Optimizing Effects of Daytime Light Exposure on Sleep and Mechanisms of Action

Authors: He Meiheng, Ru Taotao, Li Le, Li Siyu, Zhang Chenze, Zhou Guofu, Ru Taotao

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Abstract

Light, as the most important zeitgeber, exerts significant regulatory effects on circadian rhythms and sleep in organisms. Existing research has found that greater daytime light exposure, particularly high-intensity morning light, significantly promotes nighttime sleep in individuals, though this optimizing effect is modulated by light parameters and individual characteristics. Daytime light can indirectly influence sleep by phase-advancing or phase-delaying the organism' s biological rhythms; however, whether daylight exposure directly affects sleep by modulating sleep homeostatic pressure remains unclear. Future research could investigate the interactive effects of daylight levels and timing on sleep, and construct healthy human-centric lighting models for specific populations such as long-term indoor office workers, shift workers, or individuals with sleep disorders.

Full Text

The Optimization Effects of Daytime Light Exposure on Sleep and Its Mechanisms

HE Meiheng[1,2], RU Taotao[2], LI Le[3], LI Siyu[1,2], ZHANG Chenze[1,2], ZHOU Guofu[2,3]

[1] Lab of Lighting and Physio-psychological Health, School of Psychology, South China Normal University, Guangzhou 510631, China
[2] National Center for International Research on Green Optoelectronics, South China Normal University, Guangzhou 510006, China
[3] South China Academy of Advanced Optoelectronics, South China Normal University, Guangzhou 510006, China

Abstract

As the most critical Zeitgeber, ambient light exerts significant regulatory effects on circadian rhythms and sleep. Previous research has demonstrated that greater daytime light exposure, particularly high-intensity morning light, substantially improves nocturnal sleep quality. However, this optimization effect is moderated by various light parameters and individual characteristics. Daytime illumination can indirectly influence sleep by advancing or delaying circadian phase, while whether it directly affects sleep through modulation of sleep homeostatic pressure remains unclear. Future studies should investigate the interactive effects of light intensity and timing on sleep, and develop health-oriented lighting models tailored for specific populations such as indoor office workers, shift workers, and individuals with sleep disorders.

Keywords: daytime light, sleep, healthy lighting, mechanism, circadian rhythm

Sleep plays a vital role in individual growth and development. However, sleep problems—including chronic sleep restriction, insomnia, and poor sleep efficiency—are becoming increasingly prevalent and showing a trend toward younger age groups. Meta-analyses indicate that sleep disturbances are widespread in China [?, ?, ?], particularly during the COVID-19 pandemic [?, ?, ?, ?]. Poor sleep is closely associated with various physical and mental health issues, including mood disorders [?, ?], hypertension [?, ?], and diabetes [?, ?]. Therefore, improving sleep quality holds significant social value for enhancing national health and well-being.

As an indispensable environmental factor, light is ubiquitous in daily life. Serving as the most important Zeitgeber for all mammals, ambient light regulates circadian rhythms and influences sleep [?, ?, ?, ?, ?]. Prolonged exposure to insufficient or inappropriate lighting can lead to circadian disruption, poor sleep quality, and affective disorders [?, ?, ?]. Consequently, researchers have increasingly focused on the relationship between daytime light exposure and nocturnal sleep. Findings from these studies can inform the design of "Human Centric Lighting" (HCL) environments that optimize visual performance while enhancing sleep quality and psychological well-being, representing an effective and important intervention strategy. This review systematically examines the effects of daytime light on nocturnal sleep, moderating factors, and underlying mechanisms from the perspective of light' s circadian effects.

1. The Circadian Effects of Light

While light enables vision through visual neural pathways, it also significantly activates psychological functions—including alertness [?, ?, ?], cognitive performance [?, ?, ?], and mood [?, ?, ?, ?, ?]—via a unique class of photoreceptors in the mammalian retina: intrinsically photosensitive retinal ganglion cells (ipRGCs). Simultaneously, light regulates hormone secretion [?, ?], circadian rhythms, and sleep [?, ?, ?, ?, ?]. These effects are collectively termed non-image forming (NIF) functions of light [?, ?]. Among them, light' s regulation of circadian rhythms and sleep is specifically referred to as its circadian effect.

2. Light' s Regulation of Circadian Rhythms

Human sleep-wake cycles represent a prominent manifestation of circadian behavioral patterns [?, ?], and light—as a crucial Zeitgeber—exerts substantial influence on these cycles [?, ?]. The suprachiasmatic nucleus (SCN) in the hypothalamus serves as the primary pacemaker of the circadian system, receiving light signals via ipRGCs to regulate individual biological rhythms.

From a circadian perspective, research suggests two primary effects of light on human physiology: acute melatonin suppression and circadian phase shifting [?, ?]. The resetting effect of light on circadian rhythms depends critically on exposure timing. Morning light exposure can advance circadian phase [?, ?, ?]. For instance, an early study found that three days of morning bright light exposure (8:30-13:30, 6000-13000 lx) advanced participants' circadian phase by approximately 1.2 hours [?, ?]. A recent study demonstrated that an optimized dynamic lighting pattern in office settings during daytime (8:00-18:00)—with minimum 500 lx in the morning, gradually increasing to 1000 lx at noon, and decreasing to no more than 2500 lx in the afternoon—significantly advanced melatonin onset compared to conventional office lighting [?, ?]. Conversely, evening light exposure delays circadian phase [?, ?, ?, ?]. Dumont and Carrier (1997) found that evening light exposure (18:30-23:30, 6000-13000 lx) delayed circadian phase by approximately 1.6 hours, while another study showed that 6.7 hours of ~10000 lx light at night delayed melatonin phase by about 3.6 hours [?, ?]. These findings indicate that light, as a key Zeitgeber, can advance or delay circadian phase, thereby indirectly influencing sleep-wake patterns.

3. Light' s Effects on Sleep

Studies examining light-sleep relationships typically assess sleep through both objective and subjective measures. Subjective sleep is evaluated via sleep diaries and questionnaires, while objective sleep is monitored using wrist actigraphy or the gold-standard polysomnography (PSG). Subjective parameters include sleep onset time, sleep latency, sleep efficiency, total sleep time, and sleep midpoint. PSG provides additional micro-level parameters such as sleep spindle count, slow-wave sleep (SWS) duration, rapid eye movement sleep (REMS) latency, and other sleep architecture features. Biochemical markers closely related to sleepiness and alertness, such as melatonin and cortisol concentrations, also serve as objective sleep indicators. The non-visual effects of light exhibit clear time-of-day dependencies, leading researchers to investigate light-sleep relationships separately for daytime and nighttime exposure.

