness component cannot be distinguished from other cognitive factors such as inhibitory control and working memory that also play an important role in determining task performance (see e.g. [36,37]). Therefore, we will not consider performance on these cognitive tasks in this review. In the following, only data from PVT and simple reaction time tasks will be considered as performance measures of alertness.

Older studies concerning the effects of light exposure on alertness mainly focused on the effects of light intensity, or illuminance of white light [3,38–40]. More recently, however, it has been established that several non-visual effects of light, such as acute melatonin suppression and circadian phase shifts, have their peak sensitivity at wavelengths around 460–480 nm, and are mediated by a specific subset of retinal ganglion cells [41–44]. These so-called intrinsically photosensitive retinal ganglion cells (ipRGCs) express the photopigment melanopsin, making them responsive to light even in the absence of (input from) rods and cones [45,46]. This discovery has led to increasing interest in the action spectrum of various non-visual effects, including effects on alertness. Consequently, several studies have compared the alerting effects of short wavelengths (around 460 nm, appearing bluish to the human eye) versus longer wavelengths, or of higher correlated color temperatures (CCT), with more short wavelength energy, versus warmer light with less short wavelength energy.

In the literature on non-image forming functions of light it now seems generally accepted that light has acute alerting effects and that these effects are stronger for higher light intensities and shorter wavelengths or higher color temperatures [7,11,14,47,48]. However, a closer look at the literature reveals that the effects are not nearly as clear cut as this consensus suggests and that many questions remain. Here, we systematically review the literature on acute alerting effects of light published between 1990 and 2016 and assess the empirical evidence. We evaluate the effects of light on subjective alertness as well as on objective performance measures of alertness. Additionally, we evaluate the dependency of the alerting effects on time of day and assess the effects of illumination level as well as spectral composition. This is done for light sources with polychromatic spectra (with light that appears white or close to white to the human eye), as well as for monochromatic (single wavelength) and narrow band spectra (which appear colored).

2. Methods

2.1. Data sources

The main search for relevant publications was carried out in Web of Science on April 24, 2015 by author JS and updated using Scopus on January 30, 2017. Search terms used were combinations of various terms for light exposure and alertness. For light exposure, the search terms used were 'blue', 'white', 'enriched', 'short wavelength', 'morning, "evening", 'ocular', 'therapy', 'bright', 'exposure', or 'monochromatic' combined with 'light', and 'daylight', 'effect of light' or 'lighting effects'. For alertness, the search terms included 'alertness', 'cognition', 'cognitive performance', 'cognitive function', 'psychomotor vigilance' and 'sustained attention'. These search terms were used to search within the titles and the topics of publications in the database. Only publications written in English in peer-reviewed scientific journals from the last 26 years (1990–2016) were considered. The results were verified against the results from a similar search carried out by author AT, conducted on May 7, 2014 and updated on January 15, 2017, using the Scopus database. This produced one publication that was not contained in the results found by JS.

2.2. Study selection

The combined search results from Web of Science and Scopus produced 528 potentially relevant publications. This set was carefully analyzed according to the following selection criteria. Only original studies, reporting new empirical data on alerting effects of light, were considered. If a publication contained both data from a previous publication and new data, only the new data was considered for this literature review. Only studies with a randomized experimental design, including a control or baseline condition were included. These studies had to contain a manipulation of light intensity, of the light spectrum or color temperature, or of a combination of these. Only studies with subjective outcome measures (questionnaires) or with performance measures of alertness (RT performance in simple reaction time tasks or PVT) were included in the review. We did not include studies that only described physiological effects, mainly because these were too few in number and too heterogeneous in methodology to allow for a systematic review. Since this review focuses on direct alerting effects, only studies describing acute effects of light on alertness in awake participants, measured either during or immediately after light exposure, were considered. Finally, only studies that report data from healthy adult (> 17 years) human participants were included, excluding data from neurological or psychiatric patients.

The data set was analyzed according to these selection criteria in two steps (see Fig. 1). First, the criteria were applied to the titles and abstracts of all 528 publications. This resulted in a subset of 156 publications which potentially met all selection criteria. Of the other 372 publications, the majority did not report acute alerting effects of light (166 cases) or did not include a light manipulation (107 cases). Second,

