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ORIGINAL RESEARCH

Time-Dependent Effects of Altered Prebedtime Light Exposure in Enclosed Spaces on Sleep Performance Associated with Human States

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Purpose: Exposure to artificial light influences human performance, which is essential for maintaining healthy work and sleep. However, existing research has not explored the intrinsic links between sleep performance and human states over time under prebedtime light exposure interventions (LEIs).

Methods: To investigate the time-dependent effects of altered prebedtime light exposure, four LEI groupings (#L1 - #L4) and a Time factor (D8, D9, and D10) were chosen for sleep experiments in enclosed spaces. Forty-eight young adults recruited were available for data analysis. Subjective alertness (SA), negative affect (NA), subjective sleep, and objective sleep were measured via the Karolinska Sleepiness Scale, Positive and Negative Affect Schedule, Next-day Self-assessment Sleep Quality, and joint assessment of wrist actigraphy and sleep diaries, respectively. Statistical analysis was used for the effects of light exposure on the human states (corresponding to the SA and NA) and sleep performance, while the process model helped construct the associations between the two.

Results: The statistical effects revealed that the Time had a significant main effect on subjective sleep and changes in prebedtime alertness; the LEI had a significant main effect only on sleep onset latency (SOL). After undergoing altered prebedtime light exposure, the mean SA increased at prebedtime of D9 ($p = 0.022$) and D10 ($p = 0.044$); No significant effect on the NA was observed; Mean subjective sleep had a significant increase from D8 to D10. Moreover, five actigraphy-estimated sleep parameters were interrelated. In light of this, a chained pathway relationship was identified. The SOL played a mediating predictor between prebedtime state and objective sleep, which was linked to the awakening state through subjective sleep.

Conclusion: Our study suggests that time-dependent effects of altered prebedtime light exposure on sleep performance are associated with human states at prebedtime and awakening, with implications for its prediction of sleep health.

Keywords: prebedtime light exposure, sleep performance, non-visual effects, alertness, negative affect, sleep onset latency

Introduction

Light is one of the main drivers of circadian system.[1] The artificial light at night was an extremely disruptive cue;[2,3] for example, nearly half of homes experienced evening lighting detrimental to human sleep.[3] Extendedly, the impact of ocular light is categorized as photic and non-photic.[4] Rod and cone cells are mainly related to human vision, while the intrinsically photosensitive retinal ganglion cells (ipRGCs)[5] affect non-visual aspects.[6,7] Photic interacts with non-photic at the retinal level rather than being completely independent,[8] which determines the combined visual, affective, and physiological effects.[4,9] In contrast to visual effects, non-visual effects focus on circadian rhythms and neural circuits related to behavioral responses.[10]

The physical properties of lighting generally comprise illuminance or brightness,[11,12] correlated color temperature (CCT),[12] and spectral power distribution (including light wavelength).[13,14] Illuminance meets visible requirements or maintains alertness.[15] Meanwhile, the spectral profile is composed of various light wavelengths, where the color

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temperature divides the visible light into warm and cool type.[16] Furthermore, the circadian stimulus (CS), the melanopic equivalent daylight illuminance (mEDI), and the equivalent melanopic lux (EML) are leading models for measuring rhythmic effects. Nevertheless, the CIE S 026/E:2018 considers the light-sensitive contribution of ipRGCs toward non-visual effects alone,[17] while the WELL building standard proposes an EML-based model for all spaces. CS metrics were obtained as a function of amounted circadian lux (CL_A) by Rea et al,[18] and artificial light with CS values above 0.3 facilitated rhythmic regulation.[19] Although common models depend on spectral sensitivity quantities, the use of general metrics has emerged as the circadian index inferred from illuminance, CCT, and color rendering index (CRI).[20] Notably, the consistency of judging the CRI[21] is unstable owing to the diversity of luminaire types. Hence, illuminance, CCT, and mEDI are key features of a lighting environment. To date, evidence from existing studies suggests a relationship between lighting parameters and non-visual effects of light exposures. In a practical scenario of submarine patrol with 24-h-based lighting schedules, Young et al compared sleep efficiency (SE), sleepiness, melatonin concentration, and individual performance of high CCT (13500 K) and standard-issue CCT (4100 K).[22] For the high CCT, its sleepiness score was lower, but the CS value was higher. Similarly, for a traditional fluorescent lamp (high CCT, 6000 K) and a light-emitting diode (low CCT, 2000 K) in a bedroom setting, Wen et al measured sleep quantity and quality, drowsiness, and fatigue in the next morning.[23] The low CCT significantly reduced next-morning sleepiness. Three night light settings (40 lx at 6500, 2500, and 3000 K) were studied, in which 6500 K resulted in greater melatonin suppression and increased alertness.[24] The high CCT is more conducive to maintaining work schedules and human behavioral alignment, whereas subjects exposed to low CCT may have better sleep quality and fatigue recovery. However, CCT and illuminance are often inseparable. Kruithof pioneered the two to form a comfort dimension of illuminance as the vertical axis and color temperature as the horizontal.[25] Experiments on three consecutive nights revealed the bright light effects of early evening (1200 lx, 4000 K) vs later evening (750 lx, 4000 K) on melatonin levels, subjective sleepiness, body temperature, and skin blood flow.[26] Ru et al studied the diurnal effects of illuminance (100 vs 1000 lx) and CCT (3000 vs 6500 K) on subjective mood and cognitive evaluation.[12] The effects of indoor illuminance (1200 vs 200 lx) and CCT (3000 vs 6500 K) on daytime cognitive performance, subjective mood, and alertness were examined in healthy adults.[27] Based on the above-mentioned studies, both CCT and illuminance settings need to be further investigated in specific sleep-related scenarios.[28] Previous studies have not provided detailed variations for sleep parameters in the context of CCT and illuminance.

