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Non-Image-Forming Effects of Daytime Electric Light Exposure in Humans: A Systematic Review and Meta-Analyses of Physiological, Cognitive, and Subjective Outcomes

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ABSTRACT

Light exerts numerous nonvisual or non-image-forming, effects – such as its impact on melatonin suppression, circadian phase-shifts, sleep quality, and alertness. While research typically focuses on evening and nighttime effects, a growing number of studies described the nonvisual impact of light during daytime (from 7am to 7pm). In this work, we systematically analyzed 141 peer-reviewed articles (150 studies) published by March 2023, encompassing 5401 healthy volunteers mainly aged 18–30. We calculated effect sizes using data extracted from the text, tables, or graphs and conducted 43 individual multilevel meta-analyses of physiological, cognitive, and subjective outcomes, divided into effects of light intensity and light spectral properties. We retained 17 meta-analyses that were based on data from more than 10 studies. Our results showed that higher light intensity enhances EEG brain wave-activity associated with heightened cognitive processing and attention, leads to faster response times, and reduces subjective sleepiness. The effect sizes were small. Meta-analyses of the effects of spectral characteristics of light did not show any significant summary effects. Overall, our findings suggest that higher ambient light intensities during daytime may be beneficial, but benefits are likely to be modest in healthy young human adults, who already are performing at near-optimal levels.

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Non-image-forming; daytime; electric light; humans

1. Introduction

There has been a steady increase in the number of studies on nonvisual effects of light, particularly in the last two decades since the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain the photopigment melanopsin (Provencio et al. 1998). Under the control of the suprachiasmatic nucleus (SCN) – the primary circadian pacemaker (Ralph et al. 1990),—melatonin is secreted late in the evening and at night to transmit the signal of the environmental light-dark cycle (Reiter 1991). For this reason, nonvisual or non-image forming (NIF) effects of light on melatonin secretion have been most frequently investigated in the evening and at night-time. In addition to the effects on melatonin secretion (Brainard et al. 2001; Thapan et al. 2001), light in late evening or at night has been reported to affect sleep quality and circadian physiology (Cho et al. 2015), subjective and objective alertness (Cajochen 2007), as well as cognitive performance (Vandewalle et al. 2009). The neural mechanism underlying this nocturnal impact of light mainly refers to the projections of the ipRGCs to the SCN via the retinohypothalamic tract. In particular, light between 460 and 490 nm (which usually appears blue) – or the portion of these wavelengths in the spectrum, which makes light appear as cooler/more bluish – stimulates the photopigment melanopsin and activates the SCN (Berson et al. 2002; Enezi et al. 2011) late in the evening or at night, leading to NIF effects.

The question arises as to whether NIF effects of light are also present during daytime. This topic is especially relevant as we spend most of our time indoors and are constantly exposed to electric light, which is usually of lower intensity and has different spectral properties than daylight, i.e.

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certain parts of the spectrum might be more pronounced than others, as opposed to the full spectrum of daylight, while looking the same to the eye. The ipRGCs not only play an important role in entraining the central pacemaker in the SCN to the light-dark cycles, but also innervate key brain regions involved in the maintenance of cognitive performance including alertness levels (LeGates et al. 2014). Interestingly, anatomical pathways through which light affects mood and learning independent of circadian pacemaker function have been identified in mice (Fernandez et al. 2018). A functional link between light and prefrontal cortex (PFC)-mediated cognitive and affective phenomena has also been identified in humans (Sabbah et al. 2022).

Several reviews have summarized the effects of daytime light exposure on humans. However, they focused on office lighting, either limited to effects on mood and alertness in field studies (Pachito et al. 2018), on health factors of office lighting conditions (van Duijnhoven et al. 2017), or discussed the impact of light at work without a systematic review of the available evidence (van Bommel 2006; van Bommel and van den Beld 2004). Xiao et al. (2021) reviewed 27 papers on the effects of indoor lighting (including daytime light exposure) on circadian rhythms (melatonin suppression, phase shift), sleep quality, alertness (subjective and objectively assessed through EEG and performance), and mood (positive and negative affect). They counted how many studies found significant effects of illuminance levels and colorimetric conditions (such as lighting correlated color temperature or wavelength) – synthesis technique known as "vote counting" – and, based on the count and effect direction, concluded that high illuminance correlates positively with subjective alertness during daytime, increases positive mood in the morning and decreases it in the afternoon. The same "vote counting" approach was used in the review by Souman et al. (2017), which focused on the acute effects of light (both illuminance level and spectrum) on alertness, and in the review by Siraji et al. (2022), which summarized effects of daytime light exposure on alertness and higher cognitive functions, with the conclusions that the results are inconsistent, lack statistical power, due to small sample sizes, and reports frequently lack details on the nature of stimuli. Other reviews using "vote counting" strategy of counting studies were by Alwalidi and Hoffmann (2022) as well as by Xu and Lang (2018), which reviewed the alerting effects of light and highlighted the importance of environmental and individual factors for light interventions. In conclusion, the above-mentioned reviews (1) highlight an increasing number of studies on daytime NIF effects in humans, and (2) show that findings are inconsistent. Shortcomings of these reviews are that the evidence collected was only discussed descriptively or significant results were only counted. Thus, quantitative meta-analyses are needed for an in-depth analysis of the magnitude of daytime NIF effects. Mu et al. (2022) conducted the first meta-analysis of NIF light effects, focusing on alertness. The authors summarized subjective (self-reported) and objective (physiological) alerting responses to light from 27 studies. The analyses showed significant effects of light on both subjective and objective measures of alertness. Both objective and subjective alertness were increased during both daytime and nighttime. Another recent review and meta-analysis by Li et al. (2024) summarized studies and data on daytime light exposure effects on alertness, cognition, and mood on healthy persons. The analyses found that daytime light interventions improve alertness and cognition and reduces alpha wave of the EEG. However, the conclusions that can be drawn from both meta-analyses are limited because only the two most extreme lighting conditions of each individual study were included in the datasets.

Thus, given the inconclusive findings on daytime NIF effects and the lack of comprehensive quantitative analyses of available research data, our goal was to summarize all available findings concerning NIF effects of electric daytime light exposure in healthy human adults. We conducted meta-analyses for physiological, cognitive, and subjective outcomes. We divided our analyses into effects of light intensity and the spectral power distribution of light, as these are two properties of light that can be attributed to the light source. Other properties, such as spatial distribution, direction, timing, or duration, are nested in temporal or spatial dimensions and were not investigated in the present work. Our analyses included more than two lighting conditions (Li et al. 2024; cf. Mu et al. 2022) per study: We included all light manipulations for which we could extract outcome estimates. In this way, we provide a comprehensive overview and estimate of daytime NIF effects.

2. Methods

This systematic review and meta-analysis were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement (Moher et al. 2009; Page et al. 2021). The review and protocol were not registered.

2.1. Search strategy

The article search was conducted in PubMed, Scopus, and Web of Science databases, with the last search being performed in March 2023. A detailed description of the article search is provided in the Supplemental material, S1 File, which includes a complete list of keywords, filters, and limits, as well as the dates when each source was last consulted.

2.2. Inclusion and exclusion criteria

Studies were included in the final analysis if (1) participants were healthy human adults, (2) light exposure occurred during daytime (between ca. 6am and ca. 7pm) or there was no reason to assume that exposure was not during daytime, (3) lighting manipulation occurred indoors, (4) only electric light was tested, (5) sufficient information on light characteristics was provided, to allow at least relative discrimination of experimental conditions in terms of light intensity and/or spectral properties of light. Exclusion criteria were (1) clinical populations, (2) minors, (3) exposure to daylight, (4) dynamic light, (5) experimental light exposure in the late evening (from ca. 7 pm onward) or at night, (6) eyes closed during light exposure.

2.3. Data extraction

Within every selected paper, we first identified and listed all lighting conditions and outcome estimate in two ways – for light intensity and for spectral light manipulations. Each estimate was then assigned to one of three clusters: physiological, cognitive, or subjective. In a second step, we extracted mean values, variance, and sample sizes, which are necessary to calculate effect sizes, for each study, each outcome, and each lighting condition. Each data point was checked by at least two of the reviewers RL, LNW, or IS. For the cases with no descriptive statistics in the text, tables, or annexes, these data (cell means and variance) were read out from figures, when available, using the free, open-source tool WebPlotDigitizer (Rohatgi 2018). In the cases where multiple samples per light condition were measured (e.g., one group of participants in winter season and another group in summer season) and no summarized descriptive statistics, namely mean values, variance, and sample sizes, per lighting condition were provided in the report, we created surrogate data sets for each light condition, using formulas proposed by Larson (1992). These surrogate data sets have equivalent descriptive statistics to the original sample and subsequently they were used to calculate effect sizes.

2.4. Data analysis

Similar estimates covering the same domain were grouped into one outcome, e.g., sleep measures or self-reported affect. Two reviewers (RL and MR) independently categorized all items and discussed discrepancies to develop a final set of measures. We calculated effect sizes based on planned contrasts that quantified the effects of the manipulated light parameters on the dependent variables (Rosnow et al. 2000). We did not include statistical tests performed by the original authors in our analyses. Instead, we applied planned contrast calculations in a uniform manner for each study. To use this contrast strategy, we would need a complete dataset – individual values for the participants – which can be achieved by creating a surrogate dataset using the descriptive information provided in the reports (Larson 1992). However, this method only works for between-persons design datasets, as the required information for calculations for within-persons or mixed designs (full dataset) is never provided in reports. In order to combine within-persons and between-person designs within the same meta-analysis one would need to only include two (most extreme) lighting conditions into the dataset. This way, conclusions would be still limited as a large portion of datapoints would be left out. Therefore, for our analyses we chose to treat all studies, including those with mixed or within-subject designs, as between-persons design studies, which allowed us to include the maximum number of data points. However, as mentioned above, this comes at a cost of treating within-persons and mixed designs as between-person designs and calculated effect sizes may slightly deviate from the real effects, therefore our results for meta-analyses including within-person and mixed design studies should be interpreted with caution.

Several studies (Hayano et al. 2021; Huiberts et al. 2015, 2016, 2017; Kompier et al. 2021; Li et al. 2021; Qian et al. 2021; Smolders and de Kort 2014, 2017; Smolders et al. 2012, 2016; Zeng et al. 2022) reported estimated marginal means (EMMs) and their standard errors, rather than observed means. EMMs are based on statistical models and do not directly represent the data. We decided to include the data from these studies in our analyses and treated the EMMs as the means for effect size calculations.

The hypothesized effects of lighting conditions were coded by assigning contrast coefficients. They formed a linear pattern for the corresponding estimate of either increasing lighting intensity or increasing amount of spectral power proportion for light between 460 and 490 nm wavelength (either measured or estimated from spectral information provided). For light intensity, the pattern was from the least to the most intense lighting condition. For spectral distributions of light, which included not only white light of different correlated color temperatures, but also monochromatic or narrow bandwidth lights, filtered light, and white light enriched with a short wavelength within the spectrum, the pattern was estimated from the least to the most of short wavelength spectral power. For instance, if a study used four correlated color temperature conditions of 2800 K, 4000 K, 5000 K, and 6500 K, they were assigned coefficients −3, −1, 1, and 3, respectively, (or 3, 1, −1, and −3, respectively, depending on the hypothesis direction) which form a linear pattern. For monochromatic lighting conditions within a study, wavelengths between 460 and 490 nm were contrasted against another wavelength.

The planned contrasts method described above does not take into account the magnitude of differences between lighting conditions within a study. Many of the included studies lacked the required details to model the actual differences in the magnitude of the experimental conditions with our contrast coefficient. Therefore, for statistical planned contrast analyses, we decided to assign coefficients that form a linear pattern and thus consider all studies in the same way. The contrast coefficients therefore do not reflect differences in the magnitude of the manipulation but test in general whether light can have an effect.

We conducted a meta-analysis when data were available from at least two studies for an outcome. Other synthesis techniques besides meta-analysis, such as narrative conclusions, synthesizing using individual statistical tests (“vote counting”), or visual comparisons of effect sizes, are considered less transparent and less likely to be valid (Valentine et al. 2010). However, given the large number of meta-analyses, some of which included only a few studies, we only present meta-analyses that summarized the effects of more than 10 studies. The complete set of meta-analyses is provided in the Supplemental material, S2 File.

To calculate planned contrasts, first, the effect size r was calculated using the assigned coefficients. Each r was then transformed using the Fisher’s Z transformation to normalize the distribution. Overall effects (Rosenthal and DiMatteo 2001) were calculated using Fisher’s Z. Meta-analyses were performed and forest plots were generated using the metafor package for R (Tipton 2015; Tipton and Pustejovsky 2015), which allowed performing a multilevel meta-analysis. As the outcomes stemming from the same study are likely to be dependent, this was accounted for by letting the sampling errors within studies with a correlation coefficient of 0.6 (as in Harrer et al. 2022; Pustejovsky and Tipton 2022), and by using a multilevel model with random effects at the study and the estimate level. Results are reported as Fisher’s Z and as transformed summary r with corresponding confidence intervals. Summary r can be interpreted according to Cohen (1988). For each meta-analysis, two forest plots were generated, the first representing aggregated Fisher’s Z values per study with corresponding confidence intervals, and the second showing Fisher's Z values for each estimate (there may be several per study for an outcome) with corresponding confidence intervals. For meta-analyses with significant overall effects, we present a forest plot with aggregated Fisher's Z values per study in the manuscript, while the full set of all forest plots (two per outcome) is available in Supplemental material, S2 File.