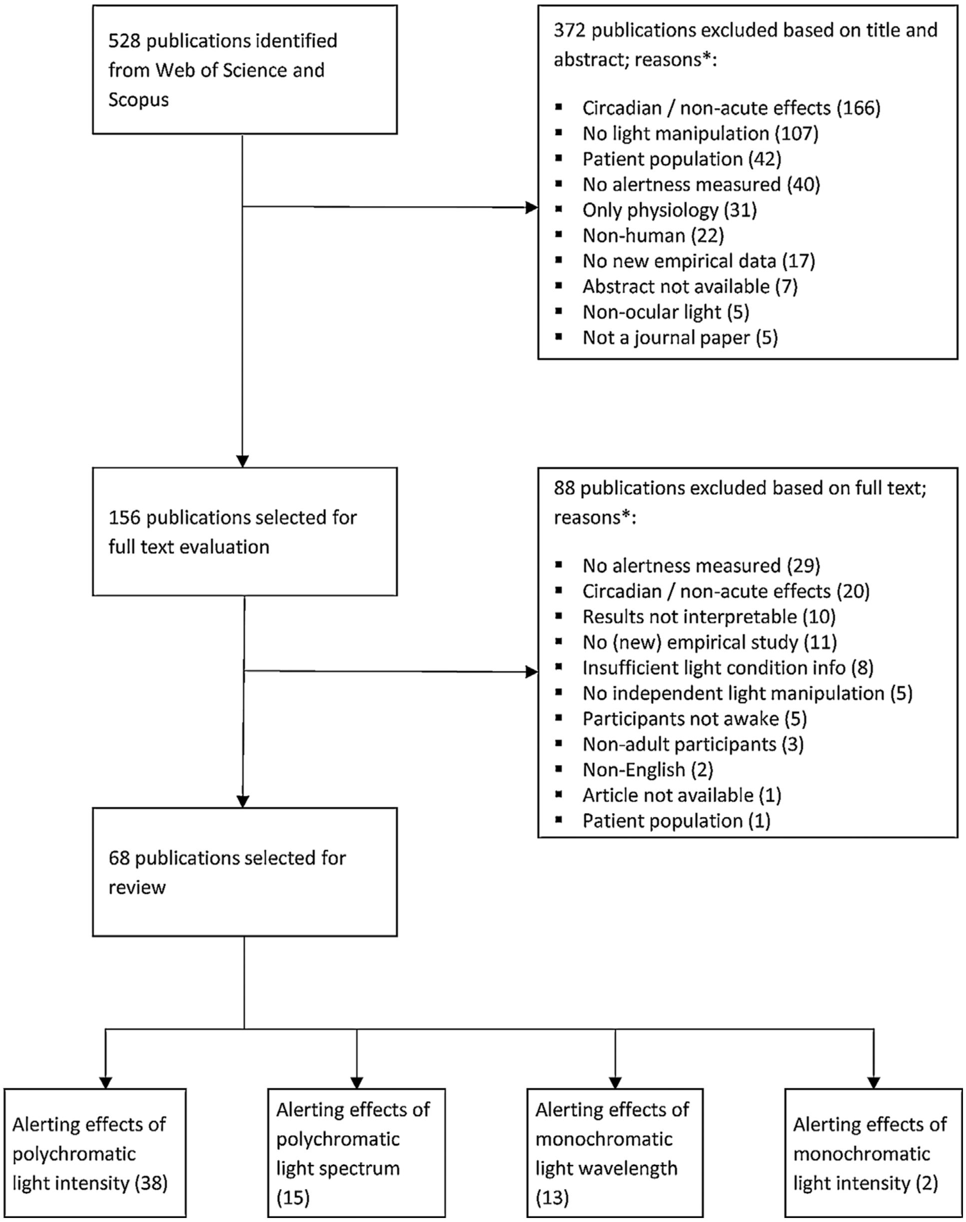

Fig. 1. Publication identification and selection process. (* Some publications were excluded for multiple reasons).

the remaining 156 publications were read in full text and another 88 of them were rejected, the main reasons being that no alertness measures as defined above were reported (29 cases) or no acute alerting effects of light were measured (20 cases). This entire selection process was conducted twice, first by author AT for the dataset identified in 2014 (with slightly different selection criteria) and then by author JS for the dataset identified in 2015 and 2017. Of the remaining 68 publications, over half (38) reported the results of changing the intensity of polychromatic white light, 15 reported the effects of changing the spectrum of polychromatic light (though this was often confounded with changes in light intensity as well), 13 reported the effects of changing the wavelengths of colored monochromatic (single wavelength) light, and 2 studies reported on the effect of changing the intensity of colored light. Below, the alertness effects in these studies will be discussed separately according to the main light manipulation in each study.

2.3. Analysis

For many of the selected studies, it was not possible to compute effect sizes, because the relevant data were missing from the publications. For this reason, and also because the set of studies was very heterogeneous in terms of light manipulation, exposure duration and light adaptation state, a meta-analysis on the alerting effects of light was not feasible. Instead, we determined for each study whether it reported significant effects of light on alertness. This was done separately for the different light manipulations mentioned above (polychromatic white light intensity or spectrum, monochromatic light wavelength or intensity). If alertness was measured several times during light exposure, the significance of the largest effect during that period was determined. In some cases, significant effects were found in the opposite direction from what was expected (e.g., higher alertness with lower light intensity). Because this only occurred in a small number of cases (eight across all studies), these results were grouped together with the non-significant results in summary tables.

As mentioned above, alerting effects of light have been linked to melatonin suppression, which under normal circumstances can only occur in the evening or at night. Moreover, the baseline alertness state has been shown to follow a circadian rhythm and therefore also depends on the time of day [10,49]. Consequently, we categorized the studies according to the time of day at which the maximum effect of light exposure was measured (night: 0:00–6:00; morning: 6:00–12:00; afternoon: 12:00–18:00; evening: 18:00–0:00). Note that for a few of the studies this allocation to time of day was somewhat arbitrary, because precise information about the time of the measurements was lacking (1 case) or because light exposure spanned more than one category (7 cases). It should also be noted that time of day effects are not just due to circadian rhythms in alertness, but can also be caused by other factors, such as increasing homeostatic sleep pressure or fatigue.

Studies on sleep/wake regulation suggest that the underlying physiology functions as a flip-flop system [50,51] and that light may play a particularly important role around the transition from wakefulness to sleep and vice versa [14,52]. Generally, sleep/wake regulation is thought to be predominantly determined by a circadian and a homeostatic process [53–55]. Most studies on alerting effects of light do not provide any information concerning the circadian phase at which light exposure was applied. However, many of them do contain information about when participants woke up and how long they had been awake before they were exposed to the different light conditions. Therefore, we determined time awake as a proxy for homeostatic sleep pressure. For every study, we determined the time participants had been awake at the moment of the largest alerting effect reported in that study. If this was not clear from the publication, the time awake was computed from the average time of getting up to the midpoint of the light exposure.