The time-space distribution of diverse light sources is another crucial consideration that determines the spatial distribution of light, dynamic patterns, and duration of exposure. Particularly, blue-depleted evening ambient light reduced melatonin suppression and alertness.[29] Likewise, amber-lens glasses are recommended to block short-wave light exposure, or reduce prebedtime media use to enhance sleep quality of recreational athletes.[30] Yet, fewer studies have examined the effects of time-dependent light factors (eg exposure time or duration)[31] on sleep.[32] Three light conditions, namely alternating intermittent blue-enriched bright lights (~1000 lx, ~6000 K) and normal dark light (~5 lx, ~3600 K), continuous bright light, and continuous dark light, were tested for subjective alertness (SA), and subsequent sleep structure after a prebedtime 3-hour (3-h) exposure.[33] Compared to dark light, intermittent and continuous bright light significantly increase SA but lower SE and total sleep time (TST).

Sleep is a ubiquitous biological phenomenon. Models of sleep regulation are the basis for exploring the intrinsic physiological mechanisms of sleep-wakefulness; for example, the two-process model involves sleep-dependent homeostatic processes (Process S) and sleep-independent circadian rhythmic processes (Process C).[34,35] The interaction between the two processes determines sleep propensity and sleep duration. The circadian system adapts to the time of day by sensing outside light signals and adjusting an organism's routine in the real-world. Phenotypic indicators of sleep rhythms have been explored as tools for assessing the effect of actual lights;[36,37] for example, students in high CCT settings had significantly later bedtime and sleep onset time than those in low CCT.[38]

The targeted enclosed space provides artificial lighting and a controllable Heating, Ventilation and Air Conditioning (HVAC) system, the situation of which is similar to that of ships or submarine vessels.[39] An enclosed space, as a place with restricted access, allows people to work or sleep within a period of time.[40,41] In an actual scenario, naval crews work in artificially lit areas without exposure to sunlight.[28] For the enclosed space onboard a submarine,[42] the compact work/rest schedule implies almost no resting gap from work to rest and back to work. Additionally, the submariners encountered a non-entrained sleep-wake pattern under a tight and atypical work scheduling arrangement, but they

were still obliged to continue the voyage.[43,44] Hence, in such a situation, the crew's psychophysiological performance undergoes subtle changes, some of which incorporate sleep, alertness, and affect.[43] The references[2,45,46] are dedicated to influential research on light; however, few scholars have explored whether prolonged pre-bedtime exposure to bright light at work and forced resting dark environment in enclosed spaces have an impact on seafarers' performance. Moreover, prebedtime light exposure interventions (LEIs) mean changing lighting parameters, and thus impose a disruption; for example, irregular lightings lead to problems with circadian rhythms and sleep, which cause mood or learning deficits.[47] Recently, irregular light/dark cycles could directly affect neuronal coordination by producing major disruptions in circadian activity and motor function.[48] In addition, emotional state progressively affects subjective sleep quality.[14]

Inspired by established research, the present study aimed to investigate influential associations between sleep performance and human states according to the time-dependent effects of altered prebedtime light exposure on sleep performance and human states (corresponding to SA and negative affect (NA)) among young healthy adults. It included the following two concerns: (1) The effects of altered prebedtime light exposure from baseline to different interventions were studied under an enclosed space experimental paradigm. Statistical methods were employed to analyze the primary effect of the LEI groups. (2) For all dependent variables, process modelling was utilized to derive possible interrelated influencing relationships based on statistical effects. Systemic regulations or predictions could be implemented in accordance with the relationships.

Materials and Methods

Experimental Setup

A between-subjects factor (LEI: the illuminances at eye level are combined with CCTs based on the orthogonal experimental design) and one within-subjects factor (Time: baseline at D8 and intervention at D9, D10) are designated in Table 1. Moderate normal lighting was set as 300 lx and 4000 K referencing the ship standard.[49] Intervention design considerations arise from enhancing or lowering light parameters, thereby the selection of which is based on CIE S 008/E-2001 recommended scales of illuminance, color appearance, and GB 50034–2013 building compartment limits.[50,51] The uniformity of illuminance measured on the tabletop was 0.80 to 0.95, and general CRI ranges from 85 to 90. The land-based paradigm of enclosed space experiments provides available simulated lighting. Figure 1 depicts the spectrum power distribution profile, primarily concerned with the sensitivity to different light wavelengths because of the electromagnetic nature.[52]

Physical length*width*height dimensions of the simulated workspace associated with light exposures, are 3.5*2.5*2.1 m in Figure 2, while the sizes of another different enclosed space, the sleep chamber, are 3.5*3.5*2.1 m. Three

Table 1 Description of LEI and Time Setting

Description		Normal	High Cool	Low Cool	High Warm	Low Warm
CCT (K)		4000	6000	6000	3000	3000
Illuminance (lx)		300	750	100	750	100
Type of night (Time)		Baseline (D8)	Intervention (D9, D10)			
LEI grouping from baseline to intervention		–	#L1	#L2	#L3	#L4
Spectrally weighted α-opic irradiances (lx)	S-cone	195.9	838.8	96.1	299.5	28.9
	Melanopsin	157.4	592.0	69.6	266.9	29.5
	M-cone	265.4	716.6	89.2	576.3	70.0
	L-cone	304.5	744.1	92.1	734.9	87.9
	Rods	185.9	628.1	75.9	341.2	39.4

Abbreviations: LEI, light exposure intervention; CCT, correlated color temperature.

