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Diurnal Intervention Effects of Electric Lighting on Alertness, Cognition, and Mood in Healthy Individuals: A Systematic Review and Meta-Analysis

YanJie Li [a,b], WeiNing Fang [a,b], HanZhao Qiu [a,c], WenLi Dong [a,c], JianXin Wang [a,b], and HaiFeng Bao [a,c]

[a]Human Factor & Ergonomics Lab of Rail Transport, State Key Laboratory of Advanced Rail Autonomous Operation, Beijing Jiaotong University, Beijing, China; [b]School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing, China; [c]School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China

ABSTRACT
Non-image forming effects of electric light can be employed to address problems related to individuals' productivity in isolated and confined extreme environments (ICEs). A systematic review and meta-analysis, registered at PROSPERO (Registration ID: CRD 42022326269), were conducted to thoroughly evaluate the efficacy of the daytime artificial light intervention on alertness, cognition, and mood using psychological, cognitive performance, and physiological multimodal measures. Twenty-eight studies were identified after an extensive search scope of major electronic databases including Web of Science, Embase, PubMed, Scopus, and PsycINFO. Results revealed that the use of daytime light interventions significantly improved alertness and cognition, and reduced the alpha wave of electroencephalogram, whereas no significant difference was observed for mood. Subgroup analyses by intervention attribute suggested that light parameters and time characteristics affected the efficacy of diurnal light intervention with varying degrees. Future work investigating the correlation between the two variables is needed to further our understanding of the impact of daytime electric light on human responses. This study and its methodology can be useful for researchers as they establish lighting design guidelines capable of improving human functions in ICEs.

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Alertness; cognition; daytime electric lighting; mood; non-image forming effects

1. Introduction

Today, some special occupational groups have to be restricted in such typical isolated and confined extreme environments (ICEs) as space stations, underground military shelters, and submarines (Hawes et al. 2012; Nieuwenhuys et al. 2021; Zhang et al. 2020) whose psychophysiological health and performance have been mostly focused by researchers. ICEs residents are exposed to a series of environmental stressors such as daylight deprivation, confinement and isolation, and monotonous sensory stimulation (Desai et al. 2022). Out of these, long-term sensory monotony, especially monotony of vision may cause serious psychological problems (Bishop et al. 2016; Connaboy et al. 2020; Kim et al. 2018). An extreme-design investigation at the Antarctic Space Simulation Station from NASA's Extreme Environment Mission Action [NEEMO] found that the ICE reduced sensory stimulation which could exacerbate the extreme conditions and aggravate residents' fatigue, anxiety, obsessive thoughts, and other psychological problems (Schlacht 2012). Similarly, other studies on long-term isolation and confinement found that ICEs residents usually exhibit hostility, unresponsiveness, poor impulse control, and other psychotic responses under the affection of visual monotony, which have serious impacts on psychophysiological functions and potentially affects work performance (Connaboy et al. 2020; Marazziti et al. 2021; Mohapatra et al. 2020; Oluwafemi et al. 2021).

Appropriate improved visual environmental cues are vital to the satisfaction of basic ICEs residents' work demands. Electric lighting as the major or even the only medium to obtain visual information in ICEs plays a significant role in affecting residents' biological responses (Nang et al. 2019). The positive intervention effects of lighting conditions on human psychophysiological and cognitive expression have been confirmed by

CONTACT WeiNing Fang wnfang@bjtu.edu.cn School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, No. 3 Shang Yuan Cun, Beijing, HD 100044

volumes of empirical studies in the human-centric lighting field (Hsieh et al. 2022; Kakitsuba 2020; Putte et al. 2022). Some relevant studies also have taken ameliorating lighting conditions as an environmental adaptation strategy in ICEs to improve psychophysiological health and performance by reducing visual monotony and have achieved plenty of valuable results. Jiang et al (Jiang et al. 2022, 2022) conducted lighting psychology investigations of space exploration at simulated habitat and found that appropriate electric lighting conditions may contribute to counteracting visual monotony, thereby reducing psychological stress. The United States Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) (Hawes et al. 2012) reported significant fatigue recovery and cognitive-enhancement when the closed military shelters were equipped with appropriate LED lighting color temperature. Nevertheless, the lighting conditions in most ICEs are relatively monotonous, which may induce detrimental effects on human psychophysiological functions (Lu et al. 2021; Nicolas et al. 2016; Yu et al. 2021). Therefore, it is necessary to provide a scientific electric lighting scheme for ICEs to ensure the safe, efficient, and comfortable work of the ICE residents.

1.1. The third photoreceptor-influenced biological response to light

The auxiliary supporting effects of lighting on human psychophysiological health benefit from the non-image forming (NIF) effects of light. Unlike classical photoreceptors (cones and rods), the human third photoreceptor-intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson et al. 2002) can directly or indirectly transmit optical information to the suprachiasmatic nucleus (SCN) through the retinohypothalamic tract (RHT) or intergenic leaf (IGL) and geniculohypothalamic tract (GHT) after receiving a light stimulus (Berson et al. 2002; Edelstein and Amir 1999; Harrington 1997). Meanwhile, neuroimaging studies reported that ipRGCs also receive signals from classical photoreceptors in the fovea centralis of the retina and combine these inputs to comprehensively influence visual and nonvisual responses (Houser et al. 2021; Lucas et al. 2012, 2014), which are collectively called photobiological effects.

The most consistent result of NIF effects is the inhibition of melatonin at night (Xiao et al. 2021). Based on the acute melatonin suppression data exposed to nocturnal light (Brainard et al. 2001; Thapan et al. 2001), the photopigment melanopsin in ipRGCs is more sensitive to short-wavelength light (~480 nm) (Bailes and Lucas 2013; Rea et al. 2012; Torii et al. 2007). Therefore, most nocturnal light intervention studies revealed higher vigilance experience, better cognitive performance, and more positive mood (Brainard et al. 2015; Rahman et al. 2019; Sanders et al. 2021). However, as human beings gradually evolve into diurnal species, an increasing number of human activities are confined to the indoor environment during the day (Allen and Macomber 2020). Whether it could be directly applied to daytime situations is far from conclusive, because human melatonin levels are generally lowest in the daytime which is sufficiently different from night scenarios (van Bommel and van den Beld 2004). Therefore, the NIF effects of daytime electric lighting (DEL) as well as the potential mechanisms need further exploration.

1.2. Regulation variables of biological effects of light

As a whole, the NIF effects of light were regulated by four types of factors, including light parameters, time characteristics, task attributes, and individual factors (e.g. [CIE] Commission Internationale de l'Eclairage 2018; Prayag et al. 2019; Siraji et al. 2022) (Fig. 1). Illuminance, correlated color temperature (CCT), and spectral power distribution (SPD) are essential considerations for the NIF effects, in which the illuminance measured in lux means the amount of light shining onto a surface; the CCT measured in degrees Kelvin (K) refers to a way to characterize the color appearance of any white light utilizing combinations of any visible spectrum distribution, and the SPD describes how much optical power the light source emits for each wavelength band measured in nanometers (nm) ([CIE] Commission Internationale de l'Eclairage 2020; Vetter et al. 2022). However, the effects of these light parameters on human health did not show a systematic pattern (Lok et al. 2018; Souman