The presence of heterogeneity was assessed as Q test (Cochran 1954), while the extent of the heterogeneity was assessed using I^2 (Higgins and Thompson 2002) for the level 3 to assess the heterogeneity between studies in the context of multilevel meta-analysis, as suggested by Harrer et al. (2021).

3. Results

3.1. Search results and basic study characteristics

The screening process, in accordance with PRISMA 2020 guidelines (Moher et al. 2009; Page et al. 2021), is depicted in Fig. 1. The databases Pubmed, Scopus, and Web of Science were searched. After removing 2873 duplicates, 8206 articles were screened by titles and by abstracts. A total of 328 reports were sought for retrieval and subsequently independently assessed for eligibility. In addition, we identified 10 studies by cross referencing and assessed them for eligibility. A total of 150 studies from 141 reports (publications) were included for the final analyses.

The basic characteristics of the studies are summarized in Table 1: sample size, study design (within, between, or mixed), intensity and spectral information of the lighting conditions, other experimental conditions (if applicable), dark or dim adaptation (if applicable), duration and timing of light exposure, and physiological, cognitive, and/or subjective outcomes included. One hundred and two studies manipulated light intensity, 110 studies manipulated the light spectrum, of which 60 studies manipulated both intensity and the spectrum of light. The sample size of the included studies ranged from 4 to 210 participants. Light intensities ranged from darkness to 12,000 lux. We considered all variations of spectral characteristics – different correlated color temperatures (CCT, ranging from 2700 K to 17,000 K), monochromatic and narrow bandwidth light, filtered light, and expression of specific wavelength within the spectrum. The description of lighting conditions, especially spectral proportions, was overall poor. For example, some studies described correlated color temperature only as "white," "warm white" and "cool white," or even "room light," monochromatic or narrow bandwidth lights as "blue," "green," "yellow," "red," or even no information on spectrum was given at all, only intensity. We still included all these studies in our review, and, where possible, meta-analyses. However there was no possibility of dose-dependency and threshold values to be defined.

3.2. Light effects

All collected data were entered into a table (Lasauskaite et al. 2025). For each entry, we marked whether light intensity and/or spectral power distribution was manipulated and clustered them into physiological, cognitive, and subjective outcomes. The results are presented in six parts according to these partitions. A complete set of forest plots and effect sizes with homogeneity scores for each meta-analysis is provided in Supplemental material, S2 File.

3.2.1. Heterogeneity

Results of Q tests, degrees of freedom, and significance, as well as $I^2_{\text{Level 3}}$ (between studies) are provided in forest plots with even numbers in the Supplemental material, S2 File. For most of the meta-analyses, the Q tests were significant, indicating presence of heterogeneity (Huedo-Medina et al. 2006). In addition, to assess the extent of heterogeneity, we calculated I^2. Most of the Q tests were significant, which may indicate a large variation in the true effect sizes of the included studies. Only analyses with a small number of studies were not significant. However, the Q statistic is highly sensitive to the number of studies – it has low power if the number of studies is small and excessive power to detect negligible variability the number of studies is high. In our case, we deliberately aimed at summarizing the largest number of measures and studies, even if the measure was used in a slightly different context or within different

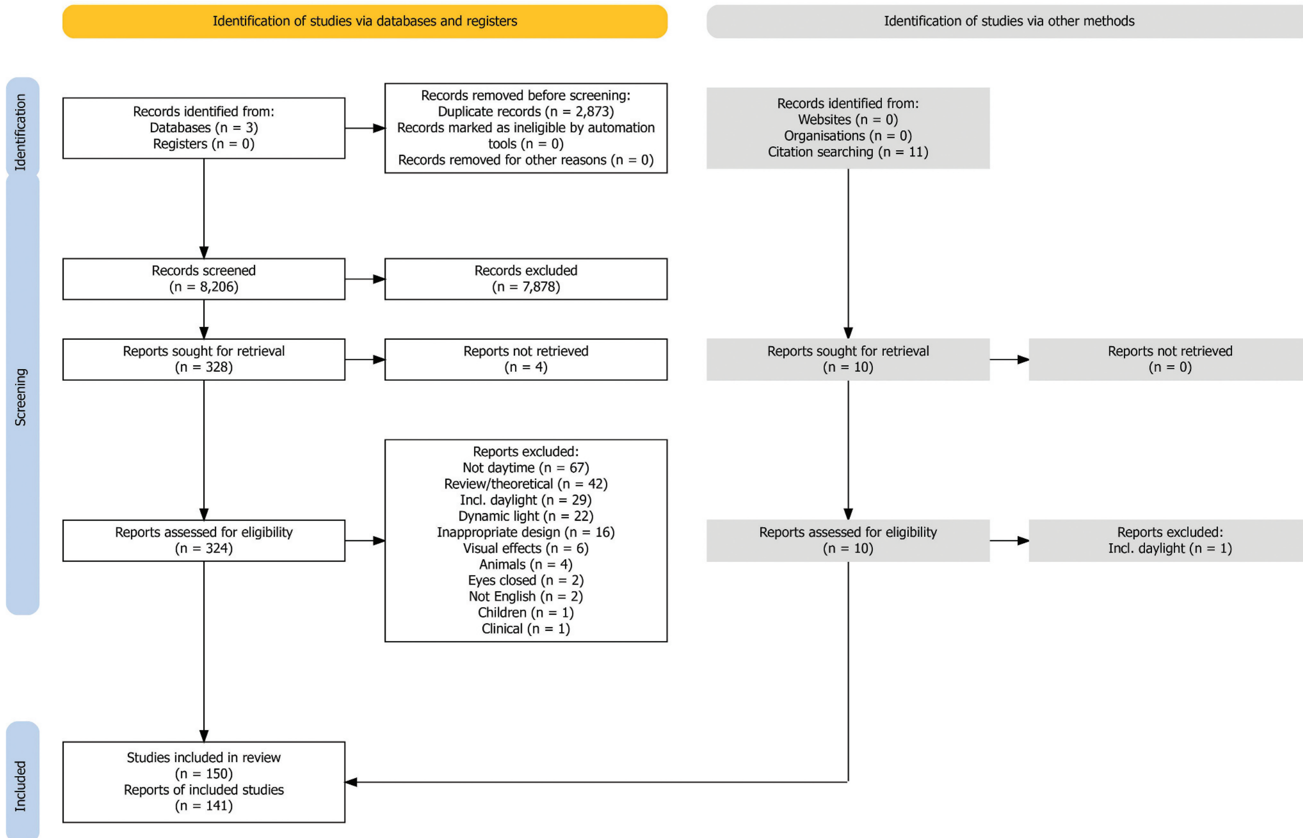

Fig. 1. Screening process, in accordance with PRISMA 2020 guidelines.

procedures in each study, which in turn also could have contributed to heterogeneity. We aimed at getting the most comprehensive overview of the literature as possible. In the case of high heterogeneity, it is recommended to proceed dissecting every analysis by identifying study groups and possible moderators (Borenstein 2009). This is, however, beyond the scope of this paper, but should be addressed in future work.

3.2.2. Effects of light intensity on physiological outcomes

We identified nine physiological outcomes for which we could obtain data from at least two studies: circadian phase, EEG activity, ocular measures, heart rate, melatonin, temperature, sleep, skin conductance, and brain regions. Here, we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. The overall effect Fisher's Z, corresponding 95% confidence intervals, p values, summary r, corresponding 95% confidence intervals, number of included studies, number of included estimates, list of included estimates, and hypotheses (i.e., the direction of effect tested) for light intensity effects on physiological outcomes are provided in Table 2.

3.2.2.1. EEG activity during wakefulness. Fifty-four effect sizes for alpha and theta power as well as alpha attenuation test (AAT) index within 13 studies (Askaripoor et al. 2018; Laszewska, Goroncy, Weber, Pracki, Tafil-Klawe, et al. 2018; Askaripoor et al. 2019; Baek and Min 2015; de Zeeuw et al. 2019; Lok et al. 2022; Luo et al. 2021; Min et al. 2013; Noguchi and Sakaguchi 1999; Noguchi et al. 1999; Sahin et al. 2014; Smolders et al. 2016; Stecher et al. 2017) were considered to summarize the effects of light intensity on EEG activity during wakefulness. We included estimates of alpha, lower alpha, upper alpha, theta, lower theta, upper theta, as well as AAT index and tested whether higher light intensity decreases EEG alpha, theta, and delta activity,

Table 1. Summary of study characteristics.

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Åkerstedt et al. (2003)	20	between	500 cd/m^2 or 2000 lux (white light), 10 cd/m^2 or 30 lux (red light)	Full spectrum white, red	Sleep restriction	30 min	30 min	At 08:30	EEG activity		Sleepiness
Ali et al. (2021)	20	within	9 cd/m^2	Blu-OLP filter, Criztal Prevencia filter, Blue Guardian filter		No	No info	No info		Accuracy	
Alkozei et al. (2016)	35	between	188–214 lux	Blue (peak 469 nm), amber (peak 578 nm)	Certain threat vs certain reward vs uncertain event	30 min	30 min	At 10:15	Brain regions		
Alkozei et al. (2021)	29	between	214 lux, 188 lux	Blue (peak 469 nm) amber (peak 578 nm)		30 min	30 min	At 10:15	Brain regions		Affect
Askaripoor et al. (2018)	22	within	<5 lux, 500 lux desk/323–333 lux at eye level	2564 K, 3730 K, 7343 K		13 min	79 min	At 08:30 or 13:15	EEG activity, heart rate	Accuracy, response time	Sleepiness, vitality
Askaripoor et al. (2019)	20	within	Dim, 41±2.36 cd/m^2	12000 K, 4000 K, 2700 K		13 min	1 h 57 min	At 13:50	EEG activity	Accuracy, response time	Affect, sleepiness
Baek and Min (2015)	20	within	<0.3 lux, 40 lux	Dark, 33% blue-enriched (peak 451nm), 66% blue-enriched, white		12 min	48 min	At 14:00	EEG activity	Accuracy, response time	
Bao et al. (2021)	12	within	300 lux, 750 lux, 1000 lux	3000 K, 4000 K, 6500 K		No	60 min	08:00–11:30 and 14:00–18:30	ERP		Performance appraisal
Baron et al. (1992) (1)	91	between	150 lux, 1500 lux	3000 K, 3600 K, 4200 K, 5000 K		No	No info	No info		Accuracy	Affect, performance appraisal of other
Baron et al. (1992) (2)	72	between	150 lux, 1500 lux	Warm white, cool white		No	No info	No info			Affect, capability to perform, conflict resolution, effort, sleepiness, tension, vitality, performance appraisal

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Baron et al. (1992) (3)	80	between	150 lux, 1500 lux	Warm white, cool white	Gift vs no gift	No	No info	No info			Affect, performance appraisal, performance appraisal of other, sleepiness, tension, vitality
Bonmati-Carrion et al. (2018) (1)	13	within	1.2×10^{13} photons/cm^2/s, 5.13×10^{13} photons/cm^2/s, 6.33×10^{13} photons/cm^2/s	Purple (437 nm), blue (479 nm), and red (627 nm) monochromatic lights alone or in combination [monochromatic purple + monochromatic red (PR) and monochromatic blue + monochromatic red (BR)]		30 min	5 min	Morning	Ocular		
Bonmati-Carrion et al. (2018) (2)	15	within	7.39–9.17 × 10^{11} photons/cm^2/s	420 nm, 430 nm, 440 nm, 450 nm, 460 nm, 470 nm, 480 nm, 490 nm, 500 nm		20 min dim, 30 min dark or 30 min dark	5 min	Morning	Ocular		
Borragán et al. (2017)	17	within	<200 lux, 2000 lux	red, white		No	20 min	9 h after wake up			
Burattini et al. (2019)	40	between	290 lux	3000 K, 6800 K		No	40 min	Between 10:00 and 12:00		Accuracy, response time	Affect, sleepiness, vitality
Cajochen et al. (2019)	15	within	100 lux	4000 K conventional, daylight LEDs		No	16 hours + 11 hours	At wake up	Sleep	Response time	Affect, comfort, sleepiness, tension
Chen et al. (2022)	67	between	175l lux, 210 lux, 280 lux, 350 lux, 420 lux, 590 lux	3000 K, 4000 K, 5500 K	Adjustable light	No	1 h	9 :30–12 :30	EEG activity, heart rate	Accuracy, response time	Comfort, performance appraisal, vitality
Choi et al. (2019)	15	within	500 lux	3500K, 6500K		60 min	1 h	At 9:00	Melatonin, stress hormones		Affect, sleepiness