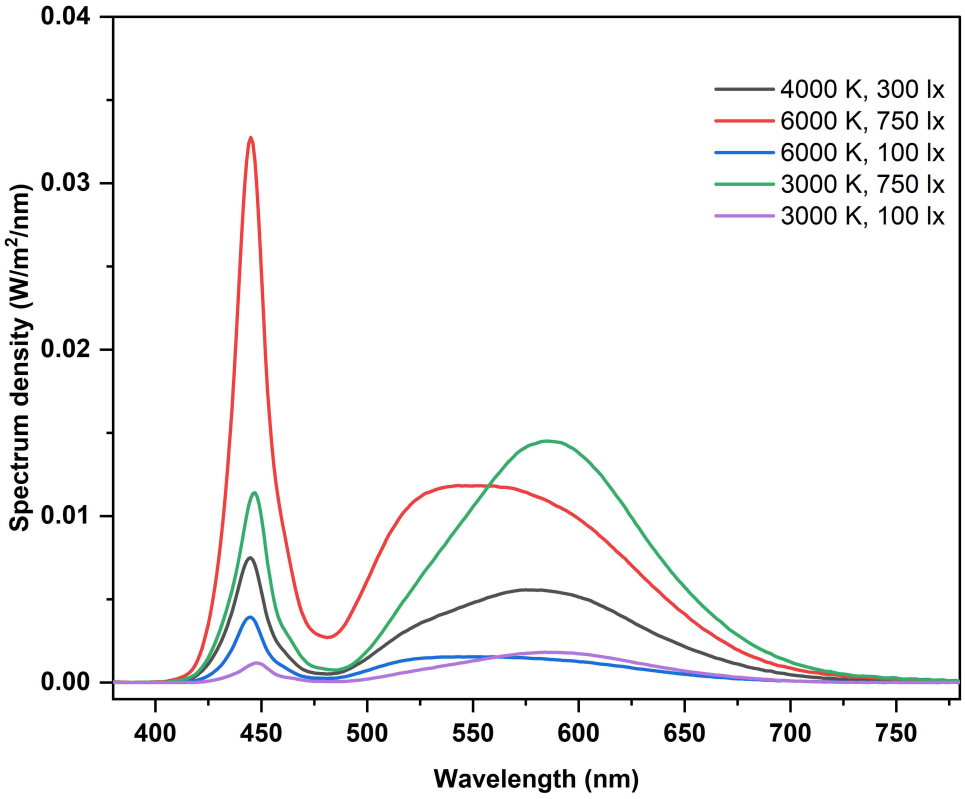

Figure 1 Spectrum power distribution measured at eye level for one baseline (300 lx, 4000 K) and four light exposure intervention settings.

sleep chambers and one workspace are offered and connected via sliding doors and a corridor. The suitable temperature and humidity in the sleep chamber in Figure 2a were maintained at approximately 25 ± 2 °C and 50%. The spatial noise was controlled to maintain a quiet environment. The ambient illuminance of the sleeping experiment required no light or was less than 1 lx. The experimenters provided disposable sheets and pillowcases for sanitation. To control the combined LEI changes, a stable experimental scenario was required to implement the easy switching of the desired parameters, which consisted of a manual control area equipped with a Lenovo desktop computer in Figure 2c and an experimental area in Figure 2b with six ceiling-mounted luminaires (HJMN-ZK02 LED round lamps) manufactured by Beijing Yisheng Taihe Technology Company.

Participants

Based on the software toolkit G*Power 3.1.9.7,[53] a repeated-measures, within-between interaction model was hypothesized prior to the formal experiment. To achieve 90% power, we settled on a correlation of 0.5 among repeated measurements, with a non-spherical correction epsilon of 1. The effect size of Cohen's f value was 0.25, indicating moderate intervention effects. Input parameters and calculation results are shown in Table 2. Hence, a total sample size of at least 44 participants was required.

Figure 3 shows a flowchart for selection of eligible participants.[54] The participants completed the Pittsburgh Sleep Quality Index (PSQI) questionnaire in Chinese version[30] for the past month before the experiment. Those who met the PSQI < 5 were included. Seventeen participants responding to extreme chronotypes based on the Chinese version of Horne and Ostberg's Morningness-Eveningness Questionnaire (intermediate MEQ, 50–62) were excluded.[55] The selected 59 postgraduates were eligible for the seven days' dormitory sleep observation survey (from D1 to D7, D1–7), who were required to eat normally. Considering whether they had engaged in pre-experiment strenuous physical exertion activities, ingested stimulant substances, sleep aids, or painkillers within one week, and smoked, consumed alcohol, or had caffeinated beverages per day, 51 participants were recruited for the in-lab sleep experiment. All of them informed about the purpose of this study signed the written consent voluntarily engaging in the trials. Finally, 2 males and 1 female