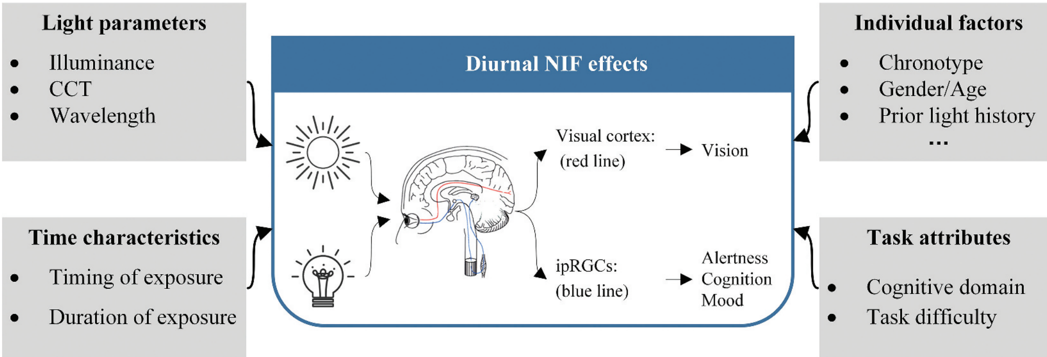

Fig. 1. Four types of influence factors of the diurnal NIF effects.

et al. 2018). Figueiro et al. (2018) proposed that the temporal aspect of lighting is one of the key elements in the NIF effects of light. This point was supported by numerous empirical studies (Iskra-Golec et al. 2017; Luo et al. 2021; Okamoto and Nakagawa 2015; Xiao et al. 2018), which found that the NIF effects of light intensity and spectral characteristics largely depend on the timing and duration of light exposure, although these current results are far from conclusive. Moreover, previous reviews (Fisk et al. 2018; Konstantzos et al. 2020; Siraji et al. 2022) on the cognitive effects of light demonstrated that the NIF effects of light on advanced cognitive functions are mainly achieved by improving alertness, but it is unclear whether this can be always translated into improvement of cognitive performance. The most likely reason for this result is that the best optical attribute of advanced cognitive function may depend on certain task attributes, such as cognitive domain and task difficulty (Huiberts et al. 2016; Ru et al. 2019, 2021). Furthermore, even the same lighting conditions can have very different NIF effects on different individuals depending on individual differences (Boyce 2022; Phillips et al. 2019). They are mainly (but not limited to) reflected in chronotype, gender, age, prior light history, and so on (Smolders and de Kort 2017; Smolders et al. 2016), most of which are strictly controlled as potential confounding variables. Hence, the results of NIF effects of light at this stage are inconsistent due to the complexity of their regulation variables.

Previous studies (Prayag et al. 2019; Vetter et al. 2022) believed in their systematic reviews that the NIF effects of DEL may be more complex than currently known, as it is heavily dependent on multiple intervention attributes such as intensity, duration, timing, pattern, and wavelengths. Therefore, the intervention attributes related to light patterns play the most critical role in the NIF effects of DEL, including light parameters and time characteristics. But notably, most literature reviews paid more attention to the qualitative description of these intervention attributes, and it is unclear to what extent they affect the NIF effects of DEL.

1.3. Quantifying the biological potency of daytime electric light

A quantitative description of the interaction of different light intervention attributes and their relationship with human photobiological responses is fundamental to developing healthy biodynamic lighting solutions. Mu et al. (2022) first used a new meta-analysis to investigate the NIF effects of electric lighting on alertness as well as the relationship between the NIF effects and intervention attributes. They integrated the most relevant laboratory studies on daytime and nighttime light intervention to investigate the impacts of intervention attributes on alertness from subjective and objective evaluation, respectively. The results found that both daytime and nighttime lighting had significant effects on subjective alertness but not on objective alertness. The study scientifically sound summarized the alertness-related light effects, however, it neither separated daytime light nor incorporated physiological measures. Considering the significant differences in photobiological mechanisms between daytime and nighttime light, the study of diurnal NIF effects of light still lacks detailed descriptions. On this basis, our meta-analysis incorporated all the psychological, cognitive response, and physiological results of daytime light exposure on alertness, cognition, and mood to further explore the NIF effects of DEL. Although the empirical studies on diurnal NIF effects are still in their exploratory stage, we shall look forward to investigating the relationship between intervention attributes and diurnal NIF effects can assist researchers and lighting practitioners in designing the artificial lighting environment in ICEs.

To this end, this study aimed to perform a more comprehensive meta-analysis of the NIF effects of DEL on human alertness, cognitive functions, and mood to explore the optimized lighting solutions, thereby contributing to the psychophysiological support of life in ICEs. The main questions of this study were as follows: (1) does DEL intervention effectively improve human alertness, cognitive functions, and mood? (2) what is the relationship between the diurnal NIF effects and light intervention attributes?

2. Materials and methods

This systematic review protocol was registered at PROSPERO (ID: CRD42022326269) and was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement published in 2020 (Page et al. 2021, 2021).

2.1. Eligibility criteria

Table 1 specifies the inclusion and exclusion criteria for this meta-analysis.

2.2. Information sources

A literature retrieval was conducted to confirm the novelty of our meta-analysis in Cochrane and PROSPERO before a formal database search. Subsequently, we performed a thorough literature retrieval with specific keywords of diurnal NIF effects of artificial light in Web of Science (1965–2022), Embase (1966–2022), PubMed (1848–2022), PsycINFO (1930–2022) and Scopus (1788–2022). Moreover, the forward and backward search was conducted.

2.3. Search strategy

Studies were identified using the following keywords: (1) the title had to contain [light OR illuminance OR correlated color temperature OR wavelength]; (2) the topics had to involve one of the words related to daytime scenarios (daytime OR diurnal OR by day OR during the day OR morning OR noon OR afternoon); and (3) the topics had to specifically evaluate human functions such as alertness, performance, and/or mood (alertness OR vigilance OR arousal OR cognition OR performance OR behavior OR mood OR emotion). All records and cited references were manually examined to search for available studies.

2.4. Study selection

After removing duplicate records, eligible studies were selected in two stages. First, two reviewers independently screened the title and abstract of each article and removed the records that were not in agreement with the inclusion criteria. Second, the two reviewers independently screened the remaining articles by assessing their full text.

Table 1. Eligibility criteria for the review.

No.	Included criteria	Excluded criteria
1	Participants were healthy adults aged 18–60 years.	Those reviews without quantitative assessment.
2	Randomized controlled (RCTs), controlled before-after (CBAs), and controlled clinical trials (CCTs) that adopted a crossover or parallel-group design.	Participants were heterogenous populations with clinical illnesses or irregular sleep-wake cycles, such as patients or shift workers.
3	At least one intervention group employed artificial lighting during the daytime working period with a control treatment	The intervention was dynamic light because whether the results were obtained due to the dynamics of light itself was inconclusive.
4	Only studies in the English language published before December 2022 were included.	The studies were non-acute NIF effects (i.e. circadian).
5	At least one of the psychological, cognitive response, or physiological measurements was used to quantify human responses.	The means and SDs were not available after contacting the authors or calculating from statistical analysis.

Discrepancies arising from both steps of the selection process were resolved by thorough discussion between them.

2.5. Data collection

Two reviewers extracted the key characteristics of the included studies using a data extraction table designed for the study including study design, sample size, intervention properties, and outcomes. Any disagreements were resolved through a thorough and systematic discussion. In case the outcomes were unavailable or incomplete in the study, we attempted to contact the authors or calculated the results from statistical analyses of the article.

2.6. Outcomes

We aimed to perform a more comprehensive meta-analysis with a multimodal data structure of psychological, physiological, and cognitive response measures. The psychological measures were a series of subjective scales, which were considered structured measures of alertness and mood. The physiological measures included the assessment of cerebral activity through an electroencephalogram (EEG), which has been a staple method to identify certain health conditions since its discovery. Cognitive response measures included the performance of various tasks that measured objective alertness and other cognitive abilities.

When a study included multiple different treatment groups, we selected only one intervention with the following priority: (1) the group with high-dose light; and (2) the group with the lower dropout rate.