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Chou et al. (2016)	8	within	500 lux	LED: 3052 K, 4057 K, 5040 K, 6595 K, fluorescent 6445 K	Room temperature, 28 vs 30 degrees	No	1 h 40 min	No info	Heart rate, skin conductance, Temperature	Accuracy	Comfort, sleepiness, tension
Danilenko and Sergeeva (2015)	16	within	1200 lux	White with superimposed peak at 469 nm, red (peak 651 nm)		5–10 min	1 h	At 7:25	Gonadotrophic hormones, melatonin, sex hormones, stress hormones		
de Vries et al. (2018)	37	within	206 lux, 227 lux, 254 lux (at eye)	4000 K		No	1 h 25 min	15:00–16:30		Accuracy, creativity, response time	Affect, cognitive depletion, dominance, sleepiness, vitality
de Zeeuw et al. (2019)	74	within	100 lux, 200 lux, 600 lux, 1200 lux	Low melanopic, high melanopic, highest melanopic		10 min dim, 40 min dark	2.5 h dark goggles, 50 min dim light	2.5 h + 50 min after wake time	EEG activity, ocular		Sleepiness
Deguchi and Sato (1992)	11	within	1000 lux	3000 K, 5000 K, 7500 K		No	8 min	No info	ERP	Response time	
Eklund et al. (2000)	15	within	45.5 fc, 23.9 fc, 45.8 fc	3500 K		No	8 h every day for four days	No info		Accuracy, response time	Affect, comfort, temperature, vitality
Fang et al. (2022)	8	within	300 lux, 500 lux	3000 K, 4000 K		No	60 min	No info	EEG activity, heart rate		Vitality
Ferlazzo et al. (2014)	38	between	100 lux Halogen, 90 lux LED	2800 K, 4000 K		No	>20 min	No info		Accuracy, Response time, Swhich cost	Performance appraisal, tension
Figueiro and Rea (2010)	12	between	Dark, 40 lux	Blue (470 nm), red (625 nm)		1 h before 1st exposure, 3 h before other exposures	1 h every 4 hours	Continuously over 27 h (only daytime considered)	Alpha amylase, cortisol, melatonin		
Fisher et al. (2014)	30	between	100–11000 lux	Full-spectrum white	Genotype groups	No	30 min daily for 3 weeks	7:00–9:00	Brain regions	Accuracy, response time	
Geerdink et al. (2016)	42	between	250–300 lux	Blue (470 nm) amber 590 nm)	Social jetlag	No	30 min daily for 9 days	Morning, along with a sleep advancing scheme	Melatonin, sleep	Response time	Sleepiness

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Grant et al. (2021)	39	between	50 lux	2984 K, 3127 K, 4864 K, 5251 K		2 h	8 h	2 h after wake up, self-selected		Accuracy, productivity, response time	Affect, performance appraisal, sleepiness, tension, vitality
Han et al. (2021)	15	within	0 lux, 375 lux, 675 lux, 1500 lux (4 lux, 125 lux, 100 lux, 27 lux, 25 lux, 52 lux, 54 lux at eye level)	3000 K, 5000 K		No info	No info	No info			Comfort, performance appraisal
Hawes et al. (2012)	24	within	17.8 fc, 22 fc, 32.6 fc, 20.3 fc	4175 K, 5448 K, 6029 K, 3345 K		No	1 h 30 min	No info		Accuracy, response time	Affect, tension, vitality
Hayano et al. (2021)	10	within	750 lux	low-low 4900 K, high-low 8250 K	Age	No	45 min	13:00–16:15	Heart rate	Response time, accuracy	Comfort, sleepiness
He et al. (2023)	12	within	300 lux, 1000 lux	4000 K, 6500 K		No	90 min for 5 days	8:00–9:30	Sleep		Sleep, sleepiness
Hou et al. (2021)	20	between	300 lux	6500 K low mel/high mel	Time of day	1 h	2 h	At 09:00 or 14:00	EEG activity	Response time	Sleep
Hu et al. (2018)	20	within	500 lux, 750 lux	4000 K, 6500 K	Working mode	No	No info	No info	Ocular	Accuracy, response time	Affect, performance appraisal
Huang et al. (2015)	210	within	500 lux	2700 K, 4300 K, 6500 K		No	No info	No info		Accuracy, productivity	
Huebner et al. (2016) (1)	32	between	500–550 lx	6500 K, 2700 K	Ambient temperature decreasing or increasing	No	1 h	At 10:30 or 15:00			Comfort
Huebner et al. (2016) (2)	32	between	500 lux	6500 K, 2700 K	Ambient temperature	No	1 h	At 10:30 or 15:00			Comfort
Huiberts et al. (2015)	64	within	200 lux, 1000 lux	4000 K	Time of day	No	1 h	9:00 to 17:15		Accuracy, response time	Affect, performance appraisal, sleepiness, tension, vitality
Huiberts et al. (2016)	39	within	165 lux, 600 lux, 1700 lux	4700 K	Time of day	No	55 min	9:00–10:30 or 15:45–17:15	Blood pressure, heart rate, skin conductance	Accuracy, response time	Affect, sleepiness, tension, Vitality

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Huiberts et al. (2017)	72	within	165 lux, 1700 lux	4700 K	Time of day, season	No	55 min	9:00–10:30 or 15:45–17:15	Heart rate, skin conductance	Accuracy, response time	Affect, sleepiness, tension, vVitality
Ishii et al. (2018)	21	within	750 lux	5000 K, 5000 K + 5000 K, 5000 K + 6200 K		No	8 hours	09:30–17:30		Concentration, productivity, response time	
Iskra-Golec et al. (2012)	30	within	500 lux	4000 K 17,000 K	Time of day	No	Office hours for 3 weeks	No info			Affect, sleepiness, tension, vitality
Iskra-Golec et al. (2017)	30	within	0.677 cd/m^2 –0.762 cd/m^2	Blue (460 nm), white	Time of day	15 min	4 h	07:00–12:20; 12:20–17:40, and 17:40–23:00 (not considered)	EEG activity		
Jiang et al. (2022)	40	within	520–570 lux	2700 K, 3300 K, 3600 K, 5000 K, 6300 K		5 min	15 min	At 12:00, approx. 3.5–5 h after wake up	Heart rate, skin conductance		
Kang et al. (2019) (1)	155	between	100 lux, 500 lux, 1000 lux	4000 K, 6000 K		No	No info	No info			Self-control
Kang et al. 20 (2019)19 (3)	176	between	100 lux, 500 lux, 1000 lux	4000 K, 6000 K		No	No info	No info			Affect, dominance, self-control, vitality
Kang et al. (2019)(4)	94	between	100 lux, 1000 lux	3000 K, 6000 K		No	No info	No info			Performance appraisal, self-control
Knez and Enmarker (1998)	80	between	1500 lux	3000 K, 4000 K		No	2 h 20 min	No info		Accuracy, memory	Affect, performance appraisal of other
Knez (1995) (1)	96	between	300 lux, 1500 lux	3000 K, 4000 K at high CRI=95		No	2 h	No info		Accuracy, memory	Affect, performance appraisal of other
Knez (1995) (2)	96	between	300 lux, 1500 lux	3000 K, 4000 K at low CRI=55		No	2 h	No info		Accuracy, memory	Affect, performance appraisal of other

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Kobayashi and Sato (1992)	4	within	320 lux, 1000 lux, 2000 lux	3000 K, 5000 K, 7500 K		No	1 h 35 min	No info	Blood pressure	CFFF	
Kompier et al. (2021)	23	within	100 lux, 1000 lux	2700 K, 5900 K		No	45 min	At 9:15, 11:15, 14:00 or 16:00	Heart rate, skin conductance, temperature	Accuracy, response time	Affect, comfort, Performance appraisal, sleepiness, tension,vitality
Kozaki et al. (2011)	11	within	750 lux, 1500 lux, 3000 lux, 6000 lux 12,000 lux	5000 K		No	3 h	At 09:00	Circadian phase, melatonin		
Kübel et al. (2021) (1)	35	within	105 cd/m^2-115 cd/m^2 (goggles)	red, green	Meditation	No	25 min	No info			Time perception, vitality
Kübel et al. (2021) (2)	30	within	105 cd/m^2-115 cd/m^2 (goggles)	red, green	Meditation	No	25 min	No info			Time perception, vitality
Lafrance et al. (1998)	14	between	100 lux 10,000 lux	White, red (filter)		No	6 h 30 min	At 09:00	Circadian phase, melatonin, sleep	Accuracy, response time	Sleepiness
Lan et al. (2020)	24	within	300 lux, 2000 lux	3000 K, 6000 K		20 min	2 h 40 min	2pm-5pm	Melatonin	Accuracy, creativity, memory	Affect
Langguth et al. (2009) (2)	13	within	Dark, red and green matched for intensity	Red, green		No	40 min	No info	Brain regions		
Lasauskaite and Cajochen (2018)	74	between	500 lux	2800 K, 4000 K, 5000 K, 6500 K		No	20 min	9:30–12:00 or 13:30–16:30	Blood pressure, cardiac contractility, Heart rate	Accuracy, response time	Performance appraisal, sleepiness
Lasauskaite et al. (2019)	71	between	500 lux	2800 K, 4000 K, 5000 K, 6500 K		No	4 min	9:30–12:00 or 13:30–16:30	Blood pressure, cardiac contractility, heart rate	Accuracy, response time	Performance appraisal, sleepiness
Lasauskaite et al. (2023)	77	between	500 lux	2800 K, 6500 K		No	20 min	9:30–12:00 or 13:30–16:30	Blood pressure, cardiac contractility, heart rate	Accuracy	Affect, performance pappraisal, sleepiness

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Laszewska, Goroncy, Weber, Pracki, Tafil-Klawe, Pracka, et al. (2018)	19	within	40 lux, 0 lux	Blue, (465 nm), red (625 nm)		15 min	15 min	At 12:00	EEG activity		Sleepiness
Laszewska, Goroncy, Weber, Pracki, and Tafil-Klawe (2018)	19	within	40 lux, 0 lux	Blue, (465 nm), red (625 nm)		15 min	15 min	At 12:00	EEG activity		
Lee and Kim (2020)	18	within	300 lux, 400 lux, 500 lux, 1000 lux	5500 K		2 min	13 min	No info		Accuracy, productivity	
Lehrl et al. (2007)	44	within	1400 lumen	Room light, yellow (580 nm), blue (455 nm), white		No	20 sec	No info		Productivity	Sleepiness
Lei et al. (2017)	11	within	Dark, 0.1 cd/m^2, 1 cd/m^2, 3.16 cd/m^2, 10 cd/m^2, 31.6 cd/m^2, 100 cd/m^2, 400 cd/m^2	Blue (470 nm), red (635 nm)		10 min	400 ms	No info	Ocular		
Leichtfried et al. (2015)	33	within	5000 lux, 400 lux	6500 K, 4000 K		No	30 min	At 07:40	Melatonin	Accuracy, response time	Affect, sleepiness, vitality
Li et al. (2020)	16	within	1.2 lux, 65.4 lux, 159.8 lux, 595.4 lux, 617.6 lux	Yellow, white		No	5 min	No info	Ocular	Accuracy, response time	
Li et al. (2021)	48	mixed	100 lux, 1000 lux	2700 K, 6500 K		No	30 min	08:30–12:30 or 14:30–17:30		Accuracy, response time	Affect, Sseepiness
Li et al. (2022)	18	within	0 lux, 10 lux, 50 lux, 100 lux, 200 lux	No info		No	55 min	08:00–11:00 and 14:00–17:00	Heart rate, respiratory rate, skin conductance		
Lima Lang et al. (2022)	40	within	100 lux, 500 lux, 900 lux	7000 K		No	No info	No info	Ocular		
Lok et al. (2018)	50	between	24 lux, 74 lux, 222 lux, 666 lux, 2000 lux	White + blue	Time of day	90 min	4 × 60 min	09:00–17:30	Ocular, temperature	Accuracy, response time	Sleepiness

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Lok et al. (2019)	10	within	10 lux, 2000 lux	White		90 min	90 min	At 14:30	Temperature	Response time	Sleepiness
Lok et al. (2022)	9	within	<10 lux, 100 lux	4000 K, mEDI: 2.25 lux, 56.2 lux, 80.6 lux, 73.2 lux		7 h of sleep	10 h	Wake up	EEG activity	Accuracy, response time, risk	Sleepiness
Luo et al. (2021)	20	within	200 lux, 1200 lux	6500 K		No	315 min	14:00–19:15	EEG activity	Response time	Sleepiness
Luo et al. (2023)	16	within	500 lux	2700 K, 5700 K	Ambient temperature	No	140 min	09:00–12:00 or 13:00–16:00		Accuracy	Comfort, performance appraisal, sleepiness, vitality
Macoveanu et al. (2016)	32	between	random 100–11000 lux	Full-spectrum white	Genotype groups	No	30 min daily for 3 weeks	07:00–09:00	Brain regions	Self-control	
Metz et al. (2017)	17	within	30 lux	red (630 nm), green (515 nm), blue (450 nm), yellow (78.5% red and 21.5% green)		8 min	10 min	08:30–18:00	Brain regions, heart rate, respiratory system, skin conductance		Affect, sleepiness, tension
Min et al. (2013)	23	within	150 lux, 700 lux	3000 K, 7100 K		3 min	17.5 min	No info	EEG activity, ERP	Accuracy, response time	
Monazzam et al. (2018)	44	between	50 lx, 500 lux, 1000 lux	No info	Whole-body vibration	No	5 min	No info	Heart rate	Response time	Comfort
Mukae and Sato (1992)	8	within	100 lux, 300 lux, 900 lux	3000 K, 5000 K, 6700 K		5 min	25min	No info	Heart rate		
Nakamoto et al. (2021)	19	within	50 lux, 2500 lux	No info		8 h	10 h	08:00–18:00	Blood pressure, heart rate, temperature, urine		Sleepiness
Nelson et al. (1984)	144	between	100 lux, 300 lux	6500 K	Ambient temperature, subjective time	No	50 min	No info		Productivity	Affect, performance appraisal, vitality
Noguchi and Sakaguchi (1999)	14	within	0.5 lux, 1 lux, 3 lux, 10 lux, 30 lux	3000 K	Age	20 min	20 s	09:00–10:30, 10:30–12:00, 13:00–14:30, 14:30–16:00, or 16:00–17:30	EEG activity, heart rate		
Noguchi and Sakaguchi (1999)	8	between	30 lux, 150 lux	3000 K, 5000 K		No	22 min	Afternoon	EEG activity, heart rate	Sleepiness	