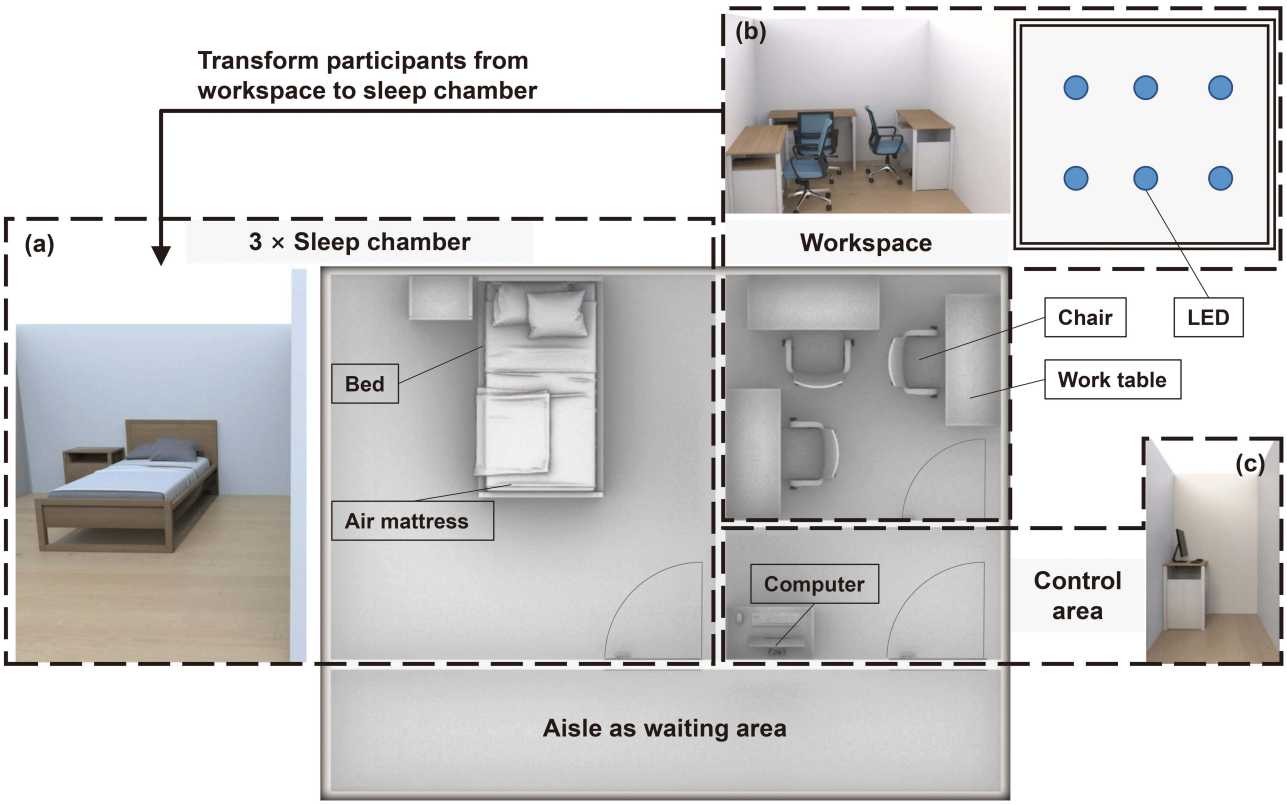

Figure 2 Experimental setting and scenes display via a 2-D graph of the whole experimental layout. (**a**) is a simulated sleep chamber equipped with a single bed, "3 × Sleep chamber" means that three identical sleep chambers are offered to 3 participants simultaneously; (**b**) is a simulated workspace with three seats and six LED round lamps in an enclosed space, where reading tasks are performed; (**c**) is a control area with a computer.
Notes: Researchers adjust light parameters of workspace from control area, and then transform participants from the workspace to the sleep chamber.

were excluded (D8–10) due to unfinished experiments, missing sleep data, and menstrual reasons. And thus, forty-eight postgraduates (male = 24) aged 23.58 ± 0.70 years were available for data analysis in total. This study was approved by the Institutional Ethical Committee of Northwest Polytechnical University (Grant No. 202202053) and was in compliance with the Declaration of Helsinki.

Table 2 Calculated Determination of Sample Size

***F*-tests - ANOVA: Repeated Measures, Within-Between Interaction**		
Analysis Objective	**A Priori: Compute Required Sample Size**	
Input parameters	Effect size f	= 0.25
	α error probability	=0.05
	Power (1-β error probability)	=0.9
	Number of groups	=4
	Number of measurements	=4
	Correlation among repeated measures	=0.5
	Nonsphericity correction ε	=1
Output results	Noncentrality parameter λ	=22.000000
	Critical F	=1.9587633
	Numerator *df*	=9.0000000
	Denominator *df*	120
	Total sample size	=44
	Actual power	=0.9116334

Abbreviation: ANOVA, analysis of variance.

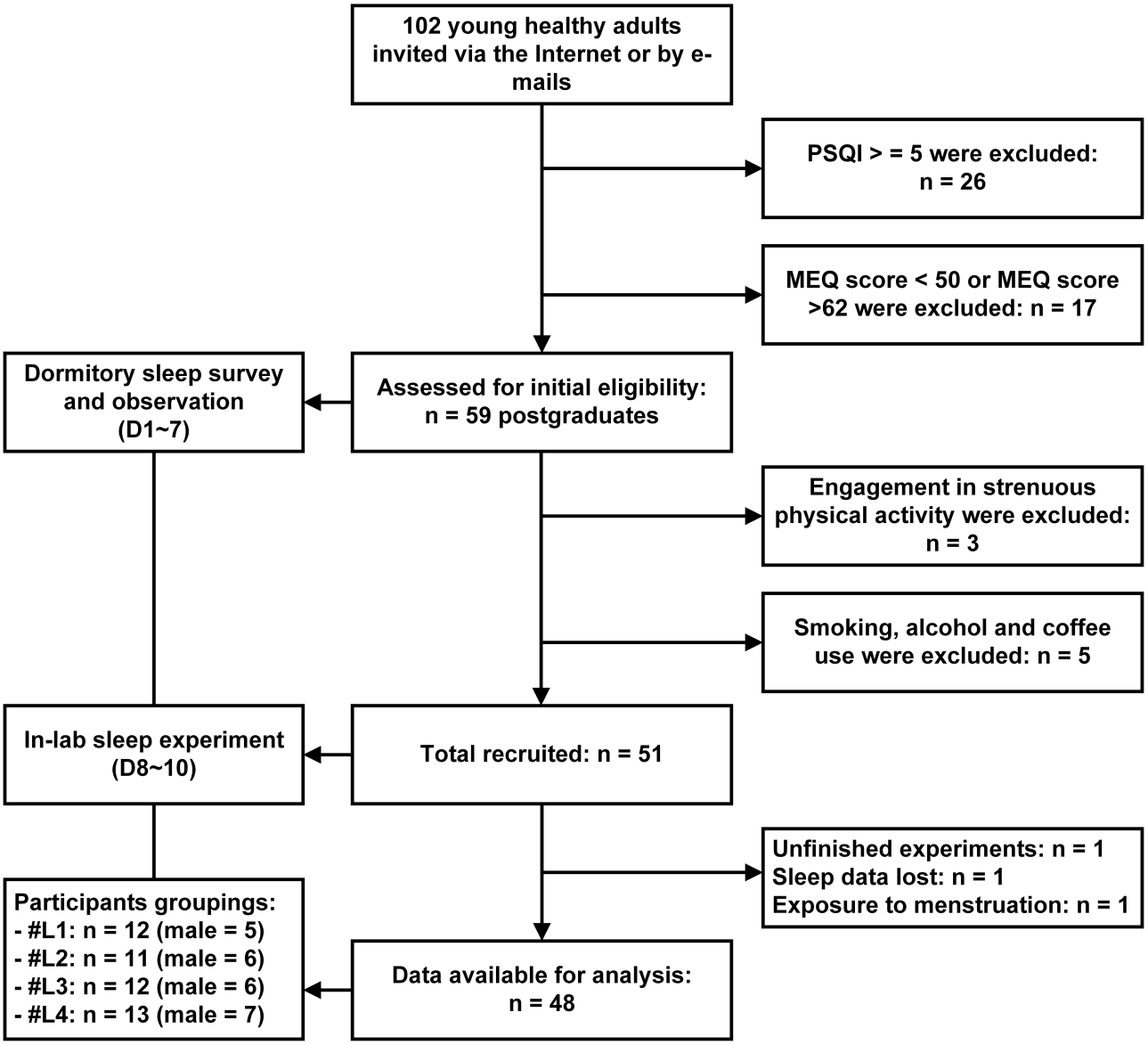

Figure 3 Flowchart of information on enrolled participants.
Abbreviations: PSQI, Pittsburgh Sleep Quality Index; MEQ, Horne and Ostberg's Morningness-Eveningness Questionnaire.