2.7. Quality assessment

The Quality Assessment Tool for Quantitative Studies developed by the Effective Public Health Practice Project (EPHPP) (Project 1998) was used to evaluate the quality of the included studies. This tool assesses various study designs, such as RCTs, CBAs, and CCTs, through the following six domains: selection bias, study design, confounders, blinding, data collection method, and withdrawals/dropouts. It has been proven to have content and construct validity (Jackson et al. 2005; Thomas et al. 2004). The guidelines of this tool (Al-Karawi and Jubair 2016) specify that each domain can be rated as "weak," "moderate," or "strong" and that the number of "weak" ratings of the above all domains could quantify the final global rating as "strong" (no "weak" rating), "moderate" (one "weak" rating) and "weak" (two or more "weak" ratings). The quality assessment of this study was carried out independently by two reviewers, and discrepancies were resolved by thorough discussion.

2.8. Statistical analysis

Statistics, including sample size, mean value, and SD for all outcomes were extracted from each study. The standardized mean difference (SMD) and 95% confidence interval (CI) were calculated which were categorized as small (<0.60), medium (0.60 to < 1.20), or large (≥1.20) effect size (Hall et al. 2013). The combined mean values and SDs were calculated when the outcome was divided into two parts, e.g., Baek and Min (2015) divided the alpha into alpha 1 and alpha 2. Therefore, the combined mean values and SDs of alpha were computed based on Equations (1) and (2):

$$\bar{X}_{combined} = (\bar{X}_{alpha1} + \bar{X}_{alpha2})/2 \tag{1}$$

$$SD_{rms} = \sqrt{(\overline{SD}^2_{alpha1} + \overline{SD}^2_{alpha2})/2} \tag{2}$$

When reported data were broken down into subgroups (i.e., morning and afternoon), the combined mean values and SD were computed across subgroups (Zhao et al. 2021) based on Equations (3) and (4):

$$\overline{X}_{combined} = (n_1\overline{X}_1 + n_2\overline{X}_2)/(n_1 + n_2) \tag{3}$$

$$SD_{combined} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2 + \frac{n_1 n_2}{n_1 + n_2}(\overline{X}_1 - \overline{X}_2)^2}{n_1 + n_2 + 1}} \tag{4}$$

where $\bar{X}_1$,$\bar{X}_2$ refer to the mean value, SD_1,SD_2 refer to the standard deviation, andn_1,n_2 refer to the sample sizes of the two subgroups.

Heterogeneity was quantified by calculating the I^2 statistics with 25%, 50%, and 75% indicating low, moderate, and high levels of heterogeneity, respectively (Higgins et al. 2003), which was considered preferable to test the consistency of evidence (Ioannidis 2008). The fixed-effects model (FEM) was employed if there was a low heterogeneity ($I^2 < 50\%$) (Mantel and Haenszel 1959). Or else, the random effects model (REM) was more suitable. Funnel plots, Begg's test (Begg and Mazumdar 1994), and Egger's regression intercept (Egger et al. 1997) were used to test the publication bias of the included studies and the trim-fill method was performed to address potential publication bias (Colditz et al. 1995). Moreover, sensitivity analyses were performed to test the stability of the results by excluding one study at a time and then reanalyzing the effect size and heterogeneity of the remaining studies. Subgroup analyses were conducted based on the intervention attributes, including light and time parameters. All analyses were performed using the "metafor" package (version 3.4–0) and graphs were made by "forestplot" package (2.0.1) in R studio version 4.2.1.

3. Results

3.1. Study characteristics

A total of 2850 studies were identified in the initial stage of the literature search. After removing duplications and screening titles/abstracts, 70 studies remained for full-text review. We removed 42 studies which left 28 studies included in the meta-analysis (Fig. 2). The reasons for removing these studies were as follows: 13 studies were omitted because research objectives or results were not relevant to the current study, seven studies adopted mixed design so that these results were muddied, 13 studies set the light intervention time in non-working time, six studies were omitted because results cannot be combined, and three studies were older version. Table 2 shows the descriptions of all included studies. The total number of participants in all included studies was 1103 with 551 participants in the experimental group [mean age = 23.44 years, 219 female] and 552 participants in the control group [mean age = 23.50 years, 219 female].

3.2. Data synthesis

The psychological measures were a series of questionnaires involving alertness and mood, in which the Karolinska Sleepiness Scale (KSS), Visual Analog Scales (VAS), and Stanford Sleepiness Scale (SSS) were used to evaluate alertness, and the State-Trait Anxiety Inventory Form Y (STAI-Y), Positive and Negative Affect Schedule (PANAS) and other Likert scales were used to test mood. These scales provided a measure of existing sleepiness and emotion with diverse measurement constructs (Minkwitz et al. 2020; Ortego et al. 2016). The cognitive response measures included psychomotor vigilance testing (PVT) and other cognitive tasks to test cognitive abilities. EEG alpha waves (8–12 Hz) were extracted to evaluate physiological responses.

3.3. Quality assessment

The quality levels of all included studies were appraised as "moderate" to "strong" according to the global ratings with higher scores indicating higher quality. But most of them had a high risk of bias in the blinding criteria, of which 85% had "weak" scoring because of the open trials, 11% had a "moderate" rating because they did not report whether the participants were aware of the research question. Moreover, 7% scored "moderate" in withdrawals and drop-outs criteria, as they mentioned that only 60–79% of participants completed the entire study.

3.4. Meta-analysis

A multimodal data structure of psychological, physiological, and cognitive response measures with sufficient data was examined to explore the diurnal NIF effects of DEL in this meta-analysis.

3.4.1. Psychological measures

The results of the pooled data from 23 studies with subjective alertness showed that DEL had a small significant effect on subjective alertness ($SMD = -0.22$; 95% $CI = [-0.35, -0.09]$; $p = .001$; $I^2 = 2\%$; $p = .44$; Fig. 3). No significant heterogeneity was observed. There was no indication of significant publication bias, either by inspection of the funnel plots or from the small-study tests (Begg's test: $z = -1.77$, $p = .08$; Egger's test: $t = -1.42$, $df = 21$,