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Nomoto et al. (2014)	14	within	540 lux, 601 lux, 210 lux, 680 lux, 150 lux, 124 lux, 129 lux	White-ice, yellow, orange, green, blue, pink, red		No	5 min	No info	Heart rate		Comfort
O'Brien and O'Connor (2000)	12	within	1320 lux, 2640 lux, 6000 lux	Different colored lenses		No	20 min	No info	Heart rate, oxygen, power output		Affect, effort, pain, sleepiness, vitality
Okamoto et al. (2014)	9	within	40 lux (40 μW/cm^2 and 19 μW/cm^2)	470 nm, 630 nm		12 min	48 min	07:00–08:00	EEG activity		
Okamoto and Nakagawa (2015)	8	within	<0.01 lux, 10 lux	470 nm, 530 nm, 620 nm		10 min	28 min	12:00–16:00	ERP	Response time	Sleepiness
Park et al. (2013)	22	within	150 lux, 700 lux	3000 K, 7100 K		No	20 min	No info	EEG activity, ERP	Accuracy, response time	
Peng et al. (2022)	10	within	2.71 cd/m^2, 3.52 cd/m^2, 3.54 cd/m^2, 3.85 cd/m^2, 4.51 cd/m^2 (perceived)/3.5 cd/m^2, 6 cd/m^2, 10 cd/m^2 (road)	No info		No	No info	No info	Heart rate		
Phipps-Nelson et al. (2003)	16	between	<5lux, 1000 lux	No info	Constant routine	5.5 h	5 h	12:00–17:00	Ocular measures	Response time	Sleepiness
Qian et al. (2021)	20	within	200 lux, 1200 lux	4000 K	Nap	No	40 min	13:00		Accuracy, Response time	Affect, self-control, sleepiness, vitality
Rahman et al. (2014)	16	between	2.8 × 1013 photons/cm2/s	blue (460 nm), green (555 nm)	Constant routine	4.75 h	6.5 h	4.75 h after scheduled wake time		Accuracy, response time	Sleepiness
Revell et al. (2006)	12	within	2.3×10^{13} photons/cm^2/s, 6.2×10^{13} photons/cm^2/s	420 nm, 440 nm, 470 nm, 600 nm		No	4 h	07:15–11:15			Affect, sleepiness, tension
Ru et al. (2019)	57	mixed	100 lux, 1000 lux	3000 K, 6500 K		No	50 min	10:00–17:00		Accuracy, response time	Affect, sleepiness
Ru et al. (2022)	78	between	100 lux, 1000 lux	4000 K		No	20 min	09:00–21:00			Affect, self-control

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Ruger et al. (2005) (3)	36	between	<10 lux, 5000 lux	No info		5 h	6 h	12:00–16:00	Melatonin		Sleepiness, vitality
Sabbah et al. (2022)	20	within	10.2, 12.1, 13.1, 13.8 log photons cm-2 s-1	No info		No info	30 sec	No info	Brain regions		
Sahin et al. (2014)	13	within	<5 lux, 213 lux, 361 lux	Red (631nm), white (2568 K)		10 min	1 h 50 min	07:00, 11:00, or 15:00	Alpha amylase, EEG activity, stress hormones	Response time, tracking	Sleepiness
Santhi et al. (2013)	11	within	19 lux, 195 lux, 200 lux, 750 lux	2700 K, 1700 K		No	4 h	After wake up		Accuracy, response time	Sleepiness
Scholkmann et al. (2017)	14	within	20 lux	682 nm (red), 515 nm (green), 465 nm (blue)		8 min	20 s	At 12:24±2.36	Blood pressure, cardiac output, heart rate, respiratory system, skin conductance		
Segal et al. (2016)	60	between	Dark, 2.8–8.4 × 10^{13} photons/ cm^2/sec	Blue (458–480 nm), green (551–555 nm)	Sleep restriction	3 h	3.5 h	3 h after wake up	Ocular, EEG activity, sleep, sleepiness	Response time	Affect, tension, vitality
Siemiginowska and Iskra-Golec (2020)	30	within	0.677 cd/m^2, 0.762 cd/m^2	Blue (460 nm), white		15 min	3 h	07:15–12:15 or 12:20–17:35 or 17:40–22:55	EEG activity		
Smolders and de Kort (2014)	28	within	1000 lux, 200 lux	4000 K		No	1 h 15 min	At 09:00, 10:20, 11:45, 13:15, 14:45, or 16.15	Heart rate, skin conductance	Accuracy, response time	Affect, self-control, sleepiness, tension, vitality
Smolders and de Kort (2017)	39	within	500 lux	2700 K, 6000 K	Time of day	No	1 h	At 09:00, 11:00 13:00, or 15:00	Heart rate, skin conductance	Accuracy, productivity, response time	Affect, sleepiness, tension, vitality
Smolders et al. (2012)	32	mixed	200 lux, 1000 lux	4000 K	Time of day	No	1 h	At 09:00 , 11:00 , 13:00, or 15.00	Heart rate	Accuracy, RT	Affect, sleepiness, tension, vitality
Smolders et al. (2016)	32	mixed	200 lux, 1000 lux	4000 K	Time of day	No	1 h	At 09:00, 11:00, 13:00, or 15:00	EEG activity		
Smolders et al. (2018)	38	between	20–2000 lux	4000 K	Time of day	No	1 h	At 09:00, 11:00, 13:00, or 15:00	Heart rate, skin conductance	Accuracy, productivity	Sleepiness, vitality

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Smotek et al. (2019)	12	within	14 mW/cm^2	455 nm, 508 nm, 629 nm		20 min	20 min	12:00–15:00	EEG activity, ERP	Response time	Sleepiness
Sone et al. (2003)	11	within	80 lux, 5000 lux	No info		No	8 h	7:00–15:00	Gastrointestinal activity, hydrogen		
Stecher et al. (2017)	33	within	Dark, 500 lux	No info	tACS	No	55 min		EEG activity	Accuracy, response time	
Stemer et al. (2015)	29	within	50 lux, 500 lux	4000 K		90 min	2 h	09:00:00–11:00	Fat hormones and adipokines, Immunity		Affect, comfort
Sun et al. (2019)	24	within	100 lux, 500 lux, 2500 lux	2700 K, 4000 K, 6500 K	Uniformity of illuminance	No	2 h 20 min	9:00–11:20 or 14:00–16:20	Ocular	Accuracy, response time	Performance appraisal, tension, vitality
Sun et al. (2020)	35	Between	180 lux, 300 lux, 570 lux, 840 lux, 1110 lux, 1380 lux	No info	Noise, temperature	No	70 min	No info	Blood pressure, heart rate, temperature		Comfort
Takasu et al. (2006)	8	within	10 lux, 5000 lux	No info		No	16 h for 7 days	After wake up	Circadian phase, melatonin, sleep, temperature		Sleepiness
Te Kulve et al. (2017)	19	within	5 lux, 1200 lux	4000 K	Room temperature (26, 29 vs. 32 °C)	No	1 h 15 min	At ca. 08:30	Blood pressure, dopamine, energy expenditure, heart rate, stress hormones, temperature	Lapses, response time	Sleepinss
Te Kulve et al. (2018)	16	within	55 lux	2700 K, 6500 K	Room temperature	No	1 h 15 min	At ca. 08:30	Blood pressure, energy expenditure, heart rate, skin blood flow, stress hormones, temperature	Response time	Comfort, sleepiness
Van de Putte et al. (2022)	76	between	44–60 lux/218 lux melanopic EDI (testperiod 2)	4000 K, blue enriched		No	8 h	06:00–14:00	Sleep	Accuracy, productivity, response time	

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Vandewalle et al. (2007)	18	within	3 x 10^{13} photons/cm^2/s	Blue (470 nm), green (550 nm)		3 h dim light, 30 min dark	18 min	5 h after wake up	Brain regions	Accuracy, response time	Sleepiness
Veitch (1997)	208	between	680 lux	5000 K, 4250 K	Information sets	No	3 h	Morning or afternoon		Accuracy	Affect, arousal, dominance, performance appraisal
Viola et al. (2008)	94	within	409 lux	17000 K, 4000 K		No	8 h 15 min for 4 weeks	08:30–16:45			Affect, concentration, headache, performance appraisal, sleepiness
Wang et al. (2020)	16	within	3000 K, 5000 K, 6500 K	3000 K, 5000 K, 6500 K		20 min	20 min	No info	Heart rate	Accuracy, productivity, mental capacity	
Warman et al. (2003)	11	between	8 lux 12,000 lux	Blue (436 + 456 nm), white		No	4 h	07:15–11:15	Circadian phase		
Weitbrecht et al. (2015)	50	within	1000 lux	3000 K, 4500 K, 6000 K		No	30 min	No info	Heart rate, skin conductance	Accuracy, creativity, productivity	
Wilhelm et al. (2011)	2	within	500 lux, 1500 lux, 2500 lux	6500 K		No	8 h	06:00–14:00	Ocular		Affect, sleepiness
Winzen et al. (2014)	59	within	135 lux, 124 lux, 175 lux, 200 lux, 223 lux	"yellow1" (603 nm), "yellow2" (607 nm), "blue1", (497 nm) "blue2" (505 nm), "neutral" (527 nm)		No	9 min	No info			Affect, comfort, performance appraisal, sleepiness, tension
Wu et al. (2022)	19	Mixed	200 lux, 300 lux, 500 lux, 750 lux, 1000 lux	4000 K, 5000 K, 6000 K	Ambient temperature	No	30 min	09:00–11:30 or 14:30–17:00	Heart rate	Accuracy, productivity	Comfort
J. Yang, et al. (2019)	59	within	200 lux, 1200 lux	6500 K	Morning, evening	No	46 min	No info		Task switching	
Yang and Moon (2018)	60	within	150 lux, 500 lux, 100 lux	6500 K	Noise	30 min	30+25 min	No info			Comfort
W. Yang and Moon (2019)	60	within	150 lux, 500 lux, 100 lux	6500 K	Noise, temperature	30 min	30+25 min	No info			Comfort

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Yasukouchi et al. (2000) (1)	7	within	500 lux	3000 K, 5000 K, 7500 K	Change in ambient temperature	25 min eyes closed	40 min	No info	Temperature		
Yasukouchi et al. (2000) (2)	11	within	500 lux	3000 K, 5000 K, 7500 K	Ambient temperature	No	1 h 30 min	No info	Temperature		
Yasukouchi et al. (2019)	10	within	440 lux	6200 K, 4800 K		No	5 h	10:00–15:06	Heart rate, melatonin	Accuracy, response time	Comfort, tension, vitality
Yoshiike et al. (2018)	29	between	431 lux, 9070 lux	6700 K	Fear learning	No	15 min	At 13:00	Brain regions, skin conductance		
Yoshiike et al. (2019)	24	between	500 lux, 8000 lux	6700 K		No	15 min	At 13:00		Accuracy, response time	Affect, sleepiness, vitality
Yu and Akita (2023)	15	within	300 lux, 500 lux, 750 lux, 1000 lu	3000 K, 5000 K, 6500 K		1 min	1 min	No info	Brain regions	Accuracy, productivity	Comfort, performance appraisal, sleepiness, vitality
Yuan et al. (2021)	30	within	0 lux, 320 lux (desk)	2500 K, 4500 K		No	No info	No info	Brain regions	Accuracy, response time	
Yuda et al. (2017)	8	within	12.9–17.7 lux	orange, blue		No	30 min	Lunch break			
Zauner et al. (2020)	27	within	500 lux (desk)/ 261 lux, 209 lux, 146 lux	2700 K,/54 lux mEDI, 4000 K/128 lux mEDI, 7000 K/241 lux mEDI		No	20 min	07:30–08:30 or 17:30–18:30	Cardiac contractility, heart rate	Accuracy, response time	Comfort, performance appraisal, sleepiness
Zauner et al. (2022) (1)	75	within	0–60 lux/0.003–0.03 W/m^2	peaks between 400 nm and 700 nm	Chronotype. time of day	90 sec	15 sec	08:00–20:00	Ocular		
Zauner et al. (2022) (2)	10	within	0–60 lux/0.003–0.03 W/m^2	peaks between 400 nm and 700 nm	Chronotype. time of day	90 sec	15 sec	08:00–20:00	Ocular		
Zauner et al. (2022) (3)	10	within	0–60 lux/0.003–0.03 W/m^2	peaks between 400 nm and 700 nm	Chronotype. time of day	90 sec	15 sec or 30 sec	08:00–20:00	Ocular		
Zeng et al. (2022)	22	within	300 lux (desk)	4000 K, 6000 K, 8000 K 10,000 K		No	90 min	08:30–12:25 or 13:30–17:25		Accuracy, productivity	Affect, comfort, performance appraisal, sleepiness, tension, vitality
Zhang et al. (2020)	8	within	300 lux, 500 lux, 1000 lux	3000 K, 4000 K, 6500 K		No info	50 min	09:00–10:00	EEG activity		Comfort, performance appraisal, vitality, affect, concentration

(*Continued*)

Table 1. (Continued).