Study Measurements

To maintain a natural work/sleep pattern unobtrusively as much as possible, some objective methods were not adopted; for example, polysomnography (PSG, including electroencephalography (EEG)) is a gold standard for recording multiple human parameters,[56,57] but its electrodes are strongly bound for natural work/sleep activities. Several measurements performed to quantify the responsive outcomes are as follows.

Alertness Assessment via Subjective Rating

Sleepiness and alertness are the most frequent factors determining mental state. The Karolinska Sleepiness Scale (KSS) was suitable for measuring changes in the sleepiness or alertness of participants.[30,58] Score ratings on the KSS range from 1 (extremely alert) to 9 (extremely sleepy, fighting sleep).

NA Assessment via Emotional Model

Well-known affect assessment models contain the Self-Assessment Manikin,[59] Plutchik wheel model,[60] Pleasure-Arousal-Dominance (PAD) affective model,[61] and Positive and Negative Affect Schedule (PANAS).[62] The Self-Assessment Manikin and the PAD affective model are very similar, and both are biased towards estimating levels of emotional arousal. The Plutchik wheel model comprises diverse affective adjectives; however, it is difficult to quantify the effect in a synthesized manner. In contrast, the PANAS scale is divided into two parts with emotional descriptors for positive affect and NA. Positive affect assessment consisted of interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, and active, whereas NA assessment covered distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid. Participants' feelings, reactions, and levels of identification were measured using a five-point scale (1 – Almost not at all, 5 – Extremely much). Thus, the scores for all negative adjectives were aggregated into NA outcomes.

Sleep Recording via Actigraphy, Sleep Diary, and Self-Reported Sleep Survey

Throughout the in-lab trial, we performed wrist actigraphy-based natural sleep measures along with feedbacks from the participants. An actigraphy device depends on the acceleration sensor-based vector amplitudes synthesized from three-axis (x, y, z) motion data. A wrist actigraphy (wGT3X-BT, United States) is usually placed on the limb part with the least impact on the body movement range, eg the non-dominant left wrist. Actigraphy-based sleep monitoring continuously obtains subjects' movement characteristics, thereby yielding the sleep onset latency (SOL), TST, wake after sleep onset (WASO), SE and sleep fragmentation index (SFI) with the Cole-Kripke algorithm. Sleep diary and actigraphy-based measures are complementary. Sleep monitoring provides a numerical basis, yet it is typically inadequate. In-depth insight into the complex sleep-wake profile was gained from the recorded sleep diary. To learn participants' epistemic uncertainties, sufficiency and quality of sleep were directly investigated via the Next-day Self-assessment Sleep Quality (NSSQ) questionnaire[63,64] in Table 3. "Do you think you get enough sleep?" denotes the perception of sleep adequacy, which reflects participants' sleep sensations. "Overall sleep quality?" focuses on the sleep quality ratings.

Study Procedures

The study procedures included two phases; Phase 1 – in dormitory (D1–7) and phase 2 – in laboratory (D8–10) are as shown in Figure 4. Besides being informed of demographic characteristics, seven days' sleep-related survey and observation was conducted in a familiar dormitory, where room temperature was maintained at 25 ± 2 °C. We learned about the routine habits of these participants from a sleep diary and details of the PSQI questionnaire, which also contained daily sleep hygiene and mealtime. Hence, the prebedtime 3-h[33] light exposure was specified for phase 2, taking the nightly timing of falling asleep inferred from the sleep diary and adequate metabolic time reserved after dinner[65] as a reference. The experimental LEI occurred approximately 19:30 h to 23:30 h, and the adjustable timing was flexibly controlled within 30 minutes. Meanwhile, combined with habitual sleep bedtime or sleep onset, the experimental sleep duration was identified as eight hours accordingly. To reduce the first-night effect, LEIs started with one baseline night (D8) in an enclosed space, followed by two consecutive intervention nights' trials (D9 and D10). Three participants were allowed to conduct experiments in parallel. The study included 51 laboratory nights trials and 413 dormitory nights observations, and lasted for approximately two months in winter.

For phase 2, 30 minutes of participants' preparation (eg bathing) were reserved for the LEI trial in addition to preparing the laboratory in advance. To measure psychophysiological changes, discrete measurement points were configured as the start of

Table 3 Next-Day Self-Assessment Sleep Quality Questionnaire

Items	Response Alternatives	Score
1. Do you think you get enough sleep? (PSA)	Yes	1
	No	0
2. Overall sleep quality? (PSQ)	Very good	4
	Fairly good	3
	Fairly bad	2
	Very bad	1

Abbreviations: PSA, Perceived sleep adequacy; PSQ, Perceived sleep quality.