3. Results

3.1. Alerting effects of higher polychromatic light intensity

The largest group of studies investigated the effect of increased white light intensity on subjective alertness (see Table 1). Of these, most simply compared alertness in a bright light condition (ranging from 100 to 10000 lx vertically at the eye) to that in a dim(mer) light condition (from < 1 to 1411 lx at the eye). Fig. 2A shows all studies according to their year of publication with the range of illumination levels used. In many studies, in particular the earlier ones, little information about the light source or the actual spectrum used is given. A majority of studies report significant differences in subjective alertness between their dim and bright light conditions, though a large group (17 out of 45 studies, or 38%) failed to find a significant effect. Only one study, by Cajochen et al. [7], systematically varied light intensity between 3 and 9100 lx to construct a dose-response function. The transition from sleepy to alert (measured towards the end of a 6.5 h light exposure during the night) occurred in a fairly narrow range of approximately 70–200 lx at the eye. The study contained too few measurements in this transition zone to conclude with confidence that alertness increases smoothly with light level, rather than according to a step function. The results from the few other studies that included multiple bright light levels concur with those from Cajochen et al. [7] in that they only found significant differences in subjective alertness between low (50 lx) and high (> 500 lx) light levels, but not between different high brightness conditions (500–6434 lx) [38,56–58]. Most studies that failed to find alerting effects used light levels in their dim light condition that were already in the higher alertness range reported in the Cajochen et al. study [7]. In addition, low statistical power due to small sample sizes may also have contributed to a lack of significant effects in these studies.

Table 2 summarizes the findings concerning alerting effects in studies that varied polychromatic white light intensity and also shows the distribution of the findings according to the time of day when alertness was measured. No clear pattern for time of day can be discerned from the results for subjective alertness. Moreover, results do not appear to depend on total exposure duration, which varied between 12 min and 24 h across the different studies (Fig. 3A). This is in agreement with results from Chang et al. [59], the only study that systematically varied exposure duration. Similarly, no systematic relationship between finding a significant effect of light intensity and the time participants had been awake at the time of testing can be seen (Fig. 4A).

Far fewer studies tested objective alertness by measuring performance on a PVT or simple reaction time task. Of the 16 studies that did, only 2 reported significant effects of increased light level on RT performance (see Tables 1 and 2). Phipps-Nelson et al. [60] reported improved PVT performance during bright light exposure in the afternoon after 5 h sleep restriction. However, Smolders et al. [34] only found a significant effect of bright light (1000 vs 200 lx) on PVT performance in the morning, not in the afternoon [32,34] (also see [58]). None of the studies that tested RT performance during bright light at night or in the evening reported significant beneficial effects. As with subjective alerting effects, there is little indication that RT performance effects of bright light depend on time of day, exposure duration or time awake (Figs. Fig. 33B and Fig. 44B).

3.2. Alerting effects of higher CCT or higher short wavelength energy in polychromatic light

In total, 15 publications investigated the alerting effects of modifying the polychromatic white light spectrum by adding or removing energy in the blue part of the spectrum (see Table 3). These studies can be divided into two categories. In six studies, the short wavelength portion of the spectrum was filtered out and alertness under this modified, yellow/orange looking spectrum was compared to that under the unfiltered white light spectrum. Filtering out the blue, short wavelength part of the spectrum (< 480 nm in [61,62], < 530 nm in [63,64], and < 540 nm in [65]) did reduce melatonin suppression, but did not have a detrimental effect on alertness. In fact, in the studies by Rahman et al. [61,62] even improved alertness was observed (both in performance and subjectively) in the filtered condition. This was true despite the fact that in all these studies the illuminance covaried with the spectrum manipulation, always being lower in the filtered than in the unfiltered condition. Higuchi et al. [66] compared alertness in participants wearing a red visor cap to that in participants who wore a blue visor or no visor. The red visor was found to reduce melatonin suppression, without causing PVT performance to deteriorate. Subjective alertness was not different between the two visor conditions, though lower than in the no visor condition. All the filtering studies were conducted at night.

In seven of the other studies, alertness in white light with a high correlated color temperature (CCT) was compared to that with a lower CCT. Four of them reported significant effects on subjective alertness with higher CCT (though in some of them the CCT increase was confounded with an increase in illumination level). Most of these studies were carried out in the evening (see Table 4). Chellappa et al. [67] reported increased alertness (both subjectively and in PVT RT, though not in lapses) for 6500 K compared to 2500/3000 K (at 40 lx). In a later study, they found this not to be true for individuals with the clock gene $PER3^{4/4}$ polymorphism (who also did not show a significant difference in melatonin suppression between high and low CCT) [68]. Subjective alerting effects of higher CCT were also reported by Cajochen et al. [30], who compared the effects of exposure to a LED-backlit screen to that of a non-LED screen, and by Wahnschaffe et al. [69]. Surprisingly, the combination of highest CCT (6000 K) and highest illuminance (500 lx) in the latter study did not produce an alerting effect. Two studies by Santhi et al., one in the morning [35] and one in the evening [70], did not find clear differences in subjective alertness between conditions with different CCTs and illumination levels (except with the near darkness baseline). In the morning study, they also failed to find a significant effect of CCT on PVT performance [35]. Canazei et al. [71] did not find significant differences in PVT performance for three CCTs between 2166 K and 4667 K.

In the last two studies, subjective alertness in polychromatic white light was compared to that in monochromatic red light. Figueiro et al. [72] (Experiment 2) combined daylight exposure during the day with intermittent exposure to monochromatic blue light during day and

Table 1
Alerting effects of illumination level (polychromatic white light). Alerting effects are indicated with + if alertness was significantly higher with higher illuminance, with – if it was significantly lower and with 0 if no significant difference was reported.