Author, year (study number)	Sample size	Study design	Intensity conditions	Spectral conditions	Other conditions	Dark/dim adaptation	Exposure duration	Time of exposure	Physiological outcomes	Cognitive outcomes	Subjective outcomes
Zhang et al. (2022) (2)	28	within	0 lux, 75 lux, 220 lux	No info	Noise	No	No info	No info	Ocular	Accuracy	
Zhou et al. (2021)	17	within	100 lux, 1000 lux	4000 K, 6500 K	Nap	40 min	30 min	At 13:00		Accuracy, response time	Affect, sleepiness
Zhu et al. (2019)	60	mixed	200 lux, 1200 lux	3000 K, 6500 K		No	3 h	09:00–12:00 or 15:20–17:30		Accuracy, response time	
Zohdi, Egli, et al. (2021)	32	within	120 lux	blue (~450 nm), red (~640 nm)		8 min	9 min	No info	Blood pressure, brain regions, heart rate, respiratory system, skin conductance	Productivity	
Zohdi, Scholkmann, et al. (2021)	32	within	120 lux	blue, red		8 min	9 min	No info	Brain regions, skin conductance	Accuracy	

EEG: electroencephalography; ERP: event-related potentials; ocular: measures related to eye and pupil, e.g., pupil response, blink duration.

Table 2. Meta-analysis results of Fisher's *Z* and summary *r* for effects of light intensity on physiological outcomes.

Outcome	Overall effect Fisher's *Z*	95%CI	*p* value	Summary *r*	Summary 95%CI	*N* (studies)	*N* (estimates)	Included estimates	Hypotheses
EEG activity	0.146	0.021 to 0.271	.0217	0.145	0.021 to 0.265	13	54	alpha power, lower alpha power, upper alpha power, AAT index, lower theta power, theta power, delta power, lower beta power, upper beta power, alpha power proportion, alpha-theta power	lower alpha, larger change in AAT index, lower theta, lower delta, higher beta, lower proportion of alpha, lower alpha-theta
Heart rate	0.082	−0.013 to 0.177	.0912	0.082	−0.013 to 0.175	14	33	heart rate, IBI, SDNN, RMSSD, LF/(LF+HF), HF, heart rate variability	higher heart rate, shorter IBI, larger deviation of IBIs, larger difference of adjacent IBIs, faster heart rate, higher heart rate variability, larger heart rate variability

Hypotheses refer to a higher light intensity. Significant effects are shown in bold. CI: confidence intervals, AAT: alpha attenuation test, IBI: interbeat interval, SDNN: standard deviation of NN intervals (the time interval between R peaks), RMSSD: root mean square of successive differences, LF: low frequency, HF: high frequency.

Table 3. Meta-analysis results of Fisher's *Z* and summary *r* for effects of light intensity on cognitive outcomes.

Outcome	Overall effect Fisher's *Z*	95%CI	*p* value	Summary *r*	Summary 95%CI	*N* (studies)	*N* (estimates)	Included estimates	Hypotheses
Response time	0.06	0.01 to 0.11	.019	0.06	0.01 to 0.109	27	128	response time, speed, 10% fastest, 10% slowest, latency switch cost	faster, faster (larger 1/RT), lower latency
Accuracy	0.007	−0.038 to 0.053	.754	0.007	−0.038 to 0.053	23	72	number of correct items, number of errors, accuracy, error rate, lapses, percentage of correct items	less errors, higher accuracy, lower error rate, higher visual memory capacity, higher echoic memory capacity, less lapses, higher number correct, lower number of errors, higher percentage correct, lower probability

Hypotheses refer to a higher light intensity. Significant effects are shown in bold. CI: confidence intervals, RT: response time.

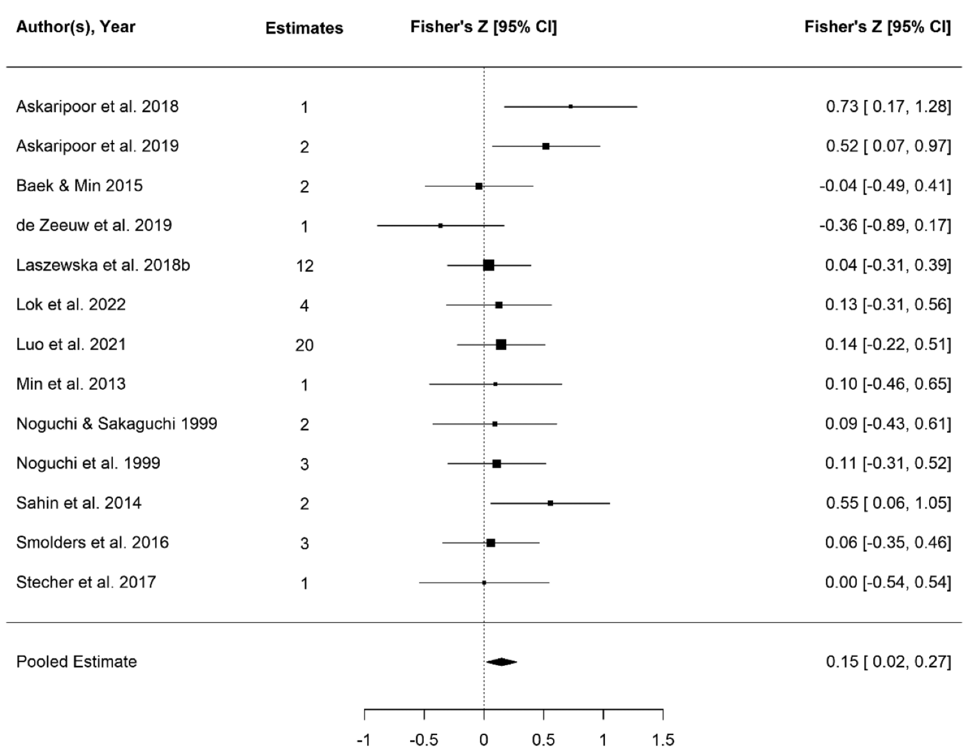

Fig. 2. Forest plot of aggregated Fisher's *Z* for light intensity effects on EEG activity during wakefulness.

and increases EEG beta activity. Meta-analysis results showed a small significant effect of light intensity on EEG activity during wakefulness (lower alpha, theta, and delta, higher beta power), summary $r = 0.156$, 95%CI 0.02 to 0.29, $p = .028$, with large heterogeneity between studies, $I^2_{\text{Level 3}} = 78.60\%$, $Q = 381.73$, $df = 53$, $p < .01$. The Forest plot of the aggregated Fisher's *Z* is presented in Fig. 2. Forest plot of Fisher's *Z* for every estimate is presented in Supplemental material, S2 File Fig. 4.

3.2.2.2. Heart rate. Fourteen reports (Askaripoor et al. 2018; Fang et al., 2022; Huiberts et al. 2016, 2017; Kompier et al. 2021; Monazzam et al. 2018; Mukae and Sato 1992; Noguchi and Sakaguchi 1999; Noguchi et al. 1999; Nomoto et al. 2014; O'Brien and

Table 4. Meta-analysis results of Fisher's Z and summary r for effects of light intensity on subjective outcomes.

Outcome	Overall effect Fisher's Z	95%CI	p value	Summary r	Summary 95%CI	N (studies)	N (estimates)	Included estimates	Hypotheses
Sleepiness	0.115	0.031 to 0.199	.007	0.114	0.031 to 0.196	26	77	sleepiness, sleepy-awake, alertness, drowsiness, sleepy-alert, wide alert-very sleepy	less sleepy, more awake, more alert, less drowsy
Vitality	0.096	−0.004 to 0.196	.061	0.095	−0.004 to 0.193	14	24	fatigue, arousal, vitality, energy, vigor, activation, energetic	lower fatigue, higher arousal, higher vitality, higher energy, more vigor, higher activation, more energetic
Affect	0.070	−0.002 to 0.142	.057	0.070	−0.002 to 0.142	20	51	mood, pleasure, happy, sad, negative affect, positive affect, happiness, sadness, good, bad, elation, composed, agreeable, elated, confident, clearheaded, well-being, positive mood, negative mood	better mood, more pleasure, more happy, less sad, less negative affect, more positive affect, less bad mood, higher elation, more composed, more agreeable, more elated, more confident, more clearheaded, higher well-being

Hypotheses refer to a higher light intensity. Significant effect is shown in bold. CI: confidence intervals.

O'Connor 2000; Smolders and de Kort 2014; Smolders et al. 2012; Te Kulve et al. 2017) provided data on heart rate, including heart rate, heart rate variability, and inter-beat-intervals, within 33 estimates (Supplemental material, S2 File Fig. 7 and Fig. 8). We tested whether higher light intensity increased heart rate, heart rate variability, and deviation of inter-beat-intervals. The overall effect was not significant ($p = .091$).

3.2.3. Effects of light intensity on cognitive outcomes

We pooled estimates for four cognitive outcomes: productivity, response time, accuracy, and creativity, for which we could extract data from at least two studies. Here we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. Overall effect Fisher's Z, corresponding 95% confidence intervals, p values, summary r, corresponding 95% confidence intervals, number of included studies, number of included estimates, list of included estimates, and hypotheses (i.e., the direction of effect tested) for the effect of light intensity on cognitive outcomes are shown in Table 3.

3.2.3.1. Response time. Response time data were available in 27 studies (Askaripoor et al. 2019; Baek and Min 2015; Borragán et al. 2017; de Vries et al. 2018; Huiberts et al. 2015, 2017; Kompier et al. 2021; Lafrance et al. 1998; Li et al. 2020, 2021; Lok, Woelders, et al. 2018; Lok et al. 2019; Min et al. 2013; Monazzam et al. 2018; Phipps-Nelson et al. 2003; Qian et al. 2021; Ru et al. 2019; Sahin et al. 2014; Segal et al. 2016; Smolders and de Kort 2014; Smolders et al. 2012; Te Kulve et al. 2017; Yang et al. 2019; Yoshiike et al. 2019; Yuan et al. 2021; Zhou et al. 2021; Zhu et al. 2019), and we could compute 128 effect sizes in total. We included estimates for mean response time, 10% slowest response times, 10% fastest response times, speed (inverted response time), and latency of switching costs. We tested whether higher light intensity leads to shorter response time and higher responding speed. The overall effect size was significant, summary $r = 0.06$, 95% CI 0.01 to 0.109, $p = .019$, showing that higher light intensity during daytime leads to faster responding. However, the effect was small. Heterogeneity between studies was moderate, $I^2 = 44.91\%$, $Q = 328.94$, $df = 127$, $p < .01$. The forest plot of aggregated Fisher's Z is presented in Fig. 3. The forest

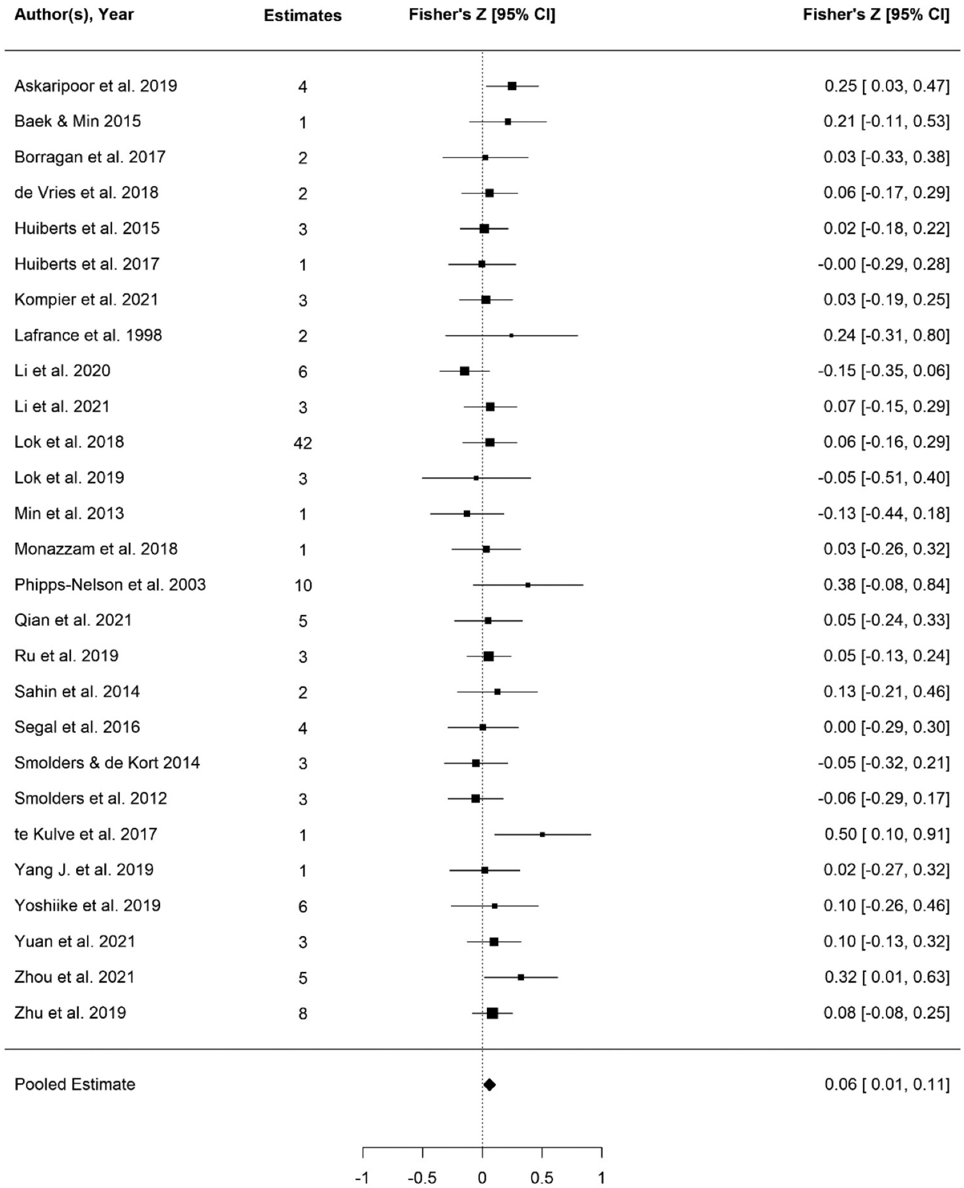

Fig. 3. Forest plot of aggregated Fisher's *Z* for light intensity effects on response time.

plot of Fisher's Z for every estimate is presented in Supplemental material, S2 File Fig. 24.