3.1 Effects of Nighttime Light on Sleep

The rapid development of artificial lighting has disrupted the natural "rise with the sun, rest at sunset" pattern, making light pollution increasingly common. Combined with widespread evening use of electronic displays, this poses significant risks to sleep health. Research consistently demonstrates that nighttime light exposure negatively impacts sleep, including prolonged sleep latency, reduced deep sleep duration, and increased sleep fragmentation [?, ?, ?, ?]. One early study found that brighter evening light and longer exposure duration were associated with longer sleep preparation time [?, ?]. Similarly, a laboratory study using PSG to monitor sleep under dim light exposure (40 lx) throughout the night revealed that, compared to near-darkness conditions, participants exhibited significantly increased Stage N1 sleep and wake episodes, along with reduced slow-wave sleep [?, ?]. As mentioned previously, ipRGCs are most sensitive to short-wavelength blue light, and evening exposure to blue or blue-enriched white light causes greater sleep disruption. A recent study examined the effects of one-hour pre-sleep exposure (21:30–22:30) to composite white light with different blue content (2000 K vs. 6000 K) at equal illuminance (160 lx) in adolescents. Results showed that after ten days of blue-enriched light exposure, adolescents experienced significantly poorer sleep quality and lower next-morning subjective alertness compared to low-blue conditions [?, ?]. This blue light hazard remains significant even at low intensities—two hours of pre-sleep iPad reading (~30 lx, peak ~450 nm) versus paper book reading (~3 lx, peak 612 nm) led to significantly lower pre-sleep sleepiness, longer sleep latency, shorter REM sleep, and higher next-day sleepiness [?, ?]. Nighttime light' s detrimental effects on sleep are thought to occur primarily through circadian phase delay and melatonin suppression [?, ?].

3.2.1 Correlational Studies on Daytime Light Exposure and Nighttime Sleep

In contrast to nighttime light' s negative effects, daytime light exposure significantly improves nocturnal sleep quality. A field study investigating the effects of daytime light intensity on mood and sleep in postmenopausal women found that higher average daytime light intensity was negatively correlated with subjective and objective sleep latency, subjective sleep onset difficulty, and objective wake-after-sleep-onset episodes, while being positively correlated with reduced depressive symptoms [?, ?]. Another study revealed that 24-hour average light intensity was negatively correlated with objective sleep onset and wake times in adolescents with evening chronotypes, while time exposed to >10 lx was positively correlated with objective sleep onset and negatively correlated with total sleep time [?, ?]. Field research in office environments has shown that total daylight exposure correlates positively with subjective sleep quality [?, ?], with window-proximate workers receiving more light and reporting better health, higher sleep quality, and longer objective sleep duration [?, ?]. A survey conducted during the pandemic also found that greater daytime light exposure (indoor or outdoor) was associated with better self-reported sleep [?, ?].

Furthermore, several field studies indicate significant seasonal and time-of-day effects on the light-sleep relationship [?, ?, ?, ?, ?]. Figueiro and Rea (2016) compared office lighting levels and sleep between winter and summer, finding significantly greater daytime light exposure and superior objective sleep quality (shorter latency, longer duration, higher efficiency) in summer. However, inconsistent results exist—a survey of adults over 65 found no significant seasonal differences in subjective sleep quality despite higher summer light exposure [?, ?]. Regarding timing, Youngstedt et al. (2004) found that morning light exposure (within 4 hours of waking) correlated positively with subjective and objective sleep time and quality, and negatively with sleep latency and awakenings. Figueiro et al. (2017) reported that higher circadian light (CLA) exposure during morning hours (8:00-12:00) was associated with shorter sleep latency, higher sleep efficiency, and better subjective sleep quality compared to lower CLA exposure. Similarly, Gasperetti et al. (2021) found that higher morning light exposure (4:00-9:00) predicted earlier sleep onset and wake times, while higher evening exposure (19:00-midnight) predicted shorter subjective sleep duration, with no significant associations for mid-day exposure (9:00-14:00).

Overall, field studies consistently suggest that higher daytime light intensity or greater exposure positively predicts nocturnal sleep quality, with effects depending on exposure timing—earlier and more intense morning light yields better nighttime sleep. However, these correlational findings cannot establish causal relationships.

3.2.2 Empirical Studies on Short-Term Daytime Light Effects on Nighttime Sleep

To investigate causal relationships, researchers have examined daytime light effects on nighttime sleep through field and laboratory interventions (Table 1), though findings remain inconsistent. An early study found no significant differences in objective sleep onset, latency, or subjective quality between morning bright light (2000 lx) and dim light (1 lx) exposure (6:00-9:00), though bright light advanced wake time and reduced Stage N2 and REM sleep [?, ?, ?]. A recent field intervention with college students found that five days of morning bright light (1000 lx, 6500K, 8:00-9:30) significantly improved sleep efficiency and reduced fragmentation index compared to control light (300 lx, 4000K) [?, ?]. Another study of Antarctic research station personnel during winter found that 14 days of morning bright light intervention (8:30-9:30, 5300K) advanced sleep-wake timing and circadian phase without significantly changing sleep efficiency or fragmentation [?, ?]. A recent intervention comparing two melanopic equivalent daylight illuminance (mel EDI) levels (192 vs. 44 mel EDI) during morning shifts (6:00-12:00) found no significant differences in sleep parameters, though high mel EDI shortened sleep latency and improved efficiency compared to baseline [?, ?].

Clinical studies have also used morning bright light to treat sleep disorders in patient populations [?, ?, ?, ?, ?]. Raikes et al. (2020) applied 30-minute morning blue light exposure (~480 nm, 8:00-10:00) to treat sleep disturbances in brain injury patients, finding reduced daytime sleepiness and depression, shorter sleep latency, and improved sleep quality after six weeks. Turco et al. (2018) reported that 15 days of morning bright light (10,000 lx for 45 minutes immediately after waking) advanced sleep-wake timing and improved subjective sleep quality in primary biliary cholangitis patients. However, some studies found no benefits —Dowling et al. (2005) observed no overall sleep improvement in Alzheimer’ s patients after 10 weeks of morning bright light (>2500 lx, 9:30-10:30) compared to controls (150-200 lx), likely due to population heterogeneity.

3.2.3 Empirical Studies on Whole-Day Light Exposure Effects on Nighttime Sleep

Beyond short-term exposure, studies have examined prolonged artificial light effects on sleep (Table 1). Wakamura and Tokura (2000) investigated four days of continuous bright (6000 lx) versus dim (200 lx) light from wake to bedtime, finding better subjective sleep experience and lower sleepiness scores under bright light despite no differences in sleep timing or duration. Stefani et al. (2021) compared whole-day dynamic versus static lighting in controlled laboratory conditions: dynamic light gradually increased from 1 lx, 3500K to 83 lx, 5000K over 2.5 hours, maintained for 7.5 hours, then decreased to 1 lx, 2700K before sleep, while static light remained at 87 lx, 4000K. Results showed no cognitive performance improvements with dynamic light, but significantly shorter N1 and N2 sleep latencies; static light delayed melatonin onset compared to baseline, while dynamic light showed no such effect. A recent laboratory study by Ru et al. (2022) found that a dynamic office lighting pattern—high-intensity blue-enriched white light (6500K, 1650 lx) in morning (9:00-10:30) and early afternoon (14:00-15:30), and low-intensity warm white light (300 lx, 3000K) at midday (12:00-14:00)—significantly improved nighttime sleep quality and daytime cognitive performance compared to static lighting (4000K, 500 lx).