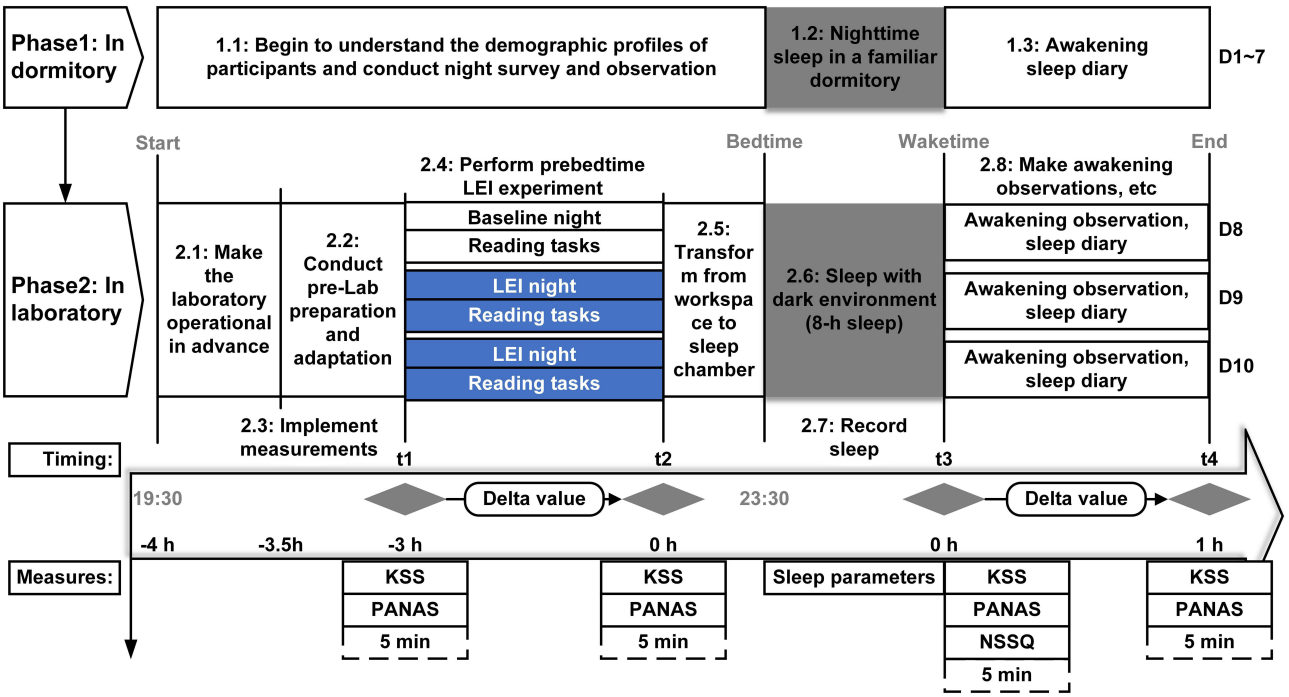

Figure 4 Study procedure and protocol design.
Notes: the whole experiment was categorized into two phases, including a survey and observation in dormitory (D1–7) and light exposure trials in laboratory (D8–10). Eight-hour sleep is required in laboratory. Particularly, four points of measurement (t1–t4) are assigned at proper times for phase 2. 0 h means the end of light exposure.
Abbreviations: LEI, light exposure intervention; KSS, Karolinska Sleepiness Scale; PANAS, Positive and Negative Affect Schedule; NSSQ, Next-day Self-assessment Sleep Quality.

timing (t1), before going to bed (t2), when waking up (t3), and 1-h after waking up (t4). For the four-measurement time, we gauged alertness via the KSS and NA via the PANAS, and figured out the self-reported sleep survey via the NSSQ questionnaire after waking up per day. Participants wore wrist actigraphy throughout the experiment. The effects of light emitted by electronic devices are imposed on alertness, sleep, and affect in the references.[66,67] To avoid the influence of blue light from electronic devices from t1 to t2 as much as possible,[14] we provided three alternative paper reading materials (eg specialty books, science fiction stories, and English test papers), which were randomly assigned to one of three days. The mobile phone carried was placed in a shielded box from t1 to t4 and was permitted to check its messages once or twice before t2, but restricted to one minute. Participants had no access to the mobile phone from t2 to t4. The cumulative duration of using electronic devices during the day was limited to two hours. Additionally, the participants maintained their most comfortable sitting posture, and three or seven short breaks were allowed for trials. The primary work of these postgraduate subjects during daytime hours was reading and attending classes. Some preferred the usage of eye masks because of self-habits from t2 to t3, although they were in a dark–light sleep chamber. In the morning, they could choose to wake up naturally or with an alarm clock. Specifically, they were asked to complete the NSSQ questionnaire with a sleep diary from t3 to t4 and allowed to leave the sleep chamber after confirming the observation.

Data Analysis

Firstly, singular values were examined and eliminated by exceeding the interquartile range (IQR) by a factor of 1.5. Only two NA values at t1 and t2 of D9 were removed. Considering time-dependent factors is reflected in the delta values of prebedtime (t1 and t2) and awakening (t3 and t4) periods. For the SA and NA, the delta value (ΔP) calculation of variations at prebedtime and awakening is given by Equation (1), respectively.

$$\begin{cases} \Delta P(Prebedtime) = P_{t2} - P_{t1} \\ \Delta P(Awakening) = P_{t4} - P_{t3} \end{cases} \quad (1)$$

An overview of the methodology, process of data processing, and analysis is presented in Figure 5. Raw data were measured and collected from the perspective of human state and sleep performance, and preprocessed to form the