First author	Year	Sample size	Bright illuminance (lx)	Dim illuminance (lx)	Exposure duration (h)	Time of day	Performance effect	Subjective alerting effect
Daurat [40]	1993	8	2000	150	24	Morning		+
Dollins [56]	1993	24	1500, 3000	300	12	Night	0	0
Myers [38]	1993	15	500, 1000, 1500	50	4	Evening		+
Daurat [105]	1996	8	1000–1500	50	14	Night		+
Daurat [105]	1996	8	1000–1500	50	14	Morning		–
Leproult [106]	1997	17	5000	300	3	Night		0
Wright [107]	1997	10	2500	100	12	Night	0	+
Foret [108]	1998	8	700–1000	50	4	Evening		0
Foret [108]	1998	8	700–1000	50	4	Morning		+
Lafrance [109]	1998	7	10000	100 (red)	4.5	Morning		0
Cajochen [7]	2000	20	3–9100	3	6.5	Night		+
Daurat[a] [110]	2000	8	2000	< 50	12	Night		+
Daurat[b] [110]	2000	8	2000	< 50	4	Evening		0
Daurat[c] [110]	2000	8	2000	< 50	4	Morning		+
Iskra-Golec [33]	2000	15	2300	100	0.5	Night	–	0
O'Brien [57]	2000	12	2788, 6434	1411	0.33	Afternoon		0
Åkerstedt [111]	2003	20	2000	30 (red)	0.5	Morning		+
Lavoie [112]	2003	14	3000	< 15 (red)	4	Night		0
Phipps-Nelson [60]	2003	16	1000	< 5	5	Afternoon	+	+
Rüger [90]	2003	12	5000	10	4	Night		+
Landström [114]	2004	6	1000	NA	0.5	Night		0
Perrin [115]	2004	13	8000	0.01	0.28	Night		+
Crasson [116]	2005	18	5000	170	0.5	Afternoon		0
Rüger [113]	2005	12	100	< 10	4	Night		0
Kaida [117]	2006	16	> 3000	< 100	0.5	Afternoon	0	+
Rüger [118]	2006	12	5000	< 5	4	Afternoon		+
Vandewalle [119]	2006	16	> 7000	< 0.1	0.35	Afternoon		+
Iskra-Golec [120]	2008	18	4000	300	0.25	Afternoon		+
Chang [59]	2012	10	> 7500	< 3	0.2–4	Night		+
Kretschmer [121]	2012	16	3500	300	6	Night	0	
Münch [122]	2012	29	1000	176	6	Evening		+
Smolders [34]	2012	32	1000	200	1	Morning	+	+
Smolders [34]	2012	32	1000	200	1	Afternoon	0	+
Teixeira[d] [123]	2013	23	8000	300	0.33	Evening		+
Teixeira[e] [123]	2013	23	8000	300	0.33	Evening		0
Bromundt [124]	2014	20	10000	< 8	0.2	Evening	0	+
Smolders[f] [32]	2014	28	1000	200	0.5	Morning/ Afternoon	0	+
Smolders[g] [32]	2014	28	1000	200	0.5	Morning/ Afternoon	0	0
Borisuit [125]	2015	29	> 1000	175	6	Afternoon		0
Leichtfried [126]	2015	33	5000	400	0.5	Morning		+
Slama [127]	2015	10	2000	< 200	0.5	Afternoon	0	
Huiberts [37]	2015	32	1000	200	1	Morning		+
Huiberts [37]	2015	32	1000	200	1	Afternoon		+
Huiberts [58]	2016	39	600, 1700	160	0.92	Morning/Afternoon	0	0
Maierova[h] [128]	2016	16	1000	< 5	16	Morning/ Afternoon/ Evening	0	+
Maierova[i] [128]	2016	16	1000	< 5	16	Morning/ Afternoon/ Evening/ Night	0	+
Weisgerber [129]	2017	21	5600	35	0.75	Morning	0	+

[a] Experiment A.
[b] Experiment B, evening.
[c] Experiment B, early morning.
[d] Light exposure 19:00–19:20.
[e] Light exposure 21:00–21:20.
[f] Mental fatigue group.
[g] Control group.
[h] Morning chronotype.
[i] Evening chronotype.

night and found higher subjective alertness during the night when compared to dim red light. In their first experiment, however, Figueiro et al. failed to find significant effects on subjective alertness of daylight exposure and monochromatic wavelength (blue, 470 nm, or red, 630 nm). Therefore, it is not clear whether the effect in their second experiment should be attributed to daylight exposure, intermittent blue light, or the combination of the two. Sahin et al. [31] did not find significant differences in subjective alertness between red light and polychromatic white light with the same irradiance.

3.3. *Alerting effects of monochromatic/narrowband spectrum manipulations*

Most of the studies that investigated alerting effects for different monochromatic wavelengths compared blue (~470 nm) to either red (~630 nm) or green (~555 nm). Only two studies by Revell et al. [73,74] compared multiple wavelengths (see Table 5). While studies by Cajochen et al. [75] and by Lockley et al. [47] reported that participants felt more alert when exposed to blue light (compared to green),

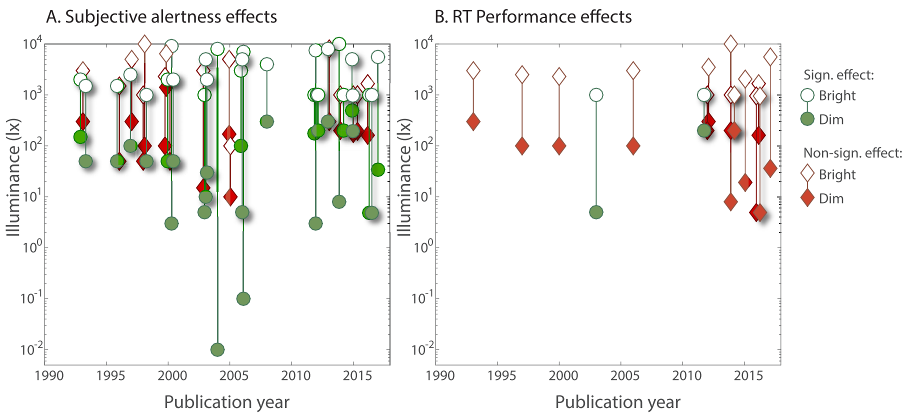

Fig. 2. Alerting effects of polychromatic illumination level on subjective alertness (left) and RT performance (right). Open symbols represent the bright light illumination level in a study, connected to closed symbols for the dim light level in the same study. Green circles indicate studies that reported a significant alerting effect of increased illuminance, while red diamonds represent studies that failed to find significant alerting effects or reported significant detrimental effects of illumination level on alertness. Studies in the same publication year have been jittered horizontally for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of alerting effects of increased illuminance (polychromatic white light). The number of studies showing significant positive effects or non-significant/negative effects of increased illuminance are shown for different times of the day at the time of testing.