3.2.3.2. Accuracy. Data from 23 studies were extracted (Borragán et al. 2017; de Vries et al. 2018; Huiberts et al. 2015, 2016, 2017; Kompier et al. 2021; Lafrance et al. 1998; Lan et al. 2020; Lee and Kim 2020; Li et al. 2020, 2021; Min et al. 2013; Qian et al. 2021; Ru et al. 2019; Smolders and de Kort 2014; Smolders et al. 2012; Stecher et al. 2017; Wang et al. 2020; Yoshiike et al. 2019; Yuan et al. 2021; Zhang et al. 2022; Zhou et al. 2021; Zhu et al. 2019) and 72 effect sizes were calculated for response accuracy (Supplemental material, S2 File Fig. 25 and Fig. 26). We included estimates for of accuracy (as a proportion or percentage of correct responses), number of atypical examples, number of errors, number of correct items, number of items solved, and error rate. We tested whether higher light intensity improves accuracy. The overall effect was not significant ($p = .754$).

3.2.4. Effects of light intensity on subjective outcomes

We combined subjective measures into seven outcomes for which we had data from at least two

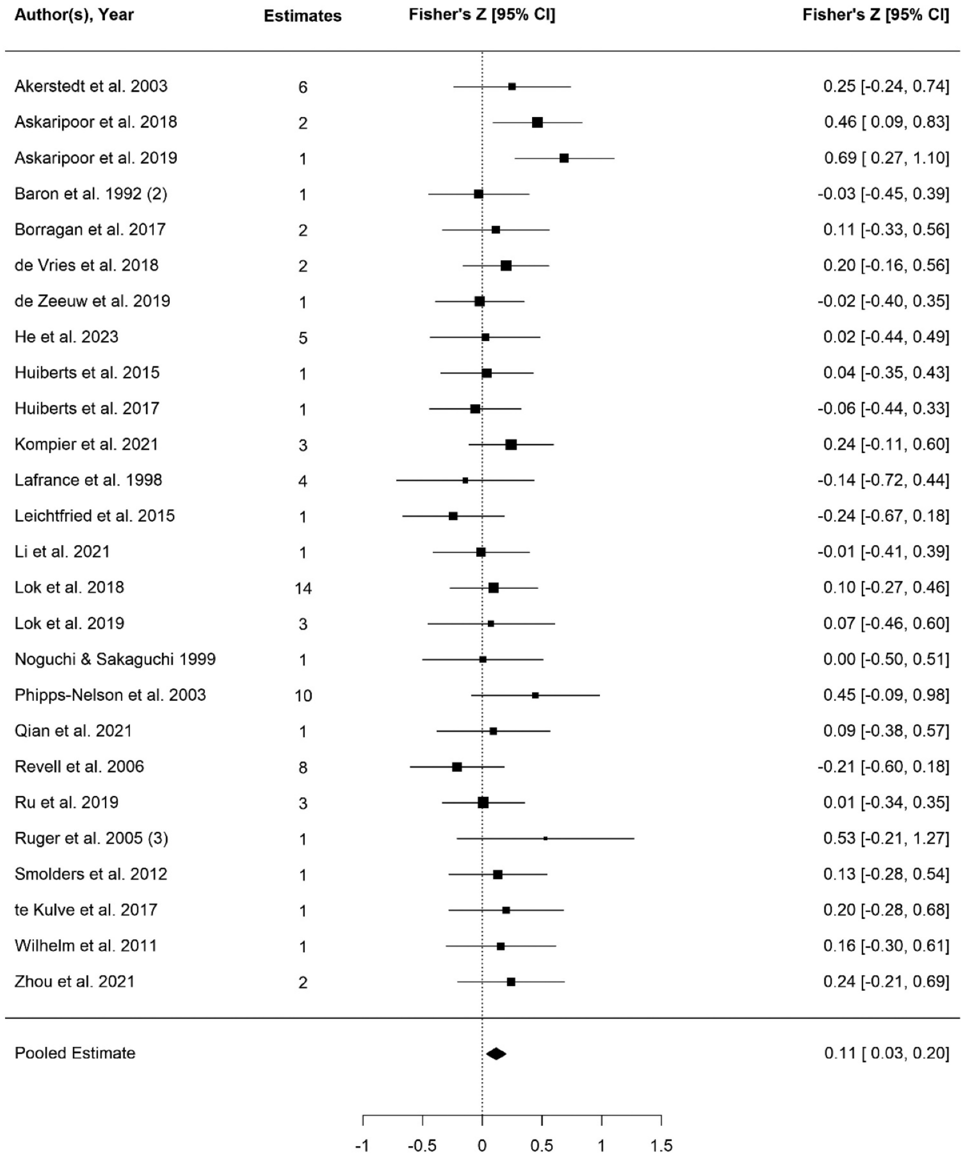

Fig. 4. Forest plot of aggregated Fisher's *Z* for light intensity effects on self-reported sleepiness.

studies: self-reports on comfort, sleepiness, vitality, performance appraisal, affect, self-control, and tension. Here we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. The overall effect Fisher's *Z*, corresponding 95% confidence intervals, *p* values, summary *r*, corresponding 95% confidence intervals, number of included studies, number of included estimates, list of included estimates, and hypotheses (i.e., the direction of effect tested) for the effects of light intensity on physiological outcomes are shown in Table 4.

3.2.4.1. Sleepiness. Twenty-six studies (Åkerstedt et al. 2003; Askaripoor et al. 2018, 2019; Baron et al. 1992; Borragán et al. 2017; de Vries et al. 2018; de Zeeuw et al. 2019; He et al. 2023; Huiberts et al. 2015, 2017; Kompier et al. 2021; Lafrance et al. 1998; Leichtfried et al. 2015; Li et al. 2021; Lok et al. 2022; Woelders, et al. 2018; Lok et al. 2019; Noguchi and Sakaguchi 1999; Qian et al. 2021; Revell et al. 2006; Ru et al. 2019; Ruger et al. 2005; Smolders et al. 2012; Te Kulve et al. 2017; Wilhelm et al. 2011; Zhou et al. 2021) provided data on sleepiness with a total of 77 outcome measures. We included ratings of sleepiness, alertness, drowsiness, and scales "sleepy-awake," and

Table 5. Meta-analysis results of Fisher's *Z* and summary *r* for effects of spectral composition of light on physiological outcomes.

Outcome	Overall effect Fisher's *Z*	95%CI	*p* value	Summary *r*	Summary 95% CI	*N* (studies)	*N* (estimates)	Included estimates	Hypotheses
EEG activity	0.07	−0.029 to 0.17	.166	0.07	−0.029 to 0.168	13	79	alpha power, lower alpha power, upper alpha power, AAT index, theta power, beta power, lower theta power, alpha-theta power, delta power	lower alpha, larger change in AAT index, lower theta, higher beta, lower alpha-theta, decrease in delta, decrease in theta, decrease in alpha, increase in beta
Heart rate	−0.012	−0.074 to 0.05	.699	−0.012	−0.074 to 0.05	17	64	heart rate, IBI, SDNN, RMSSD, low frequency, high frequency, LF/HF, total power, VLF, LF, HF, respiratory sinus arrhythmia, Mayer wave related sinus arrhythmia, LF/(LF+HF)	higher heart rate, shorter IBI, larger deviation of IBIs, larger difference of adjacent IBIs, lower LF, higher HF, higher heart rate variability, higher HR, higher change in HR, lower VLF, higher arrhythmia, larger heart rate variability

Note. Hypotheses refer to a higher proportion of short wavelength light within the spectrum. Significant effects are shown in bold. CI: confidence intervals, AAT: alpha attenuation test, SDNN: standard deviation of NN intervals, RMSSD: root mean square of successive differences, LF: low frequency, HF: high frequency, VLF: very low frequency, IBI: interbeat interval.

Table 6. Meta-analysis results of Fisher's *Z* and summary *r* for effects of spectral composition of light on cognitive outcomes.

Outcome	Overall effect Fisher's *Z*	95%CI	*p* value	Summary *r*	Summary 95%CI	*N* (studies)	*N* (estimates)	Included estimates	Hypotheses
Response time	0.074	−0.052 to 0.200	.249	0.074	−0.052 to 0.197	31	96	response time, switch cost, speed, 10% slowest, 10% fastest	faster, less cost
Accuracy	0.050	−0.035 to 0.135	.246	0.050	−0.035 to 0.134	33	110	accuracy, errors, recalls, lapses, lapse frequency, number of correct items, number of incorrect items, error rate, anticipation errors, number of correct responses, number of correct cancellations, ratio number of correct cancellations	less missing responses, less errors, higher accuracy, less lapses, more recalls, less false pedaling, lower lapse frequency, more correct items, less incorrect items, lower error rate, higher visual memory capacity, higher echoic memory capacity, more correct responses, higher number of correct cancellations, lower ratio, higher number of correct items, lower probability

Hypotheses refer to a higher proportion of short wavelength light within the spectrum. CI: confidence intervals.

Table 7. Meta-analysis results of Fisher's Z and summary r for effects of spectral composition of light on subjective outcomes.

Outcome	Overall effect Fisher's Z	95%CI	p value	Summary r	Summary 95%CI	N (studies)	N (estimates)	Included estimates	Hypotheses
Vitality	0.061	−0.020 to 0.143	.140	0.061	−0.020 to 0.142	12	26	fatigue, healthy-sick, energetic-exhausted, exhausted-sharp, tired-fresh, vigor-activity, energetic arousal, vitality, arousal, excited	lower fatigue, less sick, less exhausted, more sharp, more fresh, more activity, higher arousal, higher vitality, more excited
Sleepiness	0.043	−0.009 to 0.095	.108	0.043	−0.009 to 0.094	33	74	sleepiness, sleepy-awake, awake, sleepy-alert, alertness, drowsiness	less sleepy, more awake, more alert, less drowsy
Performance appraisal	0.024	−0.058 to 0.106	.571	0.024	−0.058 to 0.105	16	43	NASA Task Load Index, ability to perform, mental demand, physical demand, temporal demand, performance, effort, motivated-unmotivated, cognitive depletion, difficulty, capability to perform, task difficulty, motivation, attention, productivity, cannot focus, cannot concentrate	lower task load, more able to perform, lower demand, better performance, lower effort, less unmotivated, lower depletion, lower difficulty, less effort, higher motivation, higher attention, higher productivity, better focus, higher concentration
Comfort	0.001	−0.133 to 0.134	.994	0.001	−0.132 to 0.133	12	46	feeling warm, environmental feel, hot-cool, thermal comfort, thermal acceptance, extra clothing, thermal sensation, self-assessed shivering, pleasantness, whole-body thermal sensation, whole-body thermal comfort, whole-body thermal preference, whole-body thermal pleasantness, perceived shivering, comfort, comfortable feeling, headache, temperature perception, temperature evaluation, air quality perception, air quality evaluation, air draught perception, air draught evaluation, humidity perception, humidity evaluation, climate, cosiness, appeal, satisfaction	more warm, more comfortable, less cool, more comfort, accepting lower temperatures, less clothing, less hot, less shivering, more pleasant, less perceived shivering, feeling cooler, less headache, lower temperature, higher air quality, stronger air draught, less humid, more cozy, higher appeal, higher satisfaction
Affect	−0.010	−0.082 to 0.063	.793	−0.010	−0.082 to 0.063	20	44	positive affect, negative affect, mood, sad-happy, depression, hedonic tone, happy, happiness, sadness, sad, pleasure, inspired, determined, annoyed, positive mood, negative mood	more positive affect, less negative affect, better mood, more happy, less depressed, higher hedonic tone, less sad, higher pleasure, more inspired, more determined, less annoyed
Tension	−0.036	−0.094 to 0.022	.227	−0.036	−0.093 to 0.022	11	17	anxious-calm, nervous-calm, tense-relaxed, peace of mind, frustration, calm-stressed, tense arousal, calm, stress, relaxation, anxious	more calm, more peace of mind, lower frustration, less stress, lower tension, more relaxed, less anxious

Hypotheses refer to a higher proportion of short wavelength light within the spectrum. CI: confidence intervals.

"wide alert-very sleepy". We tested whether higher light intensity leads to lower sleepiness or higher alertness, respectively. The results of the meta-analysis confirmed our prediction, $r = 0.114$, 95%CI 0.03 to 0.20, $p = .007$, although the significant effect was small. Heterogeneity between studies was moderate, $I^2_{\text{Level }3} = 58.65\%$, $Q = 175.14$, $df = 74$, $p < .01$. The forest plot of aggregated Fisher's Z is presented in Fig. 4. The forest plot of Fisher's Z for every estimate is presented in Supplemental material, S2 File Fig. 30.

3.2.4.2. Vitality. Data were extracted from 13 studies (Askaripoor et al. 2018; Borragán et al. 2017; de Vries et al. 2018; Fang et al. 2022; Huiberts et al. 2015, 2017; Kompier et al. 2021; Nelson et al. 1984; O'Brien and O'Connor 2000; Qian et al. 2021; Ruger et al. 2005; Smolders and de Kort 2014; Smolders et al. 2012; Sun et al. 2019) and a total 24 estimates on vitality were summarized (Supplemental material, S2 File Fig. 31 and Fig. 32). We included estimates for fatigue, arousal, vitality, energy, vigor, activation, and feeling energetic. We tested whether higher light intensity leads to higher vitality. The overall effect of light intensity was not significant ($p = .061$).