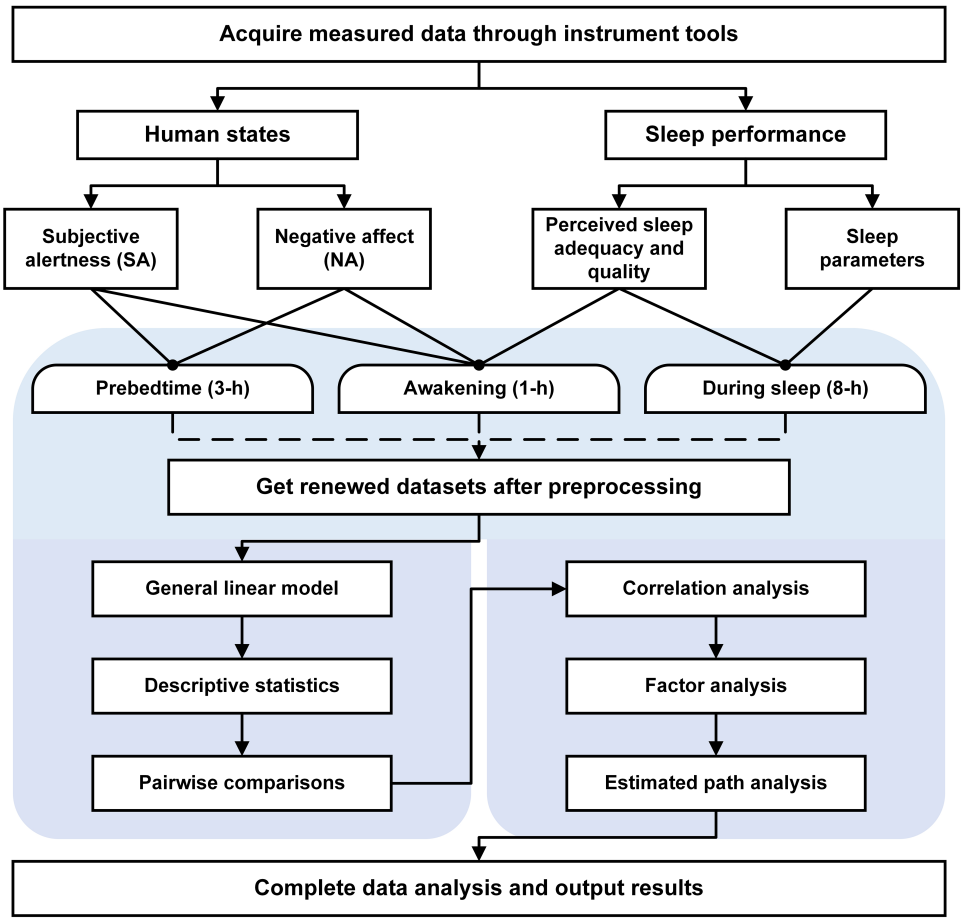

Figure 5 Methodology and process of data processing and analysis.

updated datasets. Due to repeated measurements, a general linear model (GLM) was applied to determine the main effect of LEI and Time, and the interaction effect between LEI and Time using SPSS Statistical Software 27.0. Descriptive statistics were demonstrated by the estimated marginal means (EMM) and standard errors of the mean (SEM) of four groups. The level of significance was set as 0.05. Discrepancies between pairwise comparison groups were further characterized, and we completed a post hoc test of pairwise groups (#L1–#L4 in Table 1) or pairwise Times by Fisher least significant difference (LSD) Test method.

The Pearson correlation coefficient is credited as a relational analysis of dependent variables ranging from −1 (perfect negative correlation) to +1 (perfect positive correlation). User experience and activity theory categorizes sleep within the built environment into a variety of manifestations: before, during, and after sleep.[68,69] To mitigate the influence of irrelevant variables, the maximum variance-based exploratory factor analysis (EFA) is superior in reflecting the measured variables before bedtime, during sleep, and after waking up. Additionally, path analysis was estimated with process model to uncover potential relationships, whereas a bootstrapping algorithm was applied owing to the small sample size. Finally, Smart-PLS 4.0 software suitable for generating the estimated path was chosen. Modeling of the relational effects of sleep-related stages contributed to data analysis for path coefficients and significance levels ($p < 0.05$).

Results

As its reliability test satisfied Spherical Symmetry (Mauchly's $W = 0.973$, $p = 0.768$) in the example of the change in SA before bedtime (SA_Prebedtime), a one-way analysis of variance (ANOVA) was first performed. Contrastingly, perceived sleep adequacy (PSA) dissatisfied the test of Sphericity Symmetry (Mauchly's $W = 0.631$, $p < 0.05$); hence, the results of Greenhouse-Geisser's Test were adopted. The results of statistical effects are shown in Table 4. Levene's

Table 4 Results for Statistical Effects of Dependent Variables

	LEI			Time			LEI*Time		
	F	p value	η_P^2	F	p value	η_P^2	F	p value	η_P^2
SA									
SA_Prebedtime	1.292	0.305	0.162	3.567	**0.038**	0.151	0.682	0.665	0.093
SA_Awakening	0.895	0.461	0.118	0.034	0.967	0.002	0.465	0.830	0.065
NA									
NA_Prebedtime	1.483	0.249	0.182	1.138	0.331	0.054	2.251	**0.058**	0.252
NA_Awakening	0.416	0.743	0.059	0.376	0.689	0.018	1.315	0.273	0.165
NSSQ									
PSA	0.739	0.541	0.100	3.531	**0.049**	0.271	0.246	0.958	0.036
PSQ	0.709	0.558	0.096	4.295	**0.020**	0.177	0.620	0.713	0.085
Sleep parameters									
TST	1.886	0.165	0.221	0.523	0.597	0.025	1.748	0.135	0.208
SOL	3.692	**0.029**	0.356	1.154	0.326	0.055	0.403	0.873	0.057
WASO	2.379	0.100	0.263	0.313	0.733	0.015	1.163	0.345	0.149
SE	2.229	0.116	0.251	0.609	0.549	0.030	1.374	0.249	0.171
SFI	1.400	0.272	0.174	1.157	0.325	0.055	0.453	0.838	0.064

Notes: A significant difference is indicated by bold labels, $p < 0.05$; η_P^2, Partial eta squared.
Abbreviations: LEI, light exposure intervention; SA, Subjective alertness; NA, Negative affect; SA_Prebedtime, change in subjective alertness before bedtime; SA_Awakening, change in subjective alertness after waking up; NA_Prebedtime, change in negative affect before bedtime; NA_Awakening, change in negative affect after waking up; NSSQ, Next-day Self-assessment Sleep Quality; PSA, Perceived sleep adequacy; PSQ, Perceived sleep quality; TST, total sleep time; SOL, sleep onset latency; WASO, wake after sleep onset; SE, sleep efficiency; SFI, sleep fragmentation index.

homogeneity test indicated that the probability greater than 0.05 was in accordance with a normal distribution. Almost no interaction effect existed between the LEI and Time. Notably, the interaction effect ($p = 0.058$) between the LEI and the Time on the change in NA before bedtime (NA_Prebedtime) was marginally significant. The main effect of the Time was significantly different in SA_Prebedtime, PSA, and perceived sleep quality (PSQ), while the main effect of the LEI was merely in sleep onset latency (SOL).