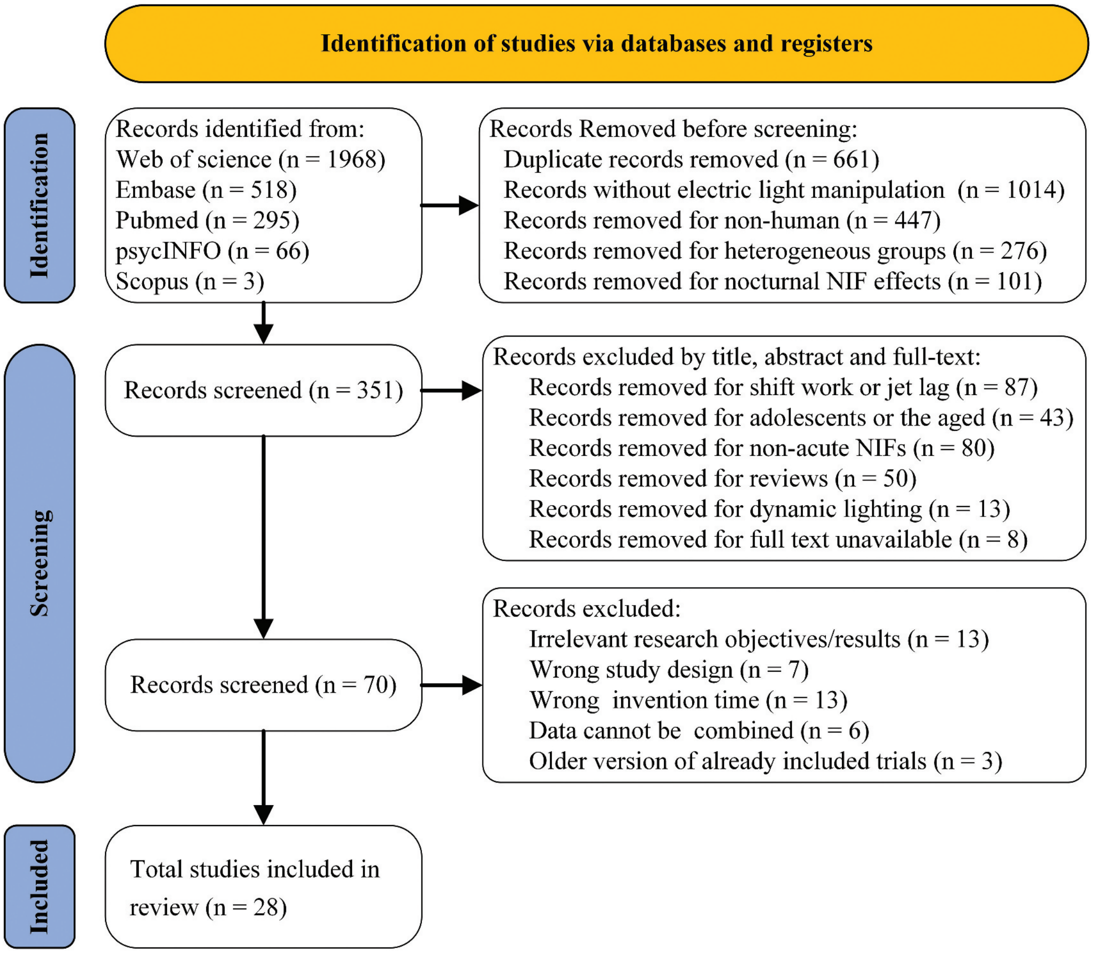

Fig. 2. PRISMA 2020 flow diagram of the study selection.

$p = .17$). Sensitivity analyses were conducted because of potentially significant differences between the 23 studies in intervention parameters and revealed that these results were relatively stable.

The meta-analysis on subjective mood showed that DEL had no significant effects on positive mood [SMD = 0.15; 95% CI = [−0.06, 0.35]; $p = .15$; $I^2 = 0\%$; $p = .59$; Fig. 4a] nor negative mood [SMD = −0.08, 95% CI: −0.29 to 0.13; $p = .47$; $I^2 = 67\%$, $p = .01$, REM; Fig. 4b]. The heterogeneity between studies was high for negative mood, whereas no heterogeneity among studies was observed for positive mood. The exclusion of the study by Zhou et al. (2021) revealed that the effect size in favor of DEL remained small and insignificant (SMD = 0.03, 95% CI: −0.19 to 0.25; $p = .78$), although the heterogeneity of the remaining studies was significantly decreased ($I^2 = 0\%$).

3.4.2. Cognitive response measures

The PVT is a simple sustained attention task that measures objective alertness by assessing the reaction time (RT, unit: ms) or response speed (RS) of the brain to external sensory stimuli (Dinges and Powell 1985), with shorter RT or faster RS representing higher alertness. Ten studies involved objective alertness (PVT) measures, six of which evaluated RT, and the other four studies evaluated RS. The results of the pooled data revealed that DEL had a medium significant effect on RT [SMD = −0.69; 95% CI = [−1.36, −0.03]; $p = .04$; $I^2 = 76\%$; $p = .001$; Fig. 5a], but not on RS [SMD = 0.13; 95% CI = [−0.18, 0.43]; $p = .42$; $I^2 = 21\%$; $p = .29$; Fig. 5b]. The heterogeneity between studies was high for RT, whereas no heterogeneity among studies was observed for RS. Sensitivity analyses showed that the heterogeneity was markedly

Table 2. Characteristics of each included study.

Author (year)	Study design	Participants (T/C)	Treatment	Control	Timing	Duration (min)	Outcomes
Crasson and Legros (2005)	Crossover	18/18	Bright light (5000 lux)	Sham exposure	13:30–14:00	30	VAS, STAI-Y, Oddball
Rüger et al. (2006)	Crossover	12/12	Bright light (5000 lux)	Dim light (< 10 lux)	12:00–16:00	240	KSS, VAS-F
Vandewalle et al. (2006)	Crossover	12/12	Bright white light (> 7000 lux)	Dim light (< 0.01 lux)	13:00–14:10	20	KSS
Vandewalle et al. (2007)	Crossover	18/18	Blue monochromatic light (470 nm)	Green monochromatic light (550 nm)	13:00–14:10	18	KSS, 2-back
Kaida et al. (2013)	Crossover	16/16	Bright light (> 2000 lux)	Dim light (< 5 lux)	04:15–15:30	75	KSS, Switching task
Sahin and Figueiro (2013)	Crossover	13/13	Short-wavelength light (470 nm, 40 lux)	Long-wavelength light (630 nm, 40 lux)	14:00–16:00	50	KSS, Alpha
Santhi et al. (2013)	Crossover	11/11	Blue-enhanced (195 lux 17,000 K)	Blue-Intermediate (200 lux, 2700 K)	06:30–10:30	240	1-back, 3-back
Rahman et al. (2014)	Parallel-group	8/8	Blue monochromatic light (460 nm)	Green monochromatic light (550 nm)	12:45–19:15	390	KSS, PVT
Sahin et al. (2014)	Crossover	13/13	Red light (631 nm, 213 lux)	Dim light (< 5 lux)	Daytime	120	Go-NoGo, Alpha
Smolders and de Kort (2014)	Crossover	28/28	Bright light (1000 lux)	Dim light (200 lux)	Daytime	30	KSS, PVT, Go-NoGo
Baek and Min (2015)	Crossover	20/20	Short-wavelength light (451 nm)	Dim light (< 0.3 lux)	14:00–15:00	48	CPT, Alpha 1, Alpha 2
Huiberts et al. (2015)	Crossover	64/64	Bright light (1000 lux)	Dim light (200 lux)	Daytime	60	KSS, mood scale
Okamoto and Nakagawa (2015)	Crossover	8/8	Short wavelength light (10 lux, 470 nm)	Long wavelength light (10 lux, 620 nm)	12:00–16:00	28	KSS
Alkozei et al. (2016)	Parallel-group	17/18	Blue wavelength light (469 nm, 214 lux)	Amber wavelength light (578 nm, 188 lux)	9:45–12:45	30	SSS, 0-back, 1-back, 2-back
Münch et al. (2016)	Crossover	18/18	Blue-enriched lighting (750 lux, 3537 K)	Control light (40 lux, 2600 K)	08:00–11:00	180/d, 3 d	VAS, PVT
Borragán et al. (2017)	Crossover	17/17	Bright light (2000 lux)	Dim light (< 200 lux)	15:00–17:00	20	KSS, VAS-F, PVT, PANAS
Iskra-Golec et al. (2017)	Crossover	30/30	Monochromatic blue light (460 nm)	Dim light (6.5 lux)	Daytime	30	Alpha 1
Askaripoor et al. (2018)	Crossover	44/44	7343 K,500 lux	2564 K, 500 lux	Daytime	92	KSS, VAS-F, CPT, Alpha
Łaszewska et al. (2018)	Crossover	19/19	Blue light (465 nm)	Red light (625 nm)	12:00–12:40	15	KSS, Alpha
Rodríguez-Morilla et al. (2018)	Crossover	17/17	Blue-enriched white light (440 nm, 469 lux)	Dim light (< 1 lux)	08:30–09:30	60	KSS, mood scale, PVT, DS
Choi et al. (2019)	Crossover	15/15	Blue-enriched white lights (500 lux, 6500 K)	Warm white light (500 lux, 3500 K)	09:00–11:00	60	KSS, VAS-Mood
de Zeeuw et al. (2019)	Crossover	24/24	Highest-mel light (480 nm, 100 lux)	Dim light (< 5 lux)	10:30–14:30	180	VAS
Lok et al. (2019)	Crossover	10/10	Bright white light (2000 lux)	Dim light (< 10 lux)	12:00–16:00	90	KSS, PVT
Šmotek et al. (2019)	Crossover	12/12	Short narrow-bandwidth light (455 nm)	Long narrow-bandwidth light (629 nm)	12:00–15:00	20	KSS, PVT
Luo et al. (2021)	Crossover	20/20	1200 lux, 6500 K	200 lux, 6500 K	13:00–19:15	300	KSS, PVT, Alpha
Ru et al. (2021)	Crossover	30/30	High light (6500 K, 1036 lux)	Low light (6500 K, 108 lux)	Afternoon	52	KSS, PANAS, PVT,
Zhou et al. (2021)	Crossover	17/17	Blue-enriched bright light (1000 lux, 6500 K)	Normal indoor light (100 lux, 4000 K)	14:00–14:30	30	KSS, PANAS, PVT
Wolska et al. (2022)	Crossover	20/20	Blue-enriched white light (470 nm)	Reference scene (4000 K)	12:00–15:00	40	Go-NoGo