Additional field studies manipulating artificial or natural lighting in real office settings have yielded mixed but ecologically valuable results. Figueiro et al. (2020) implemented a protocol with blue light (50 lx, 455nm) in morning (6:00-12:00), bright white light (200 lx, 6500K) at midday (12:00-13:30), and red light (50 lx, 634nm) in afternoon (13:30-17:00), finding advanced sleep-wake timing post-intervention. Shishegar et al. (2021) tested two dynamic lighting schemes for older adults with identical illuminance levels (300 lx 6:00-8:00, 500 lx 8:00-12:00, gradually decreasing to 100 lx by 20:00) but different color temperatures: constant 2700K versus dynamic variation (4500K-6500K during day, 2700K-3000K in evening). The dynamic color temperature condition yielded longer objective sleep duration, higher efficiency, shorter latency, and fewer subjective sleep complaints. However, other field interventions reported inconsistent results. Peeters et al. (2021) found no significant effects of dynamic high

(318 lx, 3676K, 190 lx mel EDI) versus low (42 lx, 3264K, 22 lx mel EDI) illuminance in morning or afternoon sessions across winter and spring, with some counterintuitive findings such as shorter sleep duration with morning high illuminance in winter. Kompier et al. (2022) compared two contrasting dynamic patterns— "Skeleton" (bright light 7:00-10:15 and 15:45-19:00) versus "Noon" (bright light 11:15-14:45)—finding lower subjective sleepiness in the Noon condition but no significant differences in sleep parameters.

In summary, while some studies demonstrate daytime light' s beneficial effects on sleep, findings remain inconsistent across studies, likely due to variations in research settings, sleep measures, dynamic lighting patterns, parameter levels, and participant characteristics. Laboratory studies on whole-day dynamic lighting are limited, and optimal patterns for sleep optimization require further investigation.

4. Moderating Factors in the Daytime Light-Sleep Relationship

4.1 Light Dose

Individual differences in total daytime light exposure affect sleep outcomes. Field research shows that greater cumulative daytime light exposure correlates with better subjective sleep quality [?, ?]. However, light exposure varies significantly due to geographic latitude [?, ?], season [?, ?, ?], and workplace environments [?, ?]. Office workers experience significantly higher light exposure in summer versus winter, with correspondingly better objective sleep quality [?, ?]. Notably, total light dose depends on both intensity and duration. While some evidence supports morning light' s beneficial effects, differential impacts of light exposure across different daytime periods remain unclear.

4.2 Light Level

Daytime light intensity significantly moderates its effects on sleep. Illuminance and correlated color temperature (CCT) are key lighting attributes—higher illuminance and CCT (greater short-wavelength blue content) produce more pronounced non-visual effects [?, ?, ?]. Experimental studies indicate that daytime bright light exposure benefits nighttime sleep. Morning bright light (>1000 lx vs. <7 lx) reduced nighttime awakenings [?, ?], advanced wake time, and improved subjective sleep quality [?, ?] and subjective sleep experience [?, ?]. Field studies show positive correlations between daytime light intensity and sleep quality/duration [?, ?, ?], and negative correlations with sleep onset, latency, difficulty falling asleep, and nocturnal awakenings [?, ?, ?]. Few studies directly compare different CCTs, but one found that daytime blue-enriched white light (310 lx, 17000 K) in office settings reduced subjective sleepiness and improved sleep quality compared to standard white light (421 lx, 4000 K) [?, ?]. Since both illuminance and CCT can be quantified as melanopic equivalent daylight illuminance (mel EDI), establishing the relationship between mel EDI and sleep could provide design parameters for healthy lighting environments.

4.3 Light Timing

Exposure timing critically influences light's effects on sleep. Morning bright light shows more positive effects than afternoon or evening exposure [?, ?], with field studies confirming positive correlations between morning light dose and sleep quality [?, ?, ?]. Exposure duration also affects total light dose—office workers average only 72 minutes daily at >1000 lx and approximately 16 minutes indoors [?, ?, ?], potentially compromising sleep quality. Moreover, benefits accumulate over time, with some studies detecting positive effects only after four days of intervention [?, ?] or two weeks in patients with major depression [?, ?]. Thus, timing, duration, and intervention length are important variables in light-sleep models.

4.4 Light Pattern

Most indoor spaces use constant static lighting. The International Commission on Illumination (CIE) has proposed "human-centric" dynamic lighting that adjusts illuminance and CCT throughout the day to enhance well-being [?, ?]. Dynamic patterns include artificial dynamic light, intermittent light, dawn simulation, and twilight simulation [?, ?]. Dynamic lighting generally elicits stronger non-visual effects than static lighting [?, ?], making its impact on sleep an emerging focus in engineering psychology and architectural design.

However, findings on dynamic lighting remain inconsistent. Shishegar et al. (2021) found that dynamic CCT improved objective and subjective sleep measures in older adults, while other studies found no benefits [?, ?, ?]. The dynamic patterns themselves vary considerably—some follow circadian-based changes while others use high-intensity blue-enriched light during day and low-intensity warm light at night. Optimal dynamic patterns for sleep enhancement require further investigation.

4.5 Individual Characteristics

Age-related differences in light sensitivity affect sleep responses. Younger individuals show greater sensitivity to short-wavelength light, with older adults exhibiting reduced melatonin suppression [?, ?] and increased REM latency [?, ?] under short-wavelength light. Sex also influences light effects—under high CCT light (40 lx, 6500K), males showed increased frontal slow-wave activity during sleep despite no sex differences in melatonin suppression [?, ?]. Genetic factors, particularly clock genes (e.g., PER2, casein kinase 1 epsilon), affect light sensitivity and circadian disorders [?, ?, ?]. PER2 haplotypes can reduce light sensitivity [?, ?], while PER3 polymorphisms influence melatonin suppression —6500K light suppressed melatonin in $PER3^5/^5$ individuals but not $PER3^4/^4$ individuals [?, ?].

In summary, the magnitude of daytime light' s sleep-improving effects can be modeled through equations incorporating light dose, intensity, timing, and duration, while human-centric lighting design should account for individual characteristics. Investigating these moderators may provide new insights into the underlying mechanisms.

5. Mechanisms of Daytime Light Effects on Sleep

5.1 Physiological Mechanisms

The two-process model of sleep regulation posits that sleep-wake patterns result from the interaction of sleep homeostatic (Process S) and circadian (Process C) processes [?, ?]. Process S reflects sleep debt, accumulating during wakefulness and dissipating during sleep, while Process C represents endogenous rhythmicity driven by external light cues. As discussed, light can indirectly regulate sleep by resetting circadian rhythms via the SCN [?, ?, ?, ?, ?], and dynamic lighting can facilitate circadian adaptation to shifted sleep-wake schedules [?, ?]. Core body temperature and melatonin serve as biochemical markers of Process C. Melatonin, a neurohormone produced by the pineal gland often called the "sleep hormone," begins secretion at night and plays a critical role in regulating circadian rhythms and sleep-wake cycles [?, ?, ?]. Melatonin treatment is used clinically for sleep disorders [?, ?, ?], and its secretion is exquisitely sensitive to light—even low illuminance at night significantly suppresses melatonin synthesis [?, ?, ?, ?]. Thus, light can regulate circadian rhythms and sleep-wake behavior by activating SCN receptors and suppressing melatonin secretion [?, ?].