3.2.4.3. Affect. We identified 20 studies (Askaripoor et al. 2019; Borragán et al. 2017; de Vries et al. 2018; Huiberts et al. 2015, 2017; Kang et al. 2019; Kompier et al. 2021; Lan et al. 2020; Leichtfried et al. 2015; Li et al. 2021; Nelson et al. 1984; O'Brien and O'Connor 2000; Qian et al. 2021; Ru et al. 2019, 2022; Smolders and de Kort 2014; Smolders et al. 2012; Stemer et al. 2015; Wilhelm et al. 2011; Zhou et al. 2021) from which we could extract data of affect measures and calculated in total 51 effect sizes (Supplemental material, S2 File Fig. 35 and Fig. 36). For this outcome, we included estimates for mood, pleasure, negative affect, positive affect, elation, and ratings of happy, sad, good, bad, elation, composed, agreeable, confident, and clearheaded. We tested whether higher light intensity leads to higher positive affect. The summary effect was not significant ($p = .057$).

3.2.5. Effects of spectral composition of light on physiological outcomes

We conducted meta-analyses on 11 physiological outcome measures: blood pressure, brain regions (assessed as cortical hemodynamic activity), cardiac contractility, EEG power, heart rate, melatonin, ocular measures, sleep (assessed by polysomnography; PSG), skin conductance, stress hormone, and temperature (including core body temperature and skin temperature). Here we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. The overall effect Fisher's Z, corresponding 95% confidence intervals, p values, summary r, corresponding 95% confidence intervals, number of included studies, number of included estimates, list of included estimates, and hypotheses (i.e., the direction of effect tested) for effects of light spectral composition are provided in Table 5.

3.2.5.1. EEG activity during wakefulness. We calculated 79 effect sizes with data provided from 13 studies (Askaripoor et al. 2018; Askaripoor et al. 2019; Baek and Min 2015; Hou et al. 2021; Iskra-Golec et al. 2017; Laszewska, Goroncy, de Zeeuw et al. 2019; Lok et al. 2022; Min et al. 2013; Noguchi and Sakaguchi 1999; Sahin et al. 2014; Segal et al. 2016; Siemiginowska and Iskra-Golec 2020; Weber, Pracki, Tafil-Klawe, et al. 2018). We included estimates for delta, theta, alpha, and beta power as well as the alpha attenuation test (AAT) index (Supplemental material, S2 File Fig. 45 and Fig. 46). We tested whether the spectrum with a higher proportion of short-wavelength light decreases alpha power, increases change in AAT index, decreases theta, and delta power and increases beta power. The mean effect of the light spectrum on EEG activity was not significant ($p = .166$).

3.2.5.2. Heart rate. For heart rate, we summarized effect sizes for heart rate, interbeat intervals, SSDN (standard deviations of NN intervals), RMSSD (root mean square of successive differences between normal heartbeats), heart rate variability (LF, HF, LF/HF, LF/(LF+HF)), respiratory sinus arrhythmia, and Mayer wave related to sinus arrhythmia. We extracted data from 17 studies (Askaripoor et al. 2018; Chou et al. 2016; Fang et al. 2022; Hayano et al. 2021; Jiang et al. 2022; Kompier et al. 2021; Lasauskaite and Cajochen 2018; Lasauskaite et al. 2019, 2023; Metz et al. 2017; Mukae and Sato 1992; Noguchi and Sakaguchi 1999; Nomoto et al. 2014;

Smolders and de Kort 2017; Te Kulve et al. 2018; Weitbrecht et al. 2015; Zauner et al. 2020), and calculated 64 effect sizes (Supplemental material, S2 File Fig. 53 and Fig. 54). We tested whether a higher proportion of short-wavelength light leads to higher heart rate, higher heart rate variability, and higher arrhythmia. The overall effect of the light spectrum on heart rate was not significant ($p = 0.699$).

3.2.6. Effects of spectral composition of light on cognitive outcomes

We conducted four meta-analyses on the following cognitive outcomes: accuracy, creativity, productivity, and response time. Here we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. The overall effect Fisher's Z, corresponding 95% confidence intervals, p values, summary r, corresponding 95% confidence intervals, number of included studies, number of included measures, list of included measures, and hypotheses (i.e., the direction of effect tested) for effects of spectral composition of light are provided in Table 6.

3.2.6.1. Response time. We could extract data for response time from 31 studies (Askaripoor et al. 2019; Baek and Min 2015; Borragán et al. 2017; Burattini et al. 2019; Deguchi and Sato 1992; Ferlazzo et al. 2014; Geerdink et al. 2016; Grant et al. 2021; Hawes et al. 2012; Hayano et al. 2021; Hou et al. 2021; Ishii et al. 2018; Kompier et al. 2021; Lafrance et al. 1998; Lasauskaite and Cajochen 2018; Lasauskaite et al. 2019; Li et al. 2020, 2021; Lok et al. 2022; Min et al. 2013; Rahman et al. 2014; Ru et al. 2019; Sahin et al. 2014; Segal et al. 2016; Te Kulve et al. 2018; Van de Putte et al. 2022; Vandewalle et al. 2007; Yuan et al. 2021; Zauner et al. 2020; Zhou et al. 2021; Zhu et al. 2019) and calculate 96 effect sizes (Supplemental material, S2 File Fig. 65 and Fig. 66). We summarized estimates for RT (response time), 10% fastest RT, 10% slowest RT, and response speed (1/RT). We tested whether a higher proportion of short-wavelength light within the spectrum leads to faster responses. The mean effect of light spectrum was not significant ($p = .249$).

3.2.6.2. Accuracy. We calculated 110 effect sizes for accuracy with data extracted from 32 studies (Veitch 1997; Lafrance et al. 1998; Vandewalle et al. 2007; Hawes et al. 2012; Min et al. 2013; Rahman et al. 2014; Ferlazzo et al. 2014; Huang et al. 2015; Weitbrecht et al. 2015; Chou et al. 2016; Smolders and de Kort 2017; Borragán et al. 2017; Lasauskaite and Cajochen 2018; Lasauskaite et al. 2019; Ru et al. 2019; Zhu et al. 2019; Burattini et al. 2019; Li et al. 2020; Wang et al. 2020; Lan et al. 2020; Zauner et al. 2020; Grant et al. 2021; Zhou et al. 2021; Zohdi, Scholkmann, et al. 2021; Kompier et al. 2021; Yuan et al. 2021; Li et al. 2021; Hayano et al. 2021; Van de Putte et al. 2022; Lok et al. 2022; Zeng et al. 2022; Luo et al. 2023; Lasauskaite et al. 2023). We included estimates for accuracy, errors, recalls, lapses, lapse frequency, number of correct items, number of incorrect items, error rate, anticipation errors, number of correct responses, number of correct cancelations, ratio number of correct cancellations (Supplemental material, S2 File Fig. 67 and Fig. 68). We tested whether light with a higher proportion of short wavelength light leads to higher accuracy. Our hypothesis could not be confirmed ($p = .246$).

3.2.7. Effects of spectral composition of light on subjective outcomes

Eight meta-analyses were conducted for effects of spectral composition of light on the following subjective outcomes: affect, control, performance appraisal, self-control, sleep, sleepiness, tension, and vitality. Here we present only those meta-analyses that were based on more than 10 studies, results for all meta-analyses are provided in Supplemental material, S2. Overall effect Fisher's Z, corresponding 95% confidence intervals, p values, summary r, corresponding 95% confidence intervals, number of included studies, number of included estimates, list of included estimates, and hypotheses (i.e., the direction of effect tested) for effects of light spectral composition are provided in Table 7.

3.2.7.1. Vitality. We extracted data from 12 studies (Askaripoor et al. 2018; Borragán et al. 2017; Fang et al. 2022; Grant et al. 2021; Hawes et al. 2012; Iskra-Golec et al. 2012; Kompier et al. 2021;

Luo et al. 2023; Smolders and de Kort 2017; Sun et al. 2019; Veitch 1997; Zeng et al. 2022), and calculated 26 effect sizes for vitality (Supplemental material, S2 File Fig. 71 and Fig. 72) including ratings of vitality, fatigue, energetic arousal, and scale "vigor-activity." We tested whether a higher proportion of short-wavelength light within the spectrum leads to higher vitality. The overall effect was not significant ($p = .140$).

3.2.7.2. Sleepiness. We extracted data for subjective sleepiness from 33 studies (Åkerstedt et al. 2003; Askaripoor et al. 2018, 2019; Baron et al. 1992; Borragán et al. 2017; Choi et al. 2019; Chou et al. 2016; de Zeeuw et al. 2019; Geerdink et al. 2016; Grant et al. 2021; Hayano et al. 2021; He et al. 2023; Iskra-Golec et al. 2012; Kompier et al. 2021; Lafrance et al. 1998; Lasauskaite and Cajochen 2018; Lasauskaite et al. 2019, 2023; Li et al. 2021; Lok et al. 2022; Luo et al. 2023; Metz et al. 2017; Noguchi et al. 1999; Rahman et al. 2014; Revell et al. 2006; Ru et al. 2019; Smolders and de Kort 2017; Te Kulve et al. 2018; Viola et al. 2008; Winzen et al. 2014; Zauner et al. 2020; Zeng et al. 2022; Zhou et al. 2021), and calculated 72 effect sizes (Supplemental material, S2 File Fig. 73 and Fig. 74). We included ratings of sleepiness, alertness, drowsiness, and scales "sleepy-alert," "awake," and "sleepy-awake." We tested whether exposure to a higher proportion of short-wavelength light leads to lower sleepiness/higher alertness. Results of the meta-analysis did not show a significant effect ($p = .108$).

3.2.7.3. Performance appraisal. We extracted data from 16 studies (Bao et al. 2021; Baron et al. 1992; Ferlazzo et al. 2014; Grant et al. 2021; Kang et al. 2019; Kompier et al. 2021; Lasauskaite and Cajochen 2018; Lasauskaite et al. 2019, 2023; Luo et al. 2023; Sun et al. 2019; Veitch 1997; Viola et al. 2008; Winzen et al. 2014; Zauner et al. 2020; Zeng et al. 2022) and could calculate 43 effect sizes (Supplemental material, S2 File Fig. 77 and Fig. 78) for self-reported ability to perform, mental demand, physical demand, temporal demand, performance, effort, scale "motivated-unmotivated," cognitive depletion, capability to perform, task difficulty, motivation, attention, productivity, scales "cannot focus," "cannot concentrate," as well as NASA Task Load Index. We tested whether a higher proportion of short-wavelength light within the spectrum leads to higher performance appraisals – lower task load, more able to perform, lower demand, better perceived performance, lower effort, less unmotivated, lower depletion, lower difficulty, less effort, higher motivation, higher attention, higher productivity, better focus, higher concentration. The overall effect of spectral composition of light was not significant ($p = .571$).

3.2.7.4. Comfort. For the comfort outcome, we summarized estimates on feeling warm, environmental feel, scale "hot-cool," thermal comfort, thermal acceptance, extra clothing, thermal sensation, self-assessed shivering, pleasantness, whole-body thermal sensation, whole-body thermal comfort, whole-body thermal preference, whole-body thermal pleasantness, perceived shivering, comfort, headache, temperature perception, temperature evaluation, air quality perception, air quality evaluation, air draught perception, air draught evaluation, humidity perception, humidity evaluation, climate, coziness, appeal, and satisfaction. We could extract data from 12 studies reported in 11 articles (Chou et al. 2016; Hayano et al. 2021; Huebner et al. 2016; Kompier et al. 2021; Luo et al. 2023; Nomoto et al. 2014; Te Kulve et al. 2018; Viola et al. 2008; Winzen et al. 2014; Zauner et al. 2020; Zeng et al. 2022) and calculated a total of 46 effect sizes (Supplemental material, S2 File Fig. 81 and Fig. 82). We tested whether a higher proportion of short-wavelength light within the spectrum leads to lower comfort. The overall effect was not significant ($p = .994$).

3.2.7.5. Affect. We extracted data on affect, including estimates for positive affect, negative affect, mood, the scale "sad-happy," depression, hedonic tone, happiness, sad, pleasure, inspired, determined, annoyed, positive mood, and negative mood, from 20 studies (Alkozei et al. 2021; Askaripoor et al. 2019; Borragán et al. 2017; Choi et al. 2019; Grant et al. 2021; Hawes et al. 2012; Iskra-Golec et al. 2012; Kang et al. 2019; Kompier et al. 2021; Lan et al. 2020; Lasauskaite et al. 2023; Li et al. 2021; Metz et al. 2017; Ru et al. 2019; Smolders and de Kort 2017; Veitch 1997; Viola et al. 2008; Winzen et al. 2014; Zeng et al. 2022;

Zhou et al. 2021), and calculated 44 effect sizes (Supplemental material, S2 File Fig. 83 and Fig. 84). We tested whether a higher proportion of short-wavelength light within the spectrum leads to higher positive affect. The overall effect of spectral properties of light was not significant ($p = .793$).

3.2.7.6. Tension. Data from 11 studies reported in 10 reports (Baron et al. 1992; Chou et al. 2016; Ferlazzo et al. 2014; Grant et al. 2021; Iskra-Golec et al. 2012; Kompier et al. 2021; Metz et al. 2017; Sun et al. 2019; Winzen et al. 2014; Zeng et al. 2022) were extracted to calculate 17 effect sizes (Supplemental material, S2 File Fig. 85 and Fig. 86) for estimates for tension, including ratings of tension, frustration, tense, arousal, stress, relaxation, and scales "anxious-calm," "nervous-calm," "tense-relaxed." We tested whether a higher proportion of short-wavelength light within the spectrum leads to higher self-reported tension, stress, and arousal, and lower relaxation. The meta-analysis could did not confirm our hypothesis ($p = .227$).