T/C = Treatment/Control

decreased and the effect sizes remained at the significance level when the study by Rodriguez-Morilla et al [91] was excluded [SMD = −0.30; 95% CI = [−0.62, 0.02]; $p = .07$; $I^2 = 40\%$].

A total of 10 studies were included to analyze the overall diurnal NIF effects of light on cognition, which was effectively measured based on RT to a visual or auditory stimulus with longer RT

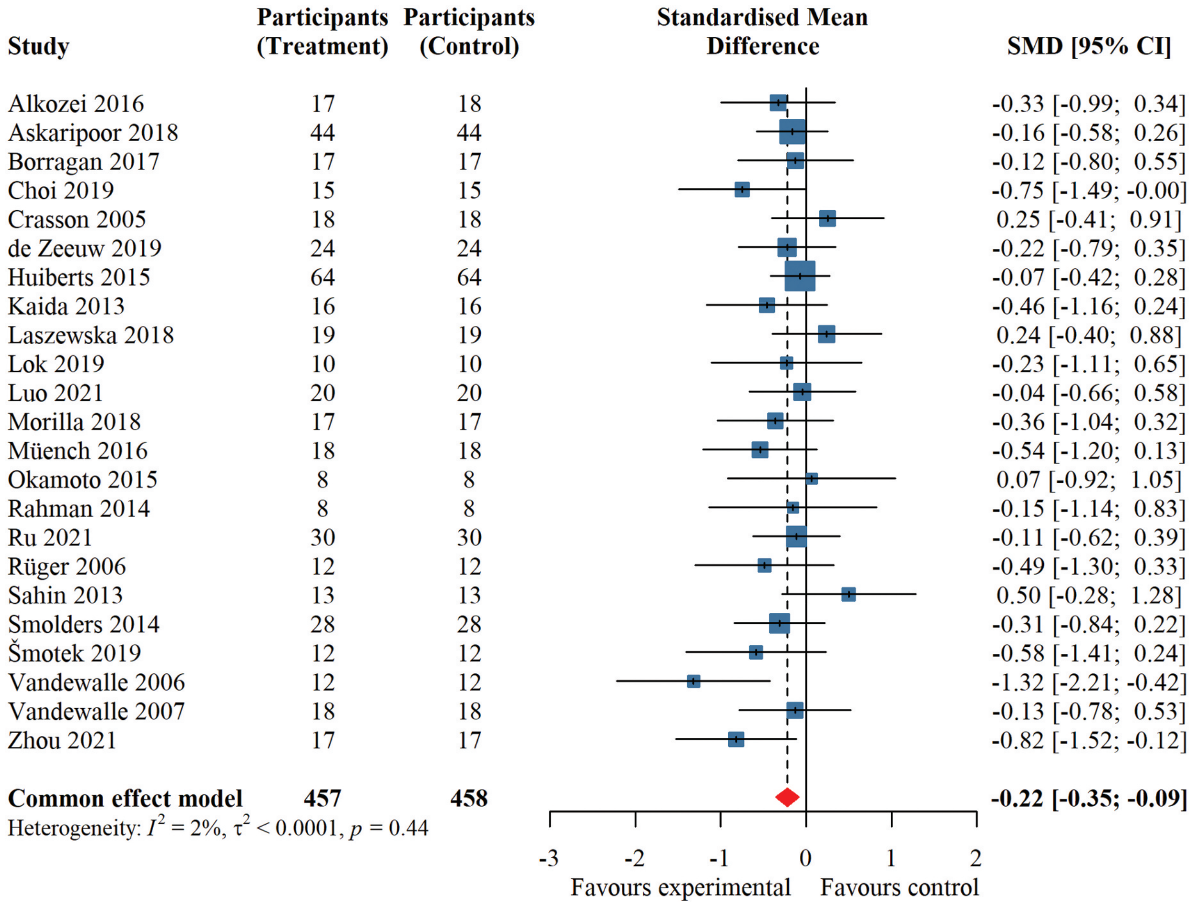

Fig. 3. Meta-analysis based on psychological measures of subjective alertness.

representing worse cognitive performance. The results showed that the DEL had a small significant effect on cognitive performance [SMD = −0.21; 95% CI = [−0.39, −0.02]; $p = .03$; $I^2 = 38\%$, $p = .09$; Fig. 6]. No significant heterogeneity was observed. Trim – and - fill adjustments were performed as the inspection of the funnel plot, Begg's test ($z = -2.10$, $p = .04$), and Egger's test ($t = -2.59$, $df = 9$, $p = .03$) revealed likely publication bias. Sensitivity analyses were conducted owing to potential significant differences between the 10 studies in task properties revealed that these results were relatively stable.

3.4.3. Physiological measures

Seven studies involving an alpha wave of EEG were included to analyze the overall diurnal NIF effects of light on cerebral activity. Meta-analysis of the pooled data from the seven studies revealed that DEL had a small significant inhibitory effect on the alpha wave [SMD = −0.26; 95% CI = [−0.49, −0.08]; $p = .007$; I2 = 57%; $p = .03$; Fig. 7], revealing moderate heterogeneity. The results of sensitivity analyses showed that the effect size in favor of DEL was significantly increased after removed Sahin et al. [83] [SMD = −0.35, 95% CI: −0.56 to −0.14; $p = .001$; I2 = 42%; FEM] with no detectable changes in heterogeneity.

3.5. Subgroup analyses

To further investigate the relationship between diurnal NIF effects and intervention properties of DEL, subgroup analyses were conducted based on light parameters and time characteristics. The subgroup analysis based on light parameters evaluated the diurnal NIF effects compared for (1) high (≥1000 lx) versus low (≤200 lx) illumination levels, (2) cool (CCT ≥ 6500 K) versus warm white light (CCT ≤ 3500 K), (3) short- or blue-enriched light (λmax ≤ 480 nm) versus medium-/long-wavelength (λmax > 500 nm), which was also referred in the study of Mu et al. (2022). The