Beyond indirect circadian modulation, light can directly affect sleep through melanopsin expressed in ipRGCs [?, ?]. Light signals project directly from ipRGCs to sleep- and wakefulness-regulating brain regions including the ventrolateral preoptic nuclei (VLPO), subparaventricular nucleus zone (SPZ), superior colliculus-pretectum (SC-PT), and lateral hypothalamus (LH) [?, ?, ?, ?]. Hubbard et al. (2013) proposed a three-process model suggesting that light' s direct effects on sleep interact with circadian and homeostatic processes to determine sleep timing and quality, though this model requires further validation in mammalian systems.

While these models explain light-sleep associations, the relationships between specific daytime light characteristics (intensity, dose, timing) and sleep appear more complex, particularly regarding whether daytime light effects on sleep and circadian rhythms are synchronized or independent.

5.2 Psychological Mechanisms

Light' s alerting effect represents a key non-visual function [?, ?, ?, ?], with dawn simulation and morning light exposure used to counteract sleep inertia and enhance alertness and cognitive function [?, ?, ?]. Some morning light interventions have reduced subjective daytime sleepiness [?, ?, ?]. Alertness levels are closely linked to circadian rhythms and sleep [?, ?]. Studies of dynamic lighting found lower pre-sleep alertness under dynamic versus static conditions [?, ?], while another study observed increased EEG spectral density associated with alertness under control lighting (100 lx, 4000K) [?, ?, ?, ?]. Recent forced desynchrony research showed that bright light during wakefulness increased subjective sleepiness and NREM delta activity (0.5–4 Hz), indicating reduced micro-arousals and increased sleep homeostatic pressure [?, ?, ?, ?, ?, ?, ?, ?, ?]. This suggests daytime light may influence sleep via modulation of daytime and pre-sleep alertness.

Mood may also mediate light' s effects on sleep. Different light intensities and CCTs can immediately affect subjective and objective mood states, while abnormal lighting patterns induce negative emotions [?, ?, ?]. Mood and sleep interact bidirectionally—positive mood predicts better sleep quality [?, ?], while sleep disturbances can trigger mood disorders [?, ?, ?]. Figueiro et al. (2021) found that greater daytime light exposure during the pandemic correlated with better self-reported sleep, reduced stress/anxiety/depression, and increased positive affect. Future research should examine dynamic causal relationships among daytime light exposure, mood, and sleep.

6. Future Directions

6.1 Whole-Day Human-Centric Dynamic Lighting Design for Circadian and Sleep Optimization

Day workers spend nearly one-third of their time indoors, where lighting directly impacts mood, productivity, and sleep health [?, ?]. Office workers have limited opportunities for high-intensity light exposure, averaging only 72 minutes daily at >1000 lx and about 16 minutes indoors [?, ?, ?]. Chronic low light exposure negatively affects physical and sleep health [?, ?]. Developing healthy human-centric lighting that optimizes daytime psychological function and nighttime sleep represents a key research challenge. Given the time-dependent effects of light and the rhythmic nature of daytime physiological functioning [?, ?, ?], dynamic indoor lighting that adjusts illuminance and CCT based on circadian timing presents a promising approach.

6.2 Mechanistic Investigations of Daytime Light Effects on Sleep

While the two-process model is well-established and light' s circadian effects are well-documented, whether light influences sleep homeostatic processes remains unclear. One study found that morning bright light advanced circadian phase and wake time without affecting NREM slow-wave activity [?, ?], while another observed that daytime bright light (250 lx) increased NREM slow-wave activity following 40 hours of sleep restriction compared to dim light (<8 lx) [?, ?, ?, ?]. Since NREM slow-wave activity is a key marker of sleep homeostasis, it remains unknown whether daytime light affects sleep via homeostatic regulation. Hubbard et al.' s (2013) three-process model requires further neurobiological validation. Future research must elucidate these mechanisms.

6.3 Light Optimization for Sleep in Special Populations

Geographic, occupational, and individual factors create significant variations in light exposure. Light intensity and day length decrease with latitude [?, ?], and workers in high-latitude regions (e.g., Sweden) experience insufficient natural light in winter, leading to sleep problems [?, ?]. Special occupational groups –including shift workers [?, ?], underground workers [?, ?, ?], and astronauts [?, ?]–experience vastly different light exposures, with insufficient daylight negatively impacting mood, sleep, and health [?, ?, ?]. Future research should develop tailored, healthy lighting environments for these populations to maintain circadian alignment, improve sleep, and enhance well-being.

6.4 Dose-Response Curve Modeling for Daytime Light Effects on Nighttime Sleep

Quantifying complex real-world lighting conditions remains challenging [?, ?, ?]. Some studies use threshold-based algorithms (e.g., time exposed to >1000 lx) to integrate intensity and duration [?, ?], which has been applied to dose-response analyses of alertness and executive function [?, ?]. However, precise thresholds for daytime light effects on sleep remain unestablished. Recent approaches use sensitivity analyses across multiple thresholds to identify time-dependent effects [?, ?], offering a method to quantify lighting parameters. While dose-response curves have been developed for alertness [?, ?] and nighttime melatonin suppression [?, ?], future research should develop dose-response models for daytime light effects on sleep to inform personalized lighting design.

Conclusion

As a crucial Zeitgeber, light significantly regulates circadian rhythms and sleep. Overall, higher daytime light levels and doses positively predict nighttime sleep quality, though effects vary due to differences in light parameters (intensity, timing, duration, pattern) across studies. Mechanistic understanding remains incomplete. Light may influence sleep indirectly through circadian phase shifts or directly via projections to sleep-wake brain regions, while effects on sleep homeostasis are uncertain. Psychologically, light may affect sleep through alertness and mood modulation. With increasing desynchronization between natural light-dark cycles and physiological rhythms, developing population- and context-specific human-centric lighting strategies is crucial for enhancing productivity, optimizing sleep, and improving public health.

References

李芸, 汝涛涛, 李丝雨, 陈涵宇, 谢舒雅, 周国富. (2022). 环境光照对情绪的影响及其作用机制. 心理科学进展, 30(02), 389–405.

汝涛涛, 李芸, 钱柳, 陈庆伟, 钟罗金, 李静华, 周国富. (2019). 环境光照的认知功效及其调节因素与作用机理. 心理科学进展, 27(10), 1687–1702.

Adamsson, M., Laike, T., & Morita, T. (2016). Annual variation in daily light exposure and circadian change of melatonin and cortisol concentrations at a northern latitude with large seasonal differences in photoperiod length. *Journal of Physiological Anthropology*, 36, 6.

Akiyama, T., Katsumura, T., Nakagome, S., Lee, S. I., Joh, K., Soejima, H., ···Oota, H. (2017). An ancestral haplotype of the human PERIOD2 gene associates with reduced sensitivity to light-induced melatonin suppression. *Plos One*, 12(6), e0178373.