Alertness measure		Time of day				
		Night	Morning	Afternoon	Evening	Total
Subjective	sign.	7	8	9	4	28
	non-sign.	6	3	5	3	17
Performance	sign.	0	1	1	0	2
	non-sign.	4	2	8	1	15

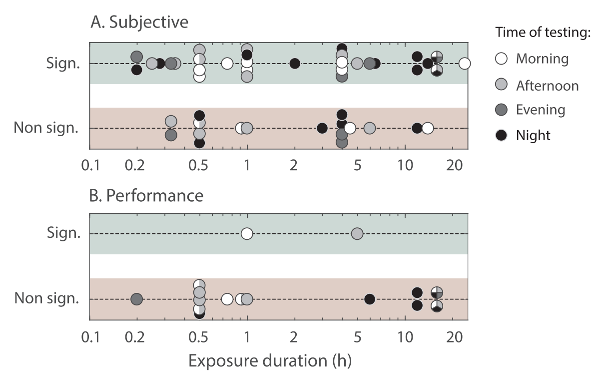

Fig. 3. Alerting effects of polychromatic illumination level on subjective alertness (A) and RT performance (B), plotted against the total exposure duration (on a log scale for clarity). Data points in the green shaded region represent studies that report significant alerting effects of increased light level, while those in red shading show studies that report non-significant or negative findings. Data points with the same exposure duration have been jittered vertically to increase visibility. Symbol grey shades indicate the time of day at the moment of testing. The data from Chang et al. [59] are shown for all 4 exposure durations used (0.2, 1.0, 2.5, 4.0 h). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

most studies failed to find similar subjective alerting effects (see Table 6). Revell et al. [73] did report that subjective alertness was higher with blue (470 nm) than with amber (600 nm), but also found that alertness was still higher with an even shorter wavelength (violet, 420 nm). Papamichael et al. [76] tested whether concurrent exposure to both blue (479 nm) and red (627 nm) light would affect subjective alertness, but found no differences between the different combinations of the two wavelengths. Adding red also did not affect melatonin suppression by blue light. Interestingly, of the eight studies that measured RT performance, five found better performance with short wavelength light (green in [77], blue in the others). Thus, in contrast to polychromatic light manipulations, there may be some evidence for effects of monochromatic blue light on RT performance, while there is little evidence for subjective effects of monochromatic wavelength. Note,

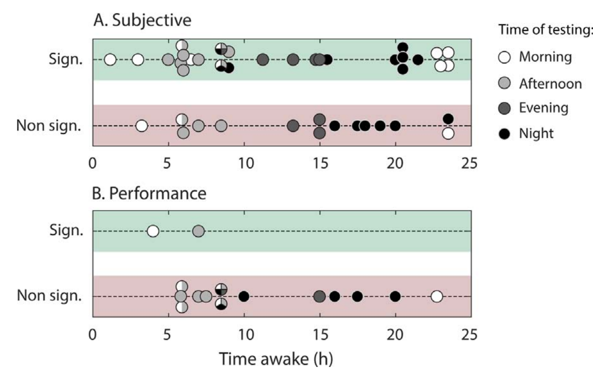

Fig. 4. Alerting effects of polychromatic illumination level on subjective alertness (A) and RT performance (B), plotted against time awake at the time when the maximum effect was found. Shading and symbol colors as in Fig. 3.

however, that a recent study in two separate labs failed to find evidence for both subjective and RT effects of exposure to blue versus green light during the day [78].

Two studies investigated the effect of higher intensities of monochromatic light on subjective alertness (see Table 7). Figueiro et al. [79] failed to find significant differences in subjective alertness at night for different illuminance levels of blue (470 nm) light, ranging from 5 to 40 lx. Plitnick et al. [80], on the other hand, compared 10 and 40 lx illumination levels for both blue (470 nm) and red (630 nm) light, also during the night, and found increased subjective alertness for higher blue light intensities and the opposite for red.

4. Discussion

4.1. Summary of the results

The studies on acute alerting effects of light that we identified form quite a heterogeneous collection. They vary in their main light manipulation (polychromatic light intensity or light spectrum, monochromatic/narrowband light intensity or dominant wavelength, constant light exposure or intermittent exposure), in their exposure duration (10 min to 24 h), the time of day at which participants were exposed to light, in sleep duration before light exposure (4–10 h), in adaptation phase duration (0–24 h) and adaptation light level (0–400 lx), in sample size (6–39) and in the dependent variables that were measured as outcome variables. Consequently, it is perhaps not surprising that they also show quite a heterogeneous pattern of results.

Overall, both increased intensity and shifts towards higher color temperatures were found to increase subjectively experienced alertness for exposure to polychromatic white light. This was the case irrespective of time of day, time awake or exposure duration. Based on the work of Cajochen et al. [7], the transition point from low to high subjective

Table 3
Alerting effects of spectrum shifts towards higher CCT or more blue (polychromatic light). Alerting effects are indicated with + if alertness was significantly higher with higher CCT/more blue, with − if it was significantly lower and with 0 if no significant difference was reported.