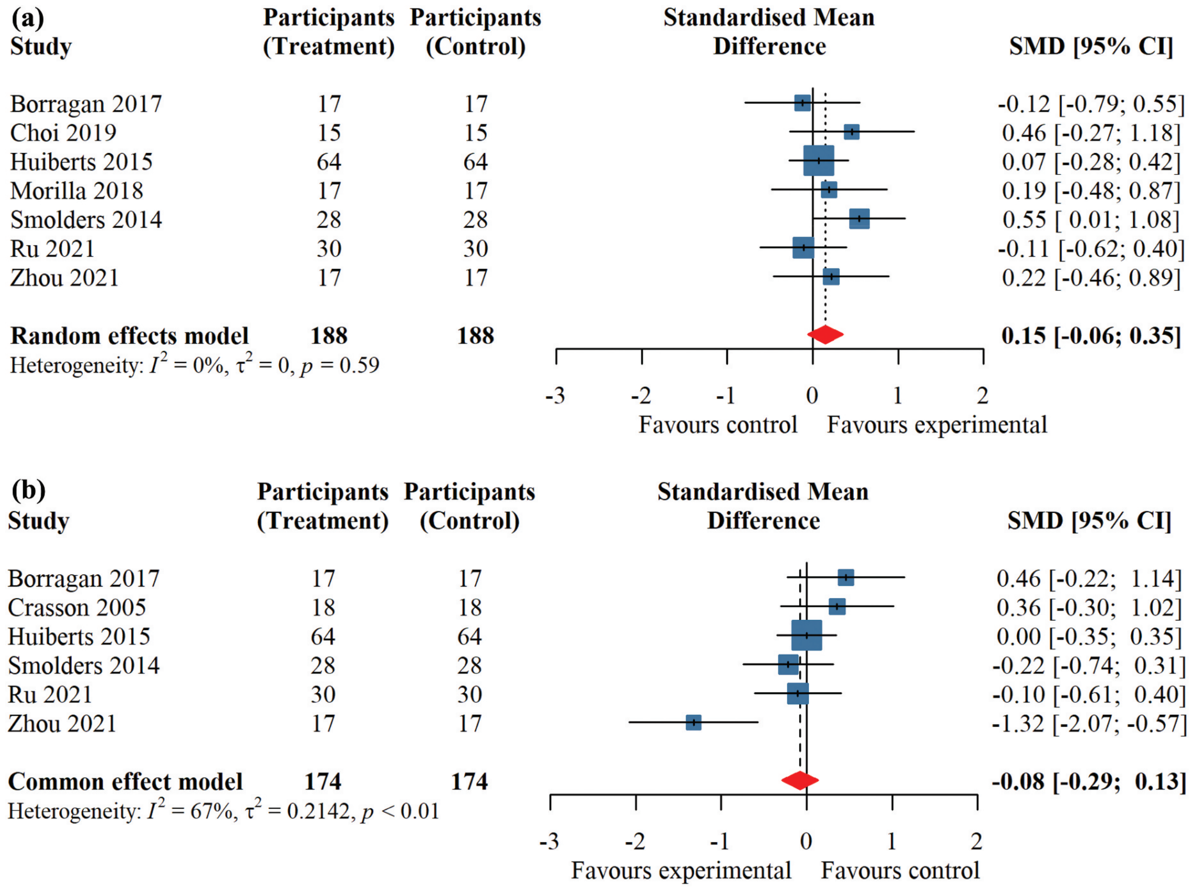

Fig. 4. Meta-analysis based on psychological measures characterized by (a) positive-, and (b) negative –mood.

subgroup analyses based on time parameters were divided into timing and duration subgroups according to the study characteristics of all included studies. More specifically, the timing subgroup analysis was performed based on whether DEL intervention was conducted in the morning (06:00–12:00 am) or afternoon (12:00–07:30 pm), which was specified in most of the included studies. The duration subgroup analysis examined differential diurnal NIF effects caused by DEL intervention whether it was conducted less than 60 min because previous studies revealed 1 h is a critical time point in distinguishing short- and long-term NIF effects (Smolders et al. 2013; Tao et al. 2020). Table 3 presents subgroup analyses of the NIF effects of DEL intervention properties on subjective alertness. The results of subgroup analysis classified by light parameters showed that, compared with control light, bright light had a small significant effect on subjective alertness [SMD = −0.25; 95% CI = [−0.43, −0.08]; p = .004; I^2 = 18%; p = .26], but cold or short-wavelength light led to no significant improvements in subjective alertness. The subgroup analysis based on the timing of light intervention revealed that a small significant effect size for both the morning [SMD = −0.41; 95% CI = [−0.71, −0.12]; p = .006; I^2 = 0%; p = .84] and afternoon (SMD = −0.18; 95% CI = [−0.37, 0.00]; p = .05; I^2 = 23%; p = .20) interventions. The subgroup analysis based on the duration of the light intervention indicated that both short-term [SMD = −0.20; 95% CI = [−0.36, −0.04]; p = .02; I^2 = 30%; p = .13] and long-term [SMD = −0.26; 95% CI = [−0.49, −0.03]; p = .03; I^2 = 0%; p = .96] light interventions had significant effects on subjective alertness.

Table 4 presents subgroup analyses of the NIF effects of DEL intervention properties on cognitive performance. The results of subgroup analysis classified by light parameters showed that, compared with the control light, short-wavelength light had significant effects on cognitive performance [SMD = −0.42; 95% CI = [−0.72, −0.13]; p = .005; I^2 = 0%; p = .84], but bright or cold light led to no significant improvements in cognitive performance. The subgroup analysis based on the timing of light intervention showed a medium significant effect size for the morning

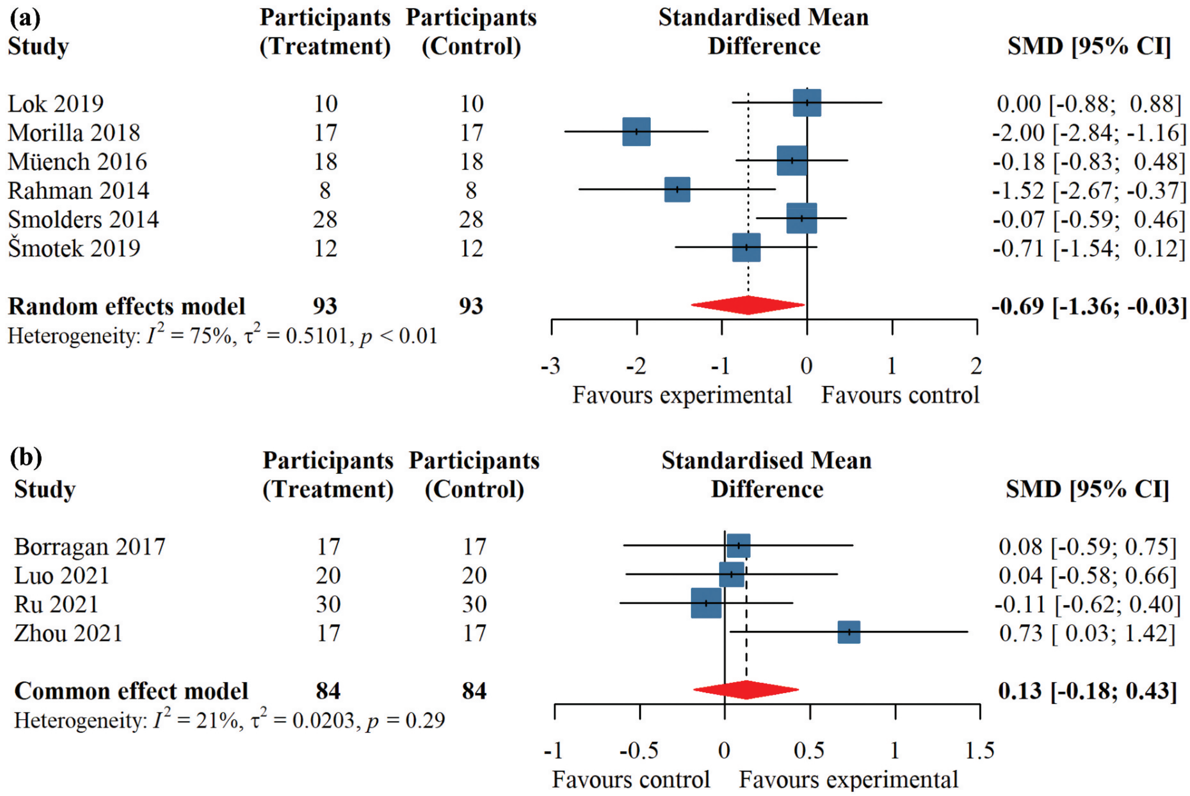

Fig. 5. Meta-analysis based on cognitive response measures characterized by (a)the RT, and (b) the RS of PVT.