Axelsson, J., Ingre, M., Kecklund, G., Lekander, M., Wright, K. P., & Sundelin, T. (2020). Sleepiness as motivation: A potential mechanism for how sleep deprivation affects behavior. *Sleep*, 43(6), zsz291.

Bedrosian, T. A., & Nelson, R. J. (2017). Timing of light exposure affects mood and brain circuits. *Transl Psychiatry*, 7(1), e1017.

Benedetti, M., Maierova, L., Cajochen, C., Scartezzini, J. L., & Munch, M. (2022). Optimized office lighting advances melatonin phase and peripheral heat loss prior bedtime. *Scientific Reports*, 12(1), 4267.

Blume, C., Garbazza, C., & Spitschan, M. (2019). Effects of light on human circadian rhythms, sleep and mood. *Somnologie (Berl)*, 23(3), 147-156.

Borbély, A. A., Daan, S., Wirz-Justice, A., & Deboer, T. (2016). The two-process model of sleep regulation: A reappraisal. *Journal of Sleep Research*, 25(2), 131-143.

Boubekri, M., Cheung, I. N., Reid, K. J., Wang, C.-H., & Zee, P. C. (2014). Impact of windows and daylight exposure on overall health and sleep quality of office workers: A case-control pilot study. *Journal of Clinical Sleep Medicine*, 10(6), 603-611.

Brainard, G. C., Barger, L. K., Soler, R. R., & Hanifin, J. P. (2016). The development of lighting countermeasures for sleep disruption and circadian misalignment during spaceflight. *Current Opinion in Pulmonary Medicine*, 22(6), 535-544.

Burgess, H. J., & Emens, J. S. (2020). Drugs used in circadian sleep-wake rhythm disturbances. *Sleep Medicine Clinics*, 15(2), 301-310.

Cajochen, C., Freyburger, M., Basishvili, T., Garbazza, C., Rudzik, F., Renz, C., ···Weibel, J. (2019). Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Lighting Research & Technology*, 51(7), 1044-1062.

Cajochen, C., Reichert, C., Maire, M., Schlangen, L. J. M., Schmidt, C., Viola, A. U., & Gabel, V. (2019). Evidence that homeostatic sleep regulation depends on ambient lighting conditions during wakefulness. *Clocks & Sleep*, 1(4), 517-531.

Canazei, M., Weninger, J., Pohl, W., Marksteiner, J., & Weiss, E. M. (2022). Effects of dynamic bedroom lighting on measures of sleep and circadian rest-activity rhythm in inpatients with major depressive disorder. *Scientific Reports*, 12(1), 6137.

Cappuccio, F. P., D' Elia, L., Strazzlillo, P., & Miller, M. A. (2010). Quantity and quality of sleep and incidence of type 2 diabetes - A systematic review and meta-analysis. *Diabetes Care*, 33(2), 414–420.

Carrier, J., & Dumont, M. (1995). Sleep propensity and sleep architecture after bright light exposure at three different times of day. *Journal of Sleep Research*, 4(4), 202–211.

Carvalho, A., & Cruz, M. M. E. (2017). Reduced light exposure negatively impacts sleep quality and alertness in underground-operating subway workers. *Sleep*, 40, A253–A254.

Chang, A.-M., Aeschbach, D., Duffy, J. F., & Czeisler, C. A. (2015). Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness. *Proceedings of the National Academy of Sciences of the United States of America*, 112(4), 1232–1237.

Chellappa, S. L., Steiner, R., Oelhafen, P., & Cajochen, C. (2017). Sex differences in light sensitivity impact on brightness perception, vigilant attention and sleep in humans. *Scientific Reports*, 7, 14215.

Chellappa, S. L., Viola, A. U., Schmidt, C., Bachmann, V., Gabel, V., Maire, M., ···Cajochen, C. (2012). Human melatonin and alerting response to blue-enriched light depend on a polymorphism in the clock gene PER3. *Journal of Clinical Endocrinology & Metabolism*, 97(3), E433-437.

Cho, C.-H., Yoon, H.-K., Kang, S.-G., Kim, L., Lee, E.-I., & Lee, H.-J. (2018). Impact of exposure to dim light at night on sleep in female and comparison with male subjects. *Psychiatry Investigation*, 15(5), 520-530.

Cho, J. R., Joo, E. Y., Koo, D. L., & Hong, S. B. (2013). Let there be no light: The effect of bedside light on sleep quality and background electroencephalographic rhythms. *Sleep Medicine*, 14(12), 1422–1425.

CIE. (2018). *System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*. Vienna.

Coles, M. E., Schubert, J. R., & Nota, J. A. (2015). Sleep, circadian rhythms, and anxious traits. *Current Psychiatry Reports*, 17(9), 73.

Corbett, R. W., Middleton, B., & Arendt, J. (2012). An hour of bright white light in the early morning improves performance and advances sleep and circadian phase during the Antarctic winter. *Neuroscience Letters*, 525(2), 146–151.

Daugaard, S., Markvart, J., Bonde, J. P., Christoffersen, J., Garde, A. H., Hansen, A. M., ···Kolstad, H. A. (2019). Light exposure during days with night, outdoor, and indoor work. *Annals of Work Exposures and Health*, 63(6), 651-665.

Dautovich, N. D., Schreiber, D. R., Imel, J. L., Tighe, C. A., Shoji, K. D., Cyrus, J., ···Dzierzewski, J. M. (2019). A systematic review of the amount and timing of light in association with objective and subjective sleep outcomes in community-dwelling adults. *Sleep Health*, 5(1), 31-48.

de Kort, Y. (2021). Opinion: On becoming smart. *Lighting Research & Technology*, 53(1), 4.

de Kort, Y. A. W., & Smolders, K. (2010). Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings. *Lighting Research & Technology*, 42(3), 345-360.

Dijk, D. J., & Archer, S. N. (2010). PERIOD3, circadian phenotypes, and sleep homeostasis. *Sleep Medicine Reviews*, 14(3), 151-160.

Dijk, D. J., Beersma, D. G. M., Daan, S., & Lewy, A. J. (1989). Bright morning light advances the human circadian system without affecting NREM sleep homeostasis. *American Journal of Physiology*, 256(2), R106-R111.

Dijk, D. J., Visscher, C. A., Bloem, G. M., Beersma, D. G. M., & Daan, S. (1987). Reduction of human sleep duration after bright light exposure in the morning. *Neuroscience Letters*, 73(2), 181-186.

Dong, X., Wu, Y. Y., Chen, X. D., Li, H., Cao, B., Zhang, X., ···Li, X. T. (2021). Effect of thermal, acoustic, and lighting environment in underground space on human comfort and work efficiency: A review. *Science of the Total Environment*, 786, 147537.

Dong, Y., & Zhang, X. (2021). Study on the effect of awakening daylight in dormitories on morning alertness, mood, fatigue and sleep quality of college students. *Building and Environment*, 203, 108060.

Dowling, G. A., Hubbard, E. M., Mastick, J., Luxenberg, J. S., Burr, R. L., & Van Someren, E. J. W. (2005). Effect of morning bright light treatment for rest-activity disruption in institutionalized patients with severe Alzheimer' s disease. *International Psychogeriatrics*, 17(2), 221-236.