For the readers to compare the results with the analyses run with studies with exclusively between-persons designs (49 studies out of 148), the Supplemental material, S3 File provides forest plots and aggregated Fisher's Z per study (figures with odd numbers) and forest plots and Fisher's Z for every estimate (figures with even numbers) for each meta-analysis. In total, we could run 29 multilevel meta-analyses. The results show that a higher proportion of short wavelength light in the spectrum during daytime leads to shorter response time, summary $r = 0.235$, 95%CI 0.02 to 0.43, $p = .032$, with large heterogeneity between studies, $I^2_{\text{Level3}} = 90.33\%$, $Q = 326.68$, $df = 37$, $p < .01$. All other meta-analyses did not yield any significant effects. Lower number of significant summary effects might have been a result of lower statistical power due to lower number of included studies with between-persons design.

4. Discussion

This work presents a systematic review and a quantitative analysis of available empirical data on the NIF effects of daytime light exposure. We tested the effects of light intensity and light spectrum on physiological, cognitive, and subjective outcomes in healthy adults. Our meta-analyses, based data from more than 10 studies, showed that light intensity during the day enhances EEG brain wave-activity associated with heightened cognitive processing and attention (lower alpha, theta, and delta, and higher beta power), decrease response time, and reduce subjective sleepiness, all with small effect sizes, while the spectral properties of light during the day were not found to have significant summary effects.

4.1. Main findings

4.1.1. Physiological outcomes

Our meta-analyses found that higher intensity of light during daytime leads to lower EEG alpha, theta, and delta activity and higher EEG beta activity during wakefulness, which we summarized as EEG activation. EEG alpha waves (8–12 hz) occur when an individual is awake, relaxed, particularly when the eyes are closed. Reduction of alpha, particularly in its lower range, and theta activity is therefore associated with cortical activation resulting in enhanced alertness and vigilance. Increases in EEG beta activity (13–30 hz) often appear during attentive wakefulness, for instance while performing a task or during stimulus presentation. EEG delta waves, which are of low frequency (< 4 hz), typically occur during sleep and are not observed during wakefulness. Thus, our analysis shows that increased levels of daytime light affect EEG correlates of human attention, alertness, and vigilance.

The significant summary effect of light intensity of EEG activity should be interpreted with caution, as large between-study heterogeneity was detected. For the physiological outcome of EEG activity, we summarized measures of different frequency ranges, that might have been obtained from different brain regions, not to mention different experimental designs, procedures, and other conditions for participants used. Potentially, this led to an additional increase in heterogeneity, A more focused approach to analyzing the effects of light on EEG activity, by limiting the selection of studies to specific tasks, specific EEG frequency bands, or to a specific range of lighting conditions used, would provide a sharper view.

Heart rate and heart rate variability, often interpreted as correlates of physiological arousal (Smolders et al. 2012; e.g.; Huiberts et al. 2016; Kompier et al. 2020), were not found to be affected by exposure to daytime light in our meta-analyses, neither in terms of intensity nor short-wavelength of light waves.

4.1.2. Cognitive outcomes

Our results show that higher light intensity during daytime shortens response times. However, effect sizes were small. We did not find effects of light intensity on accuracy nor any effects for spectral composition of light during daytime. The absence of significant findings for certain cognitive outcomes must be interpreted within the context of the participant demographic in the studies included in our analyses. Predominantly, these studies focused on young, healthy adults, who typically perform at high levels per se with a strong motivation. For future research, it would be prudent to investigate the effects of light on diverse populations beyond college students. Populations such as older people, those that are constantly experiencing sleep loss, or clinical populations may exhibit more pronounced benefits from light exposure during daytime than what our current analysis indicates.

4.1.3. Subjective outcomes

The effects of light on subjective sleepiness, which also included estimates for subjective alertness, are among the most researched NIF effects, especially for light exposures in the evening and night. Our analyses show that higher light intensity during daytime significantly reduces self-reported sleepiness levels. The effect, however, is small, with moderate heterogeneity between studies. The results of our analysis align with the conclusions of the systematic review by Souman et al. (2017) who reviewed acute alerting effects of light and found that both, light intensity and spectrum (expressed as higher color temperature of polychromatic white light), led to higher subjective alertness in the majority of reviewed studies. Our results also go in line with a meta-analysis by Mu et al. (2022) which included only two conditions from each selected study, without differentiating between light intensity and spectrum effects, found that "short-wavelength, cold, or high-illuminance light" can significantly improve subjective alertness, the effects were however summarized over the entire 24 h-day, including nighttime.

Although about one in three studies (45 out of 148) in our selection assessed affect – emotions, mood, or emotional states, – it has received little or no attention in previous reviews of the effect of NIF light, which have rather focused on alertness, cognitive function, and circadian rhythms (Mu et al. 2022; Siraji et al. 2022; Souman et al. 2017, Lok, Smolders, et al. 2018; van Bommel and van den Beld 2004; Xu and Lang 2018). The exceptions were the review by Xiao et al. (2021) and the Cochrane review (Pachito et al. 2018), which reviewed studies with effects of light on mood. Pachito et al. selected only one study (Viola et al. 2008) for the spectral effects of light on mood which was judged as of sufficient quality, therefore not being representative of the research field. Xiao et al. concluded that higher correlated color temperature of light leads to a more positive mood during daytime, while higher light intensity improves mood in the morning and worsens it in the afternoon. These conclusions echo the recent findings of Sabbah et al. (2022), that light manipulations are associated with activations of the prefrontal cortex, which is involved in cognition and emotion, among other functions. Our analyses, however, could not confirm these findings, as the summary effects for both light intensity and light spectrum manipulations were not significant. In contrast to Xiao et al. (2021), we did not assess whether time of day can modulate effects of light intensity or spectrum effects on affect, as it was out of scope for this work. Furthermore, our analyses found no significant effects on ratings of tension, vitality, comfort, or performance appraisals.

In our work, we aimed at summarizing NIF effects of light in the subjective self-report domain by assuming that they are elicited through ipRGCs. This is also supported by the latest findings such as Sabbah et al. (2022). However, different lighting conditions, if they are not metameric (of different spectrum but visually perceived as the same), might have effects on humans through their visual properties. This might be the case especially for self-report measures: for subjective judgments about one's feelings, state of comfort, or performance appraisals, information about the environment can be integrated through psychological pathways, not only through neurological pathways. For instance, it can occur by eliciting psychological representations of certain states that might be learned as rather experienced in certain lighting conditions. For example, during the day, when it is bright, we normally are not sleepy, we are alert, and therefore higher light intensity elicits mental representations of being alert. This makes it more likely to rate one's alertness as higher than under lower light intensity. The same reasoning could be followed for other subjective domains as affect (emotion, mood) or comfort. These are theoretical considerations that cannot be tested within our dataset but it could be one of the avenues for future research.

4.2. Considerations for lighting

Our analysis strategy of dividing lighting manipulations into light intensity and its spectrum was mainly chosen because these two parameters are attributable to the light source. Furthermore, these were the most reported light parameters in the studies. Future avenues for meta-analyses could be considering characteristics to examine effects of light like timing of light exposure (e.g., morning/afternoon), duration, and the direction of light. Several reviews already addressed the aspect of timing and found differential effects in the morning versus afternoon light exposure (Mu et al. 2022; Siraji et al. 2022; Zhang et al. 2020). In our collection of studies, we did not consider this variable, as information on the time of day is not systematically reported and addressing this temporal aspect would have resulted in a nonrepresentative dataset compared to overall light effects.

Analyzing NIF effects of different lighting conditions, it would be desirable to estimate them in regards of the magnitude of light manipulations. This kind of estimation would be possible with the current international standard by the International Commission on Illumination (CIE) S 026:2018 (CIE 2018), which defines light's ability to stimulate each of five retinal receptor classes. More and more studies now report α-opic equivalent daylight (D65) illuminances (α-opic EDIs). These measures, or even complete spectral information which can be used to calculate α-opic EDIs, would allow estimating the role of photoreceptors, especially ipRGCs, in NIF effects of light. With this information, it would be possible to conduct similar analyses as Giménez et al. (2022), who used published data on melatonin levels to quantitatively investigate the role of photoreceptor contributions for melatonin suppression. However, the majority of the studies in our dataset does not provide sufficient information allowing to calculate dose-response analyses. With increasing reporting of lighting conditions according to the CIE standard, there are a growing number of studies on lighting conditions which will allow for meta-analyses in the future to draw conclusions on NIF effects in regards of magnitude of light manipulations.

Our analyses of lighting effects only considered the fact that light intensity or its spectrum was different, but not the magnitude of the difference between conditions. For example, effects for light intensities of 150 lux and 1500 lux were coded the same way as 100 lux and 10,000 lux or 0 lux and 40 lux. Thus, we only considered ordering lighting conditions within a study, but as reporting on lighting conditions is very different in every study and many times poorly reported, we could not apply a unified scale throughout the meta-analyses. Conversely, we could include studies independently of how the light was measured (horizontal, vertical, eye-level, desk), as only differences between conditions mattered, and consequently we were able to include the most datapoints into the analyses. Therefore, we cannot draw conclusions on, e.g., light levels necessary to affect a certain measure or outcome. A quantifiable relationship between the different lighting conditions and the outcome measures would warrant modeling for dose-response relationships. This could be addressed in future analyses that would provide a more focused examination of light quantification.

4.3. Considerations for analytical methods

Our analyses did not take into account the original hypotheses, tests, and statistics of each individual study. We are aware that each study is different in terms of design, timing, light duration, and tasks used, only to mention a few aspects. However, we aimed to analyze the maximum amount of data in a standardized manner to uncover the overall effects. Therefore, in particular situations or conditions, our hypotheses may have differed from those of the authors. As all the studies differed greatly in their design, construction, and conditions, we did not focus on these differences. We focused on the lighting parameters of intensity and spectrum in terms of short-wavelength light. Still, aggregating evidence of light effects is particularly challenging. Studies differ in terms of light characteristics (lamp types, spectral properties, intensity, duration, timing), experimental design, sample size (and therefore often in statistical power), not to mention the wide range of reporting standards, as publications sometimes lack even trivial descriptives of measured phenomena or light parameters. This echoes a preregistered Cochrane literature review on assumed improvements in mood and alertness by office light (Pachito et al. 2018), which included only five studies in the final analysis due to high standards of inclusion and exclusion of reports which were evaluated as low-quality.

We are aware that some of our summarized effects might seem as an overstretch. For instance, meta-analyses on EEG activity or ocular measures included different measures and might have been obtained under different conditions in different studies. For EEG activity, we summarized measures of different frequency ranges, that might have been obtained from different brain regions. Such broad categorization is not optimal and meta-analyses might lack validity by including such heterogeneous dataset. However, our approach provides a broad picture of effects of daytime light exposure which is based on a transparently constructed dataset of all datapoints we could extract from published literature. This dataset is an invitation for interested researchers for further dissecting light effects on physiological, cognitive, and subjective outcomes.

As mentioned in the beginning of the Methods section, heterogeneity was high in most of our analyses. Given that we aimed at analyzing the largest dataset possible, studies with different protocols within one analysis might lead to large heterogeneity indicating large variation of true effect sizes. Heterogeneity scores were particularly high for estimates for EEG power and brain region activity, task performance in terms of response time and accuracy. In cases of high heterogeneity, it is generally recommended to perform moderator analyses or to try to identify separate groups within the study selection with more homogeneous true effect sizes, allowing for focused aggregation of results (Borenstein 2009). Depending on the outcome and on the studies included, separating studies into groups would require different criteria for each outcome, thus it was out of scope of this paper. Therefore, the conclusions of this work are very general, and should be interpreted with caution, and more in-depth analyses could be performed in future studies.

For our analyses, we considered within-persons and mixed designs as between-persons designs. This way, we could include a maximally high number of studies in each analysis. Although it is possible to combine effect sizes of within and between designs into one meta-analysis, available data and/or statistics were not sufficient for it, as full dataset with individual values for the participants would be required for such calculations. Thus, instead of including only between-persons designs or only reports with comprehensive reporting, we preferred to include the most data possible, compromising statistical exactness. For meta-analyses on only between-persons design studies, only the effect of spectral properties of light on response time was significant. Retaining only between-persons design studies led to a much more modest number of studies (49 vs 150 studies) and, consequently, lower number of meta-analyses. With this, statistical power was lower and therefore the chance to observe significant effects of effects that are small in all cases also for our whole selection of studies, comparable to our main set of meta-analyses.

It is important to note that, even if we find significant effects of light on NIF functions, we only included studies with healthy adult volunteers for our analyses. There are other populations for whom light might potentially have even stronger beneficial effects, such as children (Wessolowski et al. 2014), people with affective disorders

(Golden et al. 2005; Lam et al. 2020; Tseng et al. 2016), or circadian sleep-wake rhythm disorders (Faulkner et al. 2019; Pun et al. 2022).

5. Conclusion

Based on a large dataset that was collected from all available empirical data in the literature and on meta-analyses that included more than 10 studies, we conclude that brighter light and light with a higher proportion of short-wavelength light should be preferred during the day, based on the results of our meta-analyses of the effects of NIF lighting on physiological, cognitive and subjective outcomes. However, in healthy adults, the impact is likely to remain small.

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