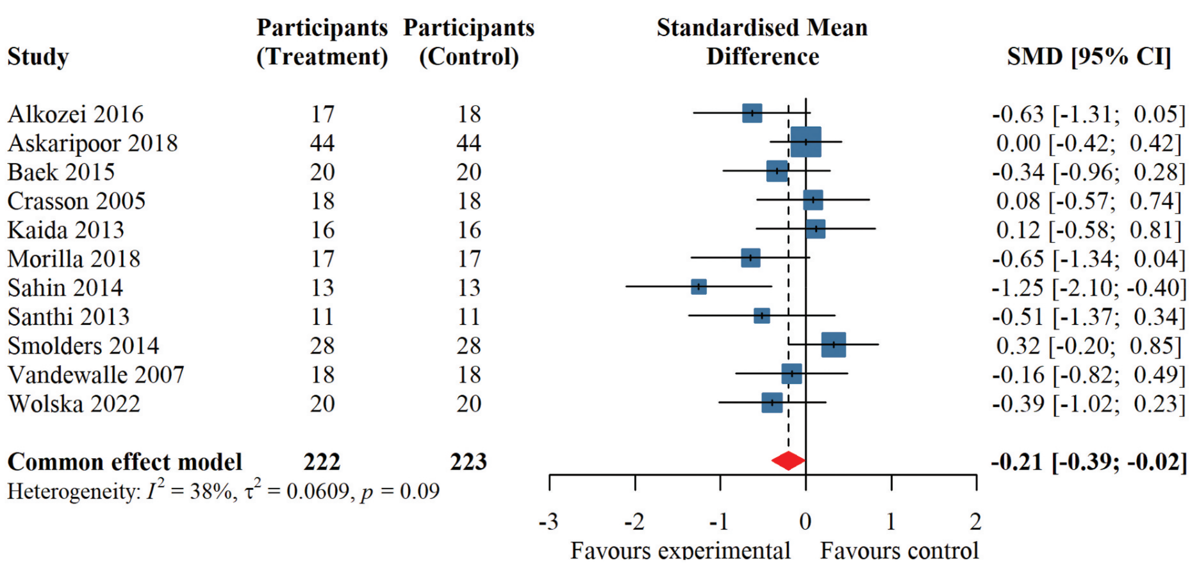

Fig. 6. Meta-analysis based on cognitive response measures characterized by the RT of cognitive tasks.

intervention [SMD = −0.61; 95% CI = [−1.03, −0.19]; p = .005; I^2 = 0%; p = .97], but not for the afternoon intervention. The subgroup analysis based on the duration of light intervention demonstrated a small significant effect size for short-term intervention [SMD = −0.34; 95% CI = [−0.61, −0.07]; p = .01; I^2 = 0%; p = .64], but not for long-term intervention.

4. Discussion

To the best of our knowledge, this study is the first meta-analysis to investigate the effects of DEL intervention based on psychological, cognitive response, and physiological multimodal measurements. The current evidence identified that DEL

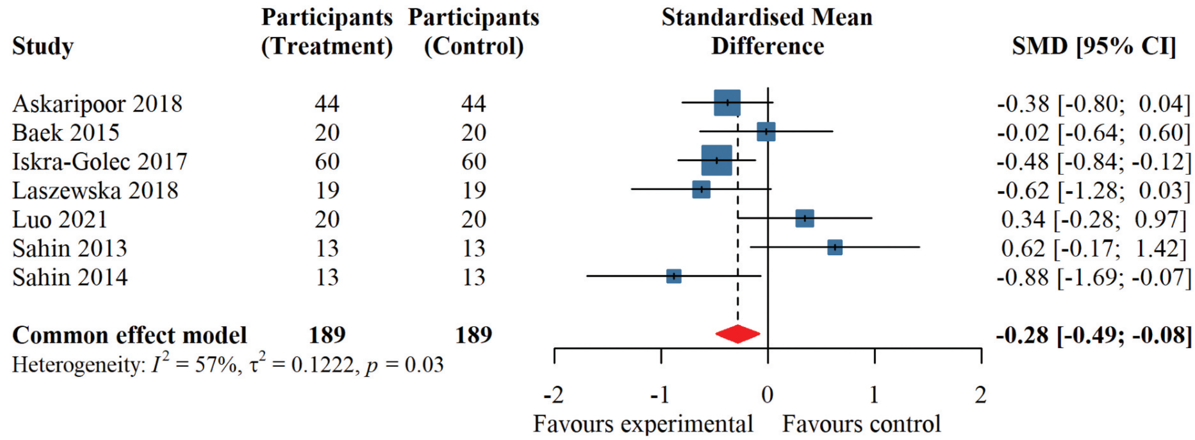

Fig. 7. Meta-analysis of EEG alpha wave.

Table 3. Subgroup analyses of the diurnal intervention effects on subjective alertness.

Subgroups	N	Sample size (T/C)	Heterogeneity test I^2	Heterogeneity test p	Statistical analysis SMD (95% CI)	Statistical analysis p
Light parameters	23	457/458	2%	0.44	−0.22 (−0.35, −0.09)	**0.001**
Illuminance	12	262/262	18%	0.26	−0.25 (−0.43, −0.08)	**0.004**
CCT	2	59/59	45%	0.18	−0.30 (−0.67, 0.06)	0.10
Wavelength light	9	136/137	0%	0.65	−0.12 (−0.36, 0.12)	0.34
Timing	20	321/322	11%	0.32	−0.25 (−0.41, −0.09)	**0.002**
Morning	5	91/92	0%	0.84	−0.41 (−0.71, −0.12)	**0.006**
Afternoon	15	230/230	23%	0.20	−0.18 (−0.37, 0.00)	**0.05**
Duration	23	457/458	2%	0.44	−0.22 (−0.35, −0.09)	**0.001**
Short-term	15	305/306	30%	0.13	−0.20 (−0.36, −0.04)	**0.02**
Long-term	8	152/152	0%	0.96	−0.26 (−0.49, −0.03)	**0.03**

Table 4. Subgroup analyses of the diurnal intervention effects on cognitive performance.

Subgroups	N	Sample size (T/C)	Heterogeneity test I^2	Heterogeneity test Q	Heterogeneity test df	Heterogeneity test p	Statistical analysis SMD (95% CI)	Statistical analysis p
Light parameters	10	209/210	11%	10.16	9	0.34	−0.15 (−0.34, 0.04)	0.12
Illuminance	3	62/62	0%	0.38	2	0.83	0.20 (−0.15, 0.55)	0.27
CCT	2	55/55	12%	1.13	1	0.29	−0.10 (−0.47, 0.28)	0.60
Wavelength	5	92/93	0%	1.43	4	0.84	−0.42 (−0.72, −0.13)	**0.005**
Timing	8	137/138	0%	5.08	7	0.65	−0.30 (−0.54, −0.06)	**0.01**
Morning	3	45/46	0%	0.06	2	0.97	−0.61 (−1.03, −0.19)	**0.005**
Afternoon	5	92/92	0%	1.99	4	0.74	−0.15 (−0.44, 0.14)	0.30
Duration	11	222/223	38%	16.25	10	0.09	−0.21 (−0.39, −0.02)	**0.03**
Short-term	7	138/139	27%	8.19	6	0.22	−0.20 (−1.02, 0.23)	0.09
Long-term	4	84/84	63%	8.06	3	**0.04**	−0.34 (−0.92, 0.23)	0.24

CI: Confidence interval; N: number of included studies; SMD: standardized mean difference.

intervention had significant effects on alertness and cognition but not on subjective mood. Moreover, the diurnal NIF effects of DEL depended largely on the coupling induction of light parameters, timing, and duration of exposure. More specifically, we found that DEL intervention 1) improved both subjective and objective alertness, especially bright light intervention; 2) had cognitive-enhancement effects, which may be regulated by light parameters and timing of exposure; and 3) can activate arousal levels by inhibiting EEG alpha wave.