Dumont, M., & Carrier, J. (1997). Daytime sleep propensity after moderate circadian phase shifts induced with bright light exposure. *Sleep*, 20(1), 11-17.

Ebisawa, T. (2007). Circadian rhythms in the CNS and peripheral clock disorders: Human sleep disorders and clock genes. *Journal of Pharmacological Sciences*, 103(2), 150-154.

Emens, J. S., Berman, A. M., Thosar, S. S., Butler, M. P., Roberts, S. A., Clemons, N. A., ···Shea, S. A. (2020). Circadian rhythm in negative affect: Implications for mood disorders. *Psychiatry Research*, 293, 113337.

Figueiro, M. G., Jarboe, C., & Sahin, L. (2021). The sleep maths: A strong correlation between more daytime light and better night-time sleep. *Lighting Research & Technology*, 53(5), 423-435.

Figueiro, M. G., & Rea, M. S. (2012). Short-wavelength light enhances cortisol awakening response in sleep-restricted adolescents. *International Journal of Endocrinology*, 2012, 301935.

Figueiro, M. G., & Rea, M. S. (2016). Office lighting and personal light exposures in two seasons: Impact on sleep and mood. *Lighting Research & Technology*, 48(3), 352-364.

Figueiro, M. G., Steverson, B., Heerwagen, J., Kampschroer, K., Hunter, C. M., Gonzales, K., ···Rea, M. S. (2017). The impact of daytime light exposures on sleep and mood in office workers. *Sleep Health*, 3(3), 204-215.

Figueiro, M. G., Steverson, B., Heerwagen, J., Yucel, R., Roohan, C., Sahin, L., ···Rea, M. S. (2020). Light, entrainment and alertness: A case study in offices. *Lighting Research & Technology*, 52(6), 736-750.

Flores-Villa, L., Unwin, J., & Raynham, P. (2020). Assessing the impact of daylight exposure on sleep quality of people over 65 years old. *Building Services Engineering Research & Technology*, 41(2), 183-192.

Gabel, V., Maire, M., Reichert, C. F., Chellappa, S. L., Schmidt, C., Hommes, V., ···Viola, A. U. (2015). Dawn simulation light impacts on different cognitive domains under sleep restriction. *Behavioural Brain Research*, 281, 258-266.

Gasperetti, C. E., Dolsen, M. R., & Harvey, A. G. (2021). The influence of intensity and timing of daily light exposure on subjective and objective sleep in adolescents with an evening circadian preference. *Sleep Medicine*, 79, 1-9.

Giménez, M. C., Stefani, O., Cajochen, C., Lang, D., Deuring, G., & Schlangen, L. J. M. (2022). Predicting melatonin suppression by light in humans: Unifying photoreceptor-based equivalent daylight illuminances, spectral composition, timing and duration of light exposure. *Journal of Pineal Research*, 72(2), e12786.

Hadi, F., Agah, E., Tavanbakhsh, S., Mirsepassi, Z., Mousavi, S. V., Talachi, N., ···Aghamollaii, V. (2022). Safety and efficacy of melatonin, clonazepam, and trazodone in patients with Parkinson’ s disease and sleep disorders: A randomized, double-blind trial. *Neurological Sciences*, 43(10), 6141-6148.

Hartstein, L. E., Diniz Behn, C., Wright, K. P., Jr., Akacem, L. D., Stowe, S. R., & LeBourgeois, M. K. (2022). Evening light intensity and phase delay of the circadian clock in early childhood. *Journal of Biological Rhythms*, 07487304221134330.

Hattar, S., Kumar, M., Park, A., Tong, P., Tung, J., Yau, K. W., & Berson, D. M. (2006). Central projections of melanopsin-expressing retinal ganglion cells in the mouse. *Journal of Comparative Neurology*, 497(3), 326-349.

He, M. H., Ru, T. T., Li, S. Y., Li, Y., & Zhou, G. F. (2022). Shine light on sleep: Morning bright light improves nocturnal sleep and next morning alertness among college students. *Journal of Sleep Research*, e13724.

Herljevic, M., Middleton, B., Thapan, K., & Skene, D. J. (2005). Light-induced melatonin suppression: Age-related reduction in response to short wavelength light. *Experimental Gerontology*, 40(3), 237-242.

Houser, K. W., & Esposito, T. (2021). Human-centric lighting: Foundational considerations and a five-step design process. *Frontiers in Neurology*, 12, 630553.

Hubalek, S., Brink, M., & Schierz, C. (2010). Office workers' daily exposure to light and its influence on sleep quality and mood. *Lighting Research & Technology*, 42(1), 33-50.

Hubbard, J., Ruppert, E., Gropp, C. M., & Bourgin, P. (2013). Non-circadian direct effects of light on sleep and alertness: Lessons from transgenic mouse models. *Sleep Medicine Reviews*, 17(6), 445-452.

Huiberts, L. M., Smolders, K. C. H. J., & de Kort, Y. A. W. (2015). Shining light on memory: Effects of bright light on working memory performance. *Behavioural Brain Research*, 294, 234-245.

Kennaway, D. J. (2022). What do we really know about the safety and efficacy of melatonin for sleep disorders? *Current Medical Research and Opinion*, 38(2), 211-227.

Khaing, N. E. E., Abuduxike, G., Posadzki, P., Divakar, U., Visvalingam, N., Nazeha, N., ···Car, J. (2019). Review of the potential health effects of light and environmental exposures in underground workplaces. *Tunnelling and Underground Space Technology*, 84, 201-209.

Khalsa, S. B. S., Jewett, M. E., Cajochen, C., & Czeisler, C. A. (2003). A phase response curve to single bright light pulses in human subjects. *Journal of Physiology-London*, 549(3), 945-952.

Kohsaka, M., Fukuda, N., Honma, H., Kobayashi, R., Sakakibara, S., Koyama, E., ···Matsubara, H. (1999). Effects of moderately bright light on subjective evaluations in healthy elderly women. *Psychiatry and Clinical Neurosciences*, 53(2), 239-241.

Kohsaka, M., Fukuda, N., Kobayashi, R., Honma, H., Sakakibara, S., Koyama, E., ···Matsubara, H. (2000). Effect of short duration morning bright light in elderly men: Sleep structure. *Psychiatry and Clinical Neurosciences*, 54(3), 367-368.

Kompier, M. E., Smolders, K. C. H. J., & de Kort, Y. A. W. (2020). A systematic literature review on the rationale for and effects of dynamic light scenarios. *Building and Environment*, 186, 107326.

Kompier, M. E., Smolders, K. C. H. J., Kramer, R. P., van Marken Lichtenbelt, W. D., & de Kort, Y. A. W. (2022). Contrasting dynamic light scenarios in an operational office: Effects on visual experience, alertness, cognitive performance, and sleep. *Building and Environment*, 212, 108844.

Lee, E. E., Amritwar, A., Hong, L. E., Mohyuddin, I., Brown, T., & Postolache, T. T. (2020). Daily and seasonal variation in light exposure among the old order amish. *International Journal of Environmental Research and Public Health*, 17(12), 4460.