First author	Year	Sample size	Light conditions	Exposure duration (h)	Time of day	Performance effect	Subjective alerting effect
Kayumov [63]	2005	19	dim white light (< 5 lx) bright white light (800 lx) filtered light > 530 nm (584 lx)	12	Night	0	0
Cajochen [30]	2011	13	4775 K (250 cd/m2) 6953 K (250 cd/m2)	5	Evening		+
Chellappa [67]	2011	16	2500 K (40 lx) 3000 K (40 lx) 6500 K (40 lx)	2	Evening	+ [a]	+
Higuchi [66]	2011	11	4200 K, no visor (500 lx) 4200 K, red visor (160 lx) 4200 K, blue visor (160 lx)	4	Night	0	0
Rahman [61]	2011	12	5000 K (513 lx) 5000 K filtered > 460 nm (460 lx) 5000 K filtered > 480 nm (439 lx) 5000 K filtered 30% (472 lx)	12	Evening/ Night/Morning	–	–
Chellappa [b] [68]	2012	18	2500 K (40 lx) 6500 K (40 lx)	2	Evening		0
Chellappa [c] [68]	2012	18	2500 K (40 lx) 6500 K (40 lx)	2	Evening		+
Santhi [70]	2012	22	Blue-depleted (TL16, 225 lx) Blue-intermediate (2700 K, 135 lx) Blue-enriched (17000 K, 135 lx) Bright blue-enriched (17000 K, 700 lx)	4	Evening		0
Rahman [62]	2013	9	5000 K (179 lx) 5000 K filtered > 480 nm	12	Evening Night/Morning	–	–
Santhi [35]	2013	11	2592 K (19 lx) 2592 (200 lx) 7717 K (195 lx) 7280 K (750 lx)	4	Morning	0	0
Van de Werken [64]	2013	33	3000 K (< 5 lx) 3000 K (256 lx) 3000 K filtered > 530 nm (193 lx)	8	Night		0
Wahnschaffe [69]	2013	9	2000 K (130 lx) 2800 K (500 lx) 5000 K (500 lx) 6000 K (130 or 500 lx)	0.5	Evening		+
Figueiro [72]	2014	8	< 1 lx red > 500 lx daylight + 40 lx blue	10	Night		+
Sahin [31]	2014	13	2568 K (361 lx) 631 nm (213 lx)	1.83	Morning Afternoon		0
Sasseville [65]	2015	10	Bright white light (500 μW/cm^2) Filtered light > 540 nm (500 μW/cm^2)	0.5	Night		0
Canazei [71]	2016	31	2116 K (49.48 μW/cm^2) 3366 K (46.25 μW/cm^2) 4667 K (44.12 μW/cm^2)	5	Night	0	

[a] Sign. effect on RT, not on lapses.
[b] PER3$^{4/4}$ polymorphism.
[c] PER3$^{5/5}$ polymorphism.

Table 4
Summary of alerting effects of increased CCT/higher short wavelength energy (polychromatic light). The number of studies showing significant positive or non-significant/negative effects of increased CCT or increased energy in the blue part of the spectrum are shown for different times of the day at the time of testing.

Alertness measure		Time of day				
		Night	Morning	Afternoon	Evening	Total
Subjective	sign.	1	0	0	4	5
	non-sign.	6	2	1	1	10
Performance	sign.	0	0	0	1	1
	non-sign.	4	2	0	0	6

alertness for illumination level at the eye appears to be around 100 lx, though this may depend on color temperature.[1] Although a substantial proportion of studies failed to find subjective alerting effects of light intensity, several of these used a baseline light level that was already above this value. Of the studies that compared subjective alertness for exposure to different color temperatures, a small majority reported higher self-rated alertness with higher CCT, but the number of studies was rather small. Surprisingly, filtering out the short wavelengths from polychromatic white light was not found to have a negative impact on subjective alertness, in some cases even a positive effect. Although this is not easy to reconcile with the results from the studies that compared different CCTs, it does match the results from studies with monochromatic light. Only a few studies found higher subjective alertness for

[1] Cajochen et al. [7] used light with a CCT of approximately 4000 K (personal communication from Jamie Zeitzer, one of the authors).

Table 5
Alerting effects of spectral shifts towards shorter wavelengths (monochromatic light). Alerting effects are indicated with + if alertness was significantly higher with shorter wavelengths, with – if it was significantly lower and with 0 if no significant difference was reported.

First author	Year	Sample size	Light conditions	Exposure duration (h)	Time of day	Performance effect	Subjective alerting effect
Horne [77]	1991	12	white (500 lx) green (2000 lx) 1 Hz red/green (300 lx)	0.17	Morning	+	+
Cajochen [75]	2005	10	460 nm (12.1 μW/cm^2) 555 nm (10.05 μW/cm^2)	2	Evening		+
Lockley [47]	2006	16	460 nm (12.1 μW/cm^2) 555 nm (10.05 μW/cm^2)	6.5	Night	+	+
Revell [73]	2006	12	420 nm (2.3e13 photons/cm^2/s) 440 nm (2.3e13 photons/cm^2/s) 440 nm (6.2e13 photons/cm^2/s) 470 nm (6.2e13 photons/cm^2/s) 600 nm (6.2e13 photons/cm^2/s)	4	Morning		+
Figueiro [84]	2009	14	470 nm (10 or 40 lx) 630 nm (10 or 40 lx)	0.75	Night	0	0
Phipps-Nelson [130]	2009	8	broadband white (0.2 lx, 0.5 μW/cm^2) 460 nm (1 lx, 2.1 μW/cm^2) 620 nm (1 lx, 0.7 μW/cm^2)	6	Night	+[a]	0
Sletten[b] [91]	2009	11	456 nm (6.0e13 photons/cm^2/s) 548 nm (6.0e13 photons/cm^2/s)	2	Morning		0
Sletten[c] [91]	2009	15	456 nm (6.0e13 photons/cm^2/s) 548 nm (6.0e13 photons/cm^2/s)	2	Morning		0
Revell [74]	2010	12	437 nm (19.1 μW/cm^2) 479 nm (10.4 μW/cm^2) 532 nm (23.8 μW/cm^2) 4000 K (36 μW/cm2) 17000 K (20.3 μW/cm^2) 437 + 479 nm (29.5 μW/cm^2) 479 + 479 nm (20.8 μW/cm^2) 479 + 532 nm (34.2 μW/cm^2)	0.5	Night	0	–
Figueiro [131]	2011	10	red (< 1 lx) 470 nm (40 lx)	0.83	Afternoon	+	0
Papamichael [76]	2012	21	479 nm (1e13, 2.5e13, 5e13, or 1e14 photons/cm^2/s) 627 nm (5e13, 1e14, or 3e14 photons/cm^2/s) 479 + 627 nm (6e13, 7.5e13, 1e14, 1.3e14, 1.5e14 or 3.3e14 photons/cm^2/s)	0.5	Night		0
Sahin [132]	2013	13	470 nm (40 lx) 630 nm (40 lx)	0.8	Afternoon		0
Rahman [89]	2014	8	460 nm (2.8e13 photons/cm^2/s) 555 nm (2.8e13 photons/cm^2/s)	6.5	Afternoon	+	0
Segal [78]	2016	23 25 12	458–480 nm (2.8-8.4e13 photons/cm^2/s) 551/555 nm (2.8-8.4e13 photons/cm^2/s) Dark (0 lx)	3	Morning Afternoon	0	0