4.1. Diurnal alerting effects

The finding that DEL intervention was found to affect subjective alertness should be taken with caution. A previous study proposed that there was a personal preference when participants were required to use the psychological scales to evaluate their subjective experience (Jahedi and Méndez 2014), especially in the non-blind trials. However, it is difficult for the participants in most of the included studies to be not aware of the research question for lighting intervention experiments, so they may expect to get more alertness under intervention than control light. Therefore, blinding randomized controlled trials as well as placebo effects should be considered in future studies to explore the diurnal NIF effects of DEL.

As the most widely used, reliable, and valid method for measuring alertness, PVT measures sustained attention more than alertness. There was an unanticipated finding that the NIF effects of DEL on the two PVT performance indicators (RT and RS) showed opposite results, although RS was obtained through the inverse transformation of RT. Wainer (1977) proposed that RT and RS are most definitely not equivalent and an interpretation of the experimental results using response time might be completely reversed if speed was the dependent variable. Specifically, this difficulty may cause ambiguous results in studies. Therefore, data conversion should be treated cautiously in future studies, as it may fundamentally change the nature of variables and complicate the interpretation of the results (Osborne 2019). Moreover, large heterogeneity between Rodríguez-Morilla et al. (2018) and the other studies was found in RT-based meta-analysis because the chronotype of participants in this study was evening types (ET). The regulation of chronotypes on the alerting effects of light has been explored in previous studies (Figueiro et al. 2014; Porcheret et al. 2018; Yang et al. 2019), in which the potential effects of different chronotypes on arousal and performance have been reported. A promising direction for future studies will be to examine the potential regulatory effects of chronotypes in the diurnal NIF effects of DEL.

Research evidence from neurocognitive has shown that light can activate neural activity in brain regions related to alertness, arousal, or cognition (Yawale et al. 2021). The alpha band of EEG activity has been used as an index for conscious alertness levels (Kalauzi et al. 2012; Ru et al. 2022), with a decrease related to higher arousal or vigilance (Gharagozlou et al. 2015). The study by Iskra-Golec et al. (2017) made the incorporated result not robust, indicating that study characteristics contributed to differences in the literature. However, due to insufficient evidence, it is difficult to study the time domain, frequency domain, and time-frequency domain characteristics of EEG related to neurobehavior mechanisms. Future research is required to use efficient approaches of EEG analysis to further characterize these neurobehavioral dynamics with more precise time and spatial resolution.

4.2. Diurnal cognitive effects

In terms of diurnal NIF effects on cognitive performance, our meta-analysis found a significant but small overall effect size, indicating that cognitive performance may be improved under DEL intervention during working hours. Considering that our meta-analysis only pooled the RT data of various tasks to characterize cognitive functions, the findings should be interpreted with caution. As mentioned previously, the photopigment melanopsin in ipRGCs is more sensitive to short-wavelength light (~480 nm), which may explain why it has a significant effect on cognition. Moreover, as reported in previous studies (Choi et al. 2019; Te Kulve et al. 2018), the cognitive – enhancement effects of DEL appeared to be more significant in the morning. It should also be noted that while none of the studies in the subgroup analysis based on the duration of light intervention showed significance individually, the pooled effect size was significant. One explanation for this phenomenon may be the pooled sample size in comparison to the much smaller individual sample sizes. Future work should be conducted to with larger sample sizes clarify the regulatory role of the duration of light intervention.

From a practical point of view, task heterogeneity (*i.e.* differences in paradigms characterizing cognitive functions) may play a potential regulatory role in diurnal NIF effects. A recent study published by Ru and colleagues found that the NIF effects of illuminance during the day on cognitive performance may be regulated by task type and task difficulty (Ru et al. 2021). Therefore, a promising direction for future research is the investigation of modulations of task heterogeneity on human photobiological response. However, the current evidence was difficult to support further study on task heterogeneity because the empirical database for calculating a single meta-analysis based on cognitive function was too small. Task paradigms representing human cognitive responses may be complex (Fan et al. 2002). Given the NIF effects of DEL appear to be influenced by task heterogeneity, it would be advised for developing new tasks that are particularly sensitive to DEL intervention in combination with research purposes and experimental schemes.

Subgroup analysis demonstrated the complexity of the influencing factors of diurnal NIF effects. These results indicate that there is a potential relationship between light parameters and time characteristics, which in conjunction, can regulate diurnal NIF effects. Therefore, it seems feasible to pay more attention to the relationships between these factors when investigating diurnal NIF effects.

4.3. Diurnal mood effects

The results based on the forest plots found that the NIF effects of DEL intervention on mood were mixed. Previous studies revealed that appropriate lighting might create a comfortable and relaxing atmosphere and directly or indirectly influence mood states (Seuntiens and Vodels 2008; Vogels 2008). However, our meta-analysis found no significant diurnal NIF effects of DEL on mood. One reason could be that mood states elicited by the lighting environment may be significantly affected by social and cultural backgrounds (Li et al. 2017). Moreover, gender differences play a significant regulatory role in lighting perception. Wang et al. (2013) found that males and females had different perceptions of safety, space, cold, etc., created by different light conditions. Unfortunately, there has been little in-depth analysis of the above-mentioned social and cultural factors in the studies included in this meta-analysis, which makes it difficult for us to discuss them thoroughly. Therefore, individual characteristics must be given appropriate attention in future studies on emotional lighting to achieve more reliable results.

4.4. Limitations

Some limitations of this meta-analysis should be noted when interpreting these results. First, 85% of the included studies had "weak" scoring in blinding criteria when undergoing quality assessment, which may lead to a high risk of bias. However, it is a bit difficult for participants to follow the blinding criteria in actual lighting experience experiments, although blinding the participants could protect against reporting bias. Therefore, the results of this meta-analysis should be interpreted with caution. Second, due to the limited data in included studies, we could not take individual factors and task attributes into account to conduct a detailed meta-analysis. Future studies should pay more attention to human NIF response differences elicited by individual and/or task factors to deepen our understanding of the diurnal NIFs. Finally, the studies included in some subgroups were surprisingly sparse, e.g., only two studies were included in the CCT subgroup for meta-analysis based on subjective alertness. With the limited number of studies, the variation of the results would increase, thereby reducing the power to detect the actual effects. Therefore, it would require extensive research to explore further to draw concrete conclusions.

5. Conclusions

Our meta-analysis provides supporting evidence from laboratory studies that DEL intervention had significant effects on the alertness and cognition of healthy individuals, in particular for light parameters and time characteristics. However, due to the limited number of comparisons, their relations and the effects of other variables, *i.e.* task attributes and individual factors, were difficult to determine and should be examined in future work.

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ORCID

YanJie Li http://orcid.org/0000-0001-6775-1851
WeiNing Fang http://orcid.org/0000-0002-3768-1845
HanZhao Qiu http://orcid.org/0000-0002-4580-5545
WenLi Dong http://orcid.org/0000-0003-1910-9666
JianXin Wang http://orcid.org/0000-0003-3050-8713

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