LeGates, T. A., Fernandez, D. C., & Hattar, S. (2014). Light as a central modulator of circadian rhythms, sleep and affect. *Nature Reviews Neuroscience*, 15(7), 443–454.

Li, L., Wang, Y. Y., Wang, S. B., Zhang, L., Li, L., Xu, D. D., ···Xiang, Y. T. (2018). Prevalence of sleep disturbances in Chinese university students: A comprehensive meta-analysis. *Journal of Sleep Research*, 27(3), e12648.

Li, Y., Zhou, Y., Ru, T. T., Niu, J. X., He, M. H., & Zhou, G. F. (2021). How does the COVID-19 affect mental health and sleep among Chinese adolescents: A longitudinal follow-up study. *Sleep Medicine*, 85, 246–258.

Lok, R., Smolders, K., Beersma, D. G. M., & de Kort, Y. A. W. (2018). Light, alertness, and alerting effects of white light: A literature overview. *Journal of Biological Rhythms*, 33(6), 589–601.

Lok, R., Woelders, T., Gordijn, M. C. M., van Koningsveld, M. J., Oberman, K., Fuhler, S. G., ···Hut, R. A. (2022). Bright light during wakefulness improves sleep quality in healthy men: A forced desynchrony study under dim and bright light (III). *Journal of Biological Rhythms*, 37(4), 429–441.

Lok, R., Woelders, T., van Koningsveld, M. J., Oberman, K., Fuhler, S. G., Beersma, D. G. M., & Hut, R. A. (2022). Bright light increases alertness and not cortisol in healthy men: A forced desynchrony study under dim and bright light (I). *Journal of Biological Rhythms*, 37(4), 403–416.

Lu, L., Wang, S. B., Rao, W. W., Ungvari, G. S., Ng, C. H., Chiu, H. F. K., ···Xiang, Y. T. (2017). Sleep duration and patterns in Chinese older adults: A comprehensive meta-analysis. *International Journal of Biological Sciences*, 13(6), 682–689.

Lubas, M. M., Maduro, R. S., & Szklo-Coxe, M. (2019). An exploratory study examining the associations between sunlight exposure, sleep behaviours and sleep outcomes during an arctic summer. *International Journal of Circumpolar Health*, 78(1), 1574698.

Lupi, D., Oster, H., Thompson, S., & Foster, R. G. (2008). The acute light-induction of sleep is mediated by OPN4-based photoreception. *Nature Neuroscience*, 11(9), 1068–1073.

Mannino, G., Pernici, C., Serio, G., Gentile, C., & Bertea, C. M. (2021). Melatonin and phytomelatonin: Chemistry, biosynthesis, metabolism, distribution and bioactivity in plants and animals—An overview. *International Journal of Molecular Sciences*, 22(18), 9996.

Misiunaite, I., Eastman, C. I., & Crowley, S. J. (2020). Circadian phase advances in response to weekend morning light in adolescents with short sleep and late bedtimes on school nights. *Frontiers in Neuroscience*, 14, 99.

Münch, M., Scheuermaier, K. D., Zhang, R., Dunne, S. P., Guzik, A. M., Silva, E. J., ···Duffy, J. F. (2011). Effects on subjective and objective alertness and sleep in response to evening light exposure in older subjects. *Behavioural Brain Research*, 224(2), 272-278.

Nicholson, W. C., & Pfeiffer, K. (2021). Sleep disorders and mood, anxiety, and post-traumatic stress disorders: Overview of clinical treatments in the context of sleep disturbances. *Nursing Clinics of North America*, 56(2), 229-247.

Nie, J. X., Zhou, T. H., Chen, Z. Z., Dang, W. M., Jiao, F., Zhan, J. L., ···Shen, B. (2020). Investigation on entraining and enhancing human circadian rhythm in closed environments using daylight-like LED mixed lighting. *Science of the Total Environment*, 732, 139334.

Obayashi, K., Saeki, K., & Kurumatani, N. (2014). Association between light exposure at night and insomnia in the general elderly population: The HEIJO-KYO cohort. *Chronobiology International*, 31(9), 976–982.

Palagini, L., Bastien, C. H., Marazziti, D., Ellis, J. G., & Riemann, D. (2019). The key role of insomnia and sleep loss in the dysregulation of multiple systems involved in mood disorders: A proposed model. *Journal of Sleep Research*, 28(6), e12841.

Pandi-Perumal, S. R., Cardinali, D. P., Zaki, N. F. W., Karthikeyan, R., Spence, D. W., Reiter, R. J., & Brown, G. M. (2022). Timing is everything: Circadian rhythms and their role in the control of sleep. *Frontiers in Neuroendocrinology*, 66, 100978.

Parsons, C. E., Schofield, B., Batziou, S. E., Ward, C., & Young, K. S. (2022). Sleep quality is associated with emotion experience and adaptive regulation of positive emotion: An experience sampling study. *Journal of Sleep Research*, 31(4), e13533.

Pearce, E., & Dunbar, R. (2012). Latitudinal variation in light levels drives human visual system size. *Biology Letters*, 8(1), 90–93.

Peeters, S. T., Smolders, K. C. H. J., Kompier, M. E., & de Kort, Y. A. W. (2022). Let me count the light. Accounting for intensity, duration and timing of light when predicting sleep and subjective alertness in field studies. *Leukos*, 18(4), 417-437.

Peeters, S. T., Smolders, K. C. H. J., Vogels, I. M. L. C., & De Kort, Y. A. W. (2021). Less is more? Effects of more vs. less electric light on alertness, mood, sleep and appraisals of light in an operational office. *Journal of Environmental Psychology*, 74, 101583.

Prayag, A. S., Munch, M., Aeschbach, D., Chellappa, S. L., & Gronfier, C. (2019). Light modulation of human clocks, wake, and sleep. *Clocks & Sleep*, 1(1), 193-208.

Prayag, A. S., Najjar, R. P., & Gronfier, C. (2019). Melatonin suppression is exquisitely sensitive to light and primarily driven by melanopsin in humans. *Journal of Pineal Research*, 66(4), e12562.

Rahman, S. A., St Hilaire, M. A., Grant, L. K., Barger, L. K., Brainard, G. C., Czeisler, C. A., ···Lockley, S. W. (2022). Dynamic lighting schedules to facilitate circadian adaptation to shifted timing of sleep and wake. *Journal of Pineal Research*, 73(1), e12805.

Raikes, A. C., Dailey, N. S., Shane, B. R., Forbeck, B., Alkozei, A., & Killgore, W. D. S. (2020). Daily morning blue light therapy improves daytime sleepiness, sleep quality, and quality of life following a mild traumatic brain injury. *Journal of Head Trauma Rehabilitation*, 35(5), E405-E421.

Ru, T., de Kort, Y. A. W., Smolders, K. C. H. J., Chen, Q., & Zhou, G. (2019). Non-image forming effects of illuminance and correlated color temperature of office light on alertness, mood, and performance across cognitive domains. *Building and Environment*, 149, 253-263.