[a] Sign. effect on RT, not on lapses.
[b] Young participants.
[c] Old participants.

Table 6
Summary of alerting effects of shorter wavelengths (monochromatic light). The number of studies showing significant positive effects or non-significant/negative effects of wavelengths in the blue part of the spectrum versus other wavelengths are shown for different times of the day at the time of testing.

Alertness measure		Time of day				
		Night	Morning	Afternoon	Evening	Total
Subjective	sign.	1	2	0	1	4
	non-sign.	4	2	4	0	10
Performance	sign.	2	1	2	0	5
	non-sign.	2	0	1	0	3

exposure to blue light compared to longer wavelengths.

Turning to performance measures, very few studies reported significant effects of higher light intensities or CCT on RT performance, which dissociates these results from the effects on subjective alertness (though the number of studies that used performance measures of alertness was also far smaller than those that used subjective measures). This may have been due to the fact that most of these studies used fairly high baseline light levels, already lying in the upper range of the dose-response function established by Cajochen et al. [7] (see Fig. 2B). Interestingly, studies that used exposure to monochromatic light appear to show a different pattern. Several of these reported improved RT performance with blue light compared to longer wavelengths.

For the potential moderating factors (time of day, exposure duration and time awake), we found little indication that they systematically influenced the alerting effects of light exposure. However, this conclusion should be taken with caution, for a number of reasons. It was sometimes hard to determine the exact time of day or the time awake because these details were lacking from the publications. Moreover, the number of studies (especially for the effects on performance and for the effects of different wavelengths of monochromatic light) was relatively low. And, finally, the studies generally employed rather small sample sizes.

4.2. Sample size, effect size, and power

Nearly all studies on acute alerting effects of light used small samples (ranging from n = 6 to 39). While understandable given the

Table 7
Alerting effects of illumination level (monochromatic or narrowband light). Alerting effects are indicated with + if alertness was significantly higher with higher intensities, with − if it was significantly lower and with 0 if no significant difference was reported. None of the reported studies used RT performance measures of alertness.

First author	Year	Sample size	Light conditions	Exposure duration (h)	Time of day	Subjective alerting effect
Figueiro [79]	2007	8	470 nm (5 lx) 470 nm (10 lx) 470 nm (20 lx) 470 nm (40 lx)	0.83	Night	0
Plitnick [80]	2010	22	470 nm (10 lx) 470 nm (40 lx)	1	Night	+
Plitnick [80]	2010	22	630 nm (10 lx) 630 nm (40 lx)	1	Night	–

complexity of this kind of studies, these small sample sizes reduce the power of the statistical results and increase the likelihood of biased results [81]. To detect a medium effect size (Cohen's $d_z = 0.5$) with a power of 0.8 and a significance level of 0.05 between two conditions in a within-subject design (paired *t*-test), sample size should exceed n = 26 (calculated with GPower 3.0 [82]). Only nine out of the 68 papers in our review used a sample size larger than this and only one single study reported sample size to be based on an a priori power calculation [78]. If the true effect size is smaller, which does not seem implausible given the results of our review, or if higher power is required, still larger sample sizes are needed ($n > 155$ to detect a small effect size $d_z = 0.2$ with power 0.8, or $n > 44$ for $d_z = 0.5$ and power 0.95). Since most studies employed repeated measures designs, with multiple measurements on each participant within each condition, these required sample sizes for a paired *t*-test may represent the 'worst case scenario'. Still, the many instances of null effects may have been due to small sample sizes and insufficient power to detect any acute alerting effects of light. At the same time, small sample sizes increase the likelihood of biased results, which is exacerbated by a potential publication bias where studies with significant effects are more likely to be published [81,83].

Besides using small samples, most studies failed to report effect sizes, or detailed results that could be used to compute these. For this reason, we decided to report significance (yes/no) as the criterion variable in this review, rather than to perform a meta-analysis on effect sizes. While allowing for an overview of the effects in different studies, this also harbours the danger of on the one hand giving more weight to significant results in small studies, which might be incidental, and on the other hand of discounting the evidence in non-significant results, which might be due to insufficient power [83]. Taken together, these factors prevent us from being able to draw strong conclusions regarding acute alerting effects of light. Overall, these effects appear to be not very large. This is suggested by the large proportion of studies (including some with larger sample sizes) that failed to find significant effects, as well as by the comparison to the effects of other factors in the same studies. Several studies reported a significant decrease in alertness (measured either subjectively or in RT performance) in the course of the light exposure interval, even when the light exposure itself did not have a significant effect (e.g., [35,63,71,84]). Thus, the power of these studies was sufficiently large to detect effects of time (be it due to fatigue, increasing sleep pressure, or circadian effects), but not of the light exposure.