Ru, T., Kompier, M. E., Chen, Q., Zhou, G., & Smolders, K. C. H. J. (2022). Temporal tuning of illuminance and spectrum: Effect of a full-day dynamic lighting pattern on well-being, performance and sleep in simulated office environment. *Building and Environment*, 228, 109842.

Ru, T., Smolders, K., Chen, Q., Zhou, G., & de Kort, Y. A. W. (2021). Diurnal effects of illuminance on performance: Exploring the moderating role of cognitive domain and task difficulty. *Lighting Research & Technology*, 53(8), 727-747.

Schmidt, T. M., Chen, S. K., & Hattar, S. (2011). Intrinsically photosensitive retinal ganglion cells: Many subtypes, diverse functions. *Trends in Neurosciences*, 34(11), 572-580.

Schnupp, T., Heinze, C., & Golz, M. (2017). Circadian rhythmicity of cognitive performance. *Current Directions in Biomedical Engineering*, 3(2), 569-572.

Shishegar, N., Boubekri, M., Stine-Morrow, E. A. L., & Rogers, W. A. (2021). Tuning environmental lighting improves objective and subjective sleep quality in older adults. *Building and Environment*, 204, 108096.

Smolders, K. C. H. J., Peeters, S. T., Vogels, I. M. L. C., & de Kort, Y. A. W. (2018). Investigation of dose-response relationships for effects of white light exposure on correlates of alertness and executive control during regular daytime working hours. *Journal of Biological Rhythms*, 33(6), 649-661.

Souman, J. L., Tinga, A. M., te Pas, S. F., van Ee, R., & Vlaskamp, B. N. S. (2018). Acute alerting effects of light: A systematic literature review. *Behavioural Brain Research*, 337, 228-239.

Stefani, O., Freyburger, M., Veitz, S., Basishvili, T., Meyer, M., Weibel, J., ··· Cajochen, C. (2021). Changing color and intensity of LED lighting across the day impacts on circadian melatonin rhythms and sleep in healthy men. *Journal of Pineal Research*, 70(3), e12714.

Toh, K. L., Jones, C. R., He, Y., Eide, E. J., Hinz, W. A., Virshup, D. M., ··· Fu, Y. H. (2001). An hPer2 phosphorylation site mutation in familial advanced sleep phase syndrome. *Science*, 291(5506), 1040-1043.

Turco, M., Cazzagon, N., Franceschet, I., Formentin, C., Frighetto, G., Giordani, F., ···Montagnese, S. (2018). Morning bright light treatment for sleep-wake disturbances in primary biliary cholangitis: A pilot study. *Frontiers in Physiology*, 9, 1530.

Uchino, B. N., Cribbet, M., de Grey, R. G. K., Cronan, S., Trettevik, R., & Smith, T. W. (2017). Dispositional optimism and sleep quality: A test of mediating pathways. *Journal of Behavioral Medicine*, 40(2), 360-369.

van de Putte, E., Kindt, S., Bracke, P., Stevens, M., Vansteenkiste, M., Vandevivere, L., & Ryckaert, W. R. (2022). The influence of integrative lighting on sleep and cognitive functioning of shift workers during the morning shift in an assembly plant. *Applied Ergonomics*, 99, 103618.

van Duijnhoven, J., Aarts, M. P. J., Aries, M. B. C., Rosemann, A. L. P., & Kort, H. S. M. (2019). Systematic review on the interaction between office light conditions and occupational health: Elucidating gaps and methodological issues. *Indoor and Built Environment*, 28(2), 152-174.

van Duijnhoven, J., Aarts, M. P. J., & Kort, H. S. M. (2021). Personal lighting conditions of office workers: An exploratory field study. *Lighting Research & Technology*, 53(4), 285-310.

Viola, A. U., James, L. M., Schlangen, L. J. M., & Dijk, D.-J. (2008). Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. *Scandinavian Journal of Work Environment & Health*, 34(4), 297-306.

Wakamura, T., & Tokura, H. (2000). The influence of bright light during the daytime upon circadian rhythm of core temperature and its implications for nocturnal sleep. *Nursing and Health Sciences*, 2(1), 41-49.

Wams, E. J., Woelders, T., Marring, I., van Rosmalen, L., Beersma, D. G. M., Gordijn, M. C. M., & Hut, R. A. (2017). Linking light exposure and subsequent sleep: A field polysomnography study in humans. *Sleep*, 40(12), zsx165.

Wang, Y. X., Hou, W. Y., Siddiqi, S. M., Sun, C. H., Han, T. S., & Yang, J. J. (2020). Association of sleep trajectory in adulthood with risk of hypertension and its related risk factors: The China Health and Nutrition Survey. *Journal of Clinical Sleep Medicine*, 16(4), 515-521.

Wen, P. J., Tan, F. Y., Wu, M., Cai, Q. J., Xu, R. P., Zhang, X. W., ···Hu, X. D. (2021). The effects of different bedroom light environments in the evening on adolescents. *Building and Environment*, 206, 108321.

Yang, B., Yao, H. C., & Wang, F. M. (2022). A review of ventilation and environmental control of underground spaces. *Energies*, 15(2), 409.

Youngstedt, S. D., Leung, A., Kripke, D. F., & Langer, R. D. (2004). Association of morning illumination and window covering with mood and sleep among post-menopausal women. *Sleep and Biological Rhythms*, 2(3), 174-183.

Zalta, A. K., Bravo, K., Valdespino-Hayden, Z., Pollack, M. H., & Burgess, H. J. (2019). A placebo-controlled pilot study of a wearable morning bright light treatment for probable PTSD. *Depression and Anxiety*, 36(7), 617-627.

The optimization effects of daytime light exposure on sleep and its mechanisms

HE Meiheng[1,2], RU Taotao[2], LI Le[3], LI Siyu[1,2], ZHANG Chenze[1,2], ZHOU Guofu[2,3]

[1] Lab of Lighting and Physio-psychological Health, School of Psychology, South China Normal University, Guangzhou 510631, China
[2] National Center for International Research on Green Optoelectronics, South China Normal University, Guangzhou 510006, China
[3] South China Academy of Advanced Optoelectronics, South China Normal University, Guangzhou 510006, China

Abstract: As a dominant Zeitgeber, ambient light can regulate sleep-wake patterns in humans. Exposure to higher light levels or more light exposure during the daytime, especially during the morning, positively predict nighttime sleep quality, but this effect is mediated by the light parameters (e.g., light level or spectrum), timing factors (e.g., time of day and duration), and light pattern. On the one hand, light can indirectly influence the sleep-wake cycle by regulating individuals' circadian rhythms through the suprachiasmatic nucleus (SCN). On the other hand, light can directly affect sleep through the projection of melanopsin expressed by intrinsically photosensitive retinal ganglion cells (ipRGCs) to sleep- and wakefulness-related brain regions. However, there is still no clear consensus on whether light can affect sleep via regulation of sleep homeostatic process, which was another process driven the sleep-wake cycle. Future research should pay more attention on how to create "Human centric lighting" for those who work in the absence of daylight or need personal light to support their mental and physical requirement.

Keywords: daytime light, sleep improvement, healthy lighting, mechanism, circadian rhythm

Note: Figure translations are in progress. See original paper for figures.