For future studies, we recommend the use of a-priori power analyses to determine adequate sample sizes. Moreover, the reporting of effect sizes would help other researchers to determine the necessary sample size for their studies, as well as facilitate meta-analyses of the acute alerting effects of light exposure. The field would also benefit tremendously from more studies that measure an entire dose-response curve (such as that by Cajochen et al. [7]), rather than only two or three points on that curve. This would provide a much more comprehensive insight into the effects of different aspects of light exposure on alertness, as well as increase confidence in the reliability of these results. A recent retrospective analysis of eight studies reconstructed such a curve and showed that changes in KSS due to exposure to bright or blue light could be better described by the change in melanopic activation than by changes in photopic light levels [85]. New empirical studies specifically designed to test the relationship between activation of the different photoreceptors and alertness are needed to get a better understanding and to provide input to the modelling of these effects.

4.3. Other methodological issues

In several studies included in this review, details regarding the methodology or the results were lacking, hampering interpretation and replication. This was even true for descriptions of the light manipulation used (see [86] for similar observations in studies on light therapy). While more recent studies tended to include more information concerning the light conditions than earlier ones, most still did not comply with the recommendation of a recent review paper to at least report the irradiance spectrum weighted by the sensitivity curves of the five known different photoreceptors (S/M/L cones, rods, and ipRGCs) and to make the entire spectrum available to other researchers [87] (also see [88]).

Another potential issue concerns the actual light exposure in the studies reviewed in this paper. Administration of the light conditions was done in various ways. While some studies exposed participants to light via custom made goggles (e.g. [72,75]), others used integrating spheres [47,74,89], light boxes [70,84], normal light fixtures [32,34,69] or electronic displays [30]. Given sufficient control of the actual stimulus at the eye, the physiological effects of light exposure would not be expected to vary with these different methods (possibly with the exception of the stimulated area of the retina; see [90]). However, the method of stimulus delivery may have affected more subjective measures of alertness, which may be susceptible to the effects of expectation or association. Moreover, only a few studies controlled pupil size during light exposure (via pupil dilation: [47,74,76,89–91]; it was not controlled but measured in [66,75,80,84]). Pupil size is largely determined by photic activation of a subset of ipRGCs which project onto the olivary pretectal nucleus and therefore is reduced with higher light levels and higher energy in the short wavelength part of the visible light spectrum [46,92–94]. Consequently, the increase in light levels reaching the retina will typically be smaller than that specified at the cornea in different light conditions, which may reduce the effects on alertness (see [95] for a similar effect on melatonin suppression). Even when it may be undesired to interfere with the normal pupillary reflex in more applied settings, it is still important to take this factor into account when designing a study.

4.4. Other factors

In contrast to most studies in this review, which exposed participants to various light conditions during a restricted period of time after an initial adaptation period with dim light, patterns of light exposure in daily life are usually very different. People are typically exposed to varying light levels throughout the day and then continue to be exposed to light in the evening or at night, albeit at lower levels [96–98]. Recently, Chang et al. reported that exposure to 90 lx during daytime in the two days preceding 6.5 h light exposure at night reduced the effects of nocturnal light exposure on subjective sleepiness and melatonin [99] (also see [100]). Similarly, melatonin suppression by light at night has been reported to be greater during winter time (with less light exposure during the day) than in summer [101]. Here, too, it seems that light with high short wavelength energy is particularly effective in modifying the effects of light at night [102]. Although these effects of prior light history may be partially confounded with circadian phase shifts, they indicate that one needs to be cautious in generalizing findings concerning effects of light from lab studies to daily life.

Little attention has been paid in the literature to individual differences in the effects of light. However, some studies indicate that these differences exist and may have a genetic basis. Different polymorphisms of the PER3 gene have been shown to be related to the effects of sleep deprivation on cognitive performance, with PER3$^{4/4}$ individuals showing smaller detrimental effects of sleep loss than PER3$^{5/5}$ individuals [103]. As noted above, exposure in the evening to light with a higher CCT has been shown to increase subjective alertness in PER3$^{5/5}$, but not in PER3$^{4/4}$ individuals [68]. Brain activation in the prefrontal cortex and intraparietal sulcus was shown to be enhanced by blue versus green light after a night of sleep in PER3$^{4/4}$, but not in PER3$^{5/5}$ individuals, while the opposite pattern was found after sleep deprivation [104]. These results suggest that the alerting effects of light depend on genotype, circadian phase and sleep homeostasis and that light may exert its alerting effect particularly when the combination of these factors negatively impacts the arousal state of the person [14,52,104].

5. Conclusions

Light affects humans in various ways. Here, we have reviewed the evidence for acute alerting effects of light on subjective alertness and on reaction time tasks that measure alertness. Exposure to higher intensities of polychromatic white light has been found to increase subjective alertness in many studies. Still, a substantial portion of studies failed to find these effects, which may have been partially due to high baseline intensities, as well as to low statistical power because of small sample sizes. The latter also makes it difficult to draw definitive conclusions from studies with other kinds of light manipulations. Increased color temperature of white light (containing more power in the short, blue appearing wavelengths) has been reported in some papers to lead to higher levels of subjective alertness, but at the same time participants in other studies did not report to feel less alert when the short wavelength part of the spectrum was filtered out. Similarly, studies using monochromatic light exposure do not present a clear pattern of results on the subjectively alerting effects of blue light versus longer wavelengths (red or green).

Far fewer studies investigated the alerting effects of light using reaction time tasks. Of those that did, very few found evidence of improved performance with higher light levels or increased color temperature of white light. A higher number of studies reported these effects for exposure to monochromatic blue light compared with longer wavelengths, but overall the number of studies was small and, again, sample sizes did not allow for high statistical power. For the same reasons, we could not draw strong conclusions regarding possible moderating factors, such as time of day, time awake, or exposure duration. In general, the field needs studies with larger sample sizes, higher statistical power and with multiple levels of the independent variable of interest, allowing for the construction of dose-response curves.

Conflicts of interest

JS is employed by Philips Lighting; RvE is employed by Philips Electronics and worked for the Philips Lighting research program until Dec. 31st, 2015. BV was employed by Philips Electronics until Febr. 28th, 2017 and worked for the Philips Lighting research program until Dec. 31st, 2015. AT did part of her M.Sc. thesis at Philips Research in 2014.

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