Effect of Light Exposure on Subjective Alertness

An SA score of five (= "neither alert nor sleepy") is a key cutoff point for alertness or sleepiness of the human state;[58] for example, the SA at t1 reached above 5 in Figure 6. Among these LEI groups, the subjects did not hit high levels of alertness soon after waking up (t3), which was always lower than before bedtime (t2). The recovery of alertness in high illuminance and high CCT (#L1) after waking up is the slowest in Figure 6b. Yet this study emphasized the relative changes in alertness. Hence, Figure 7a and b displayed the alertness variation before and after sleep under the four groupings, respectively. When exposed to continuous lighting, human alertness decreased while the sleepiness increased during the prebedtime 3-h period. The insignificant interaction effect between the LEI and the Time leads to a Time-focused impact analysis; for instance, the intervention and the baseline on the Time were significantly different as depicted in Table 5 and the probability of significance ($p < 0.05$) is marked in Figure 7. Low warm light (#L4) had the most evident increase in sleepiness at prebedtime, because the mean difference of D8 minus D9 was −1.83 (significant, $p = 0.009$), or the mean difference of D8 minus D10 was −1.67 (significant, $p = 0.035$). The overall EMM of SA_Prebedtime is 1.94 (SEM = 0.20). In detail, both #L2 and #L4 had larger SA_Prebedtime estimates than the overall EMM, suggesting that changing to low illuminance conditions was more likely to cause sleepiness. Although the SA_Prebedtime estimates for #L1 and #L3 were lower than the overall EMM, the mean sleepiness increased over time when exposed to prebedtime light. The estimated alertness at awakening for the remaining three lighting conditions

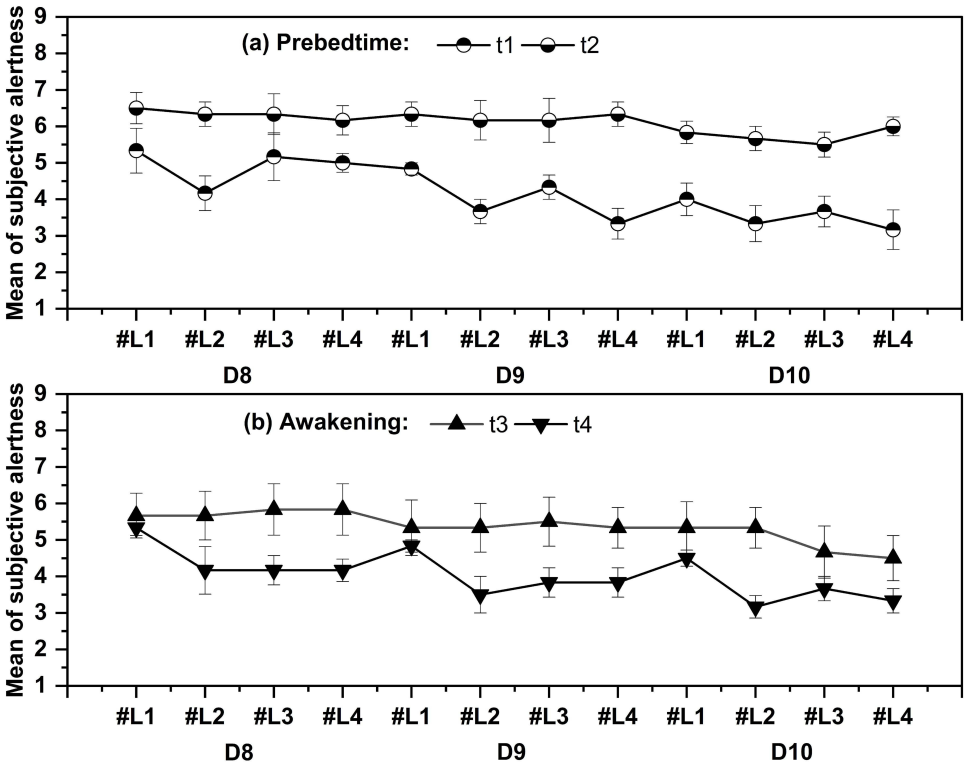

Figure 6 Mean of subjective alertness for (**a**) t1 and t2 at prebedtime, (**b**) t3 and t4 at awakening.

exceed the overall EMM level. Combined with the statistical effect, altering the lighting condition had no significant effect on alertness variation at awakening but was significant at t1 and t2 of the prebedtime.

Effect of Light Exposure on Negative Affect

Figure 7c and d illustrated the results of NA_Prebedtime and change in NA after waking up (NA_Awakening). The NA_Prebedtime of participants on three days (D8–10) was negative. At D8, NA_Prebedtime between #L1 and #L4 was significant (its mean difference of #L1 minus #L4 was −5.33, $p = 0.020$). However, mean of the NA was very high at the t1 timing of D8 in Figure 8a. At D9, #L2 differed from #L1 (the mean NA_Prebedtime difference of #L2 minus #L1 was −2.33, $p = 0.054$) and #L3 (the mean NA_Prebedtime difference of #L2 minus #L3 was −2.00, $p = 0.094$), respectively, where a marginally significant effect was observed. When changing to high illuminance and high CCT (#L1), a significant difference between D8 and D9 ($p = 0.006$) suggested that the enhancement of lighting parameters had a positive effect on NA regardless of prebedtime or awakening in Table 6. The NA varied less significantly among measured outcomes after waking up. The rhythm of NA variations in the uplifted illuminance groups (#L1 and #L3) was highly synchronized. After waking up, a boundedly significant discrepancy between #L1 and #L4 at D9 (the mean NA_Awakening difference of #L1 minus #L4 was −2.83, $p = 0.071$). Especially for #L1, there was an obvious difference between D8 and D9 after waking up (see Table 6). Compared to the numerical variations of NA delta values at prebedtime, the outcome of NA_Awakening was chaotic, which may be attributed to the neuroregulatory impact of sleep recovery[70] or other causes to be explored.

Effect of Light Exposure on Sleep Performance

The EMM profiles of subjective sleep are described in Figure 9. For PSA and PSQ, no participants experienced very bad sleep quality. The global EMM of PSA was 0.708 (SEM = 0.072), whereas that of PSQ was 2.847 (SEM = 0.087) indicating that all LEI groups exceeded its median level. A remarkable difference between the intervention of D10 and the baseline of D8 was described in Table 7. Additionally, a marginal significance was found between the PSQ of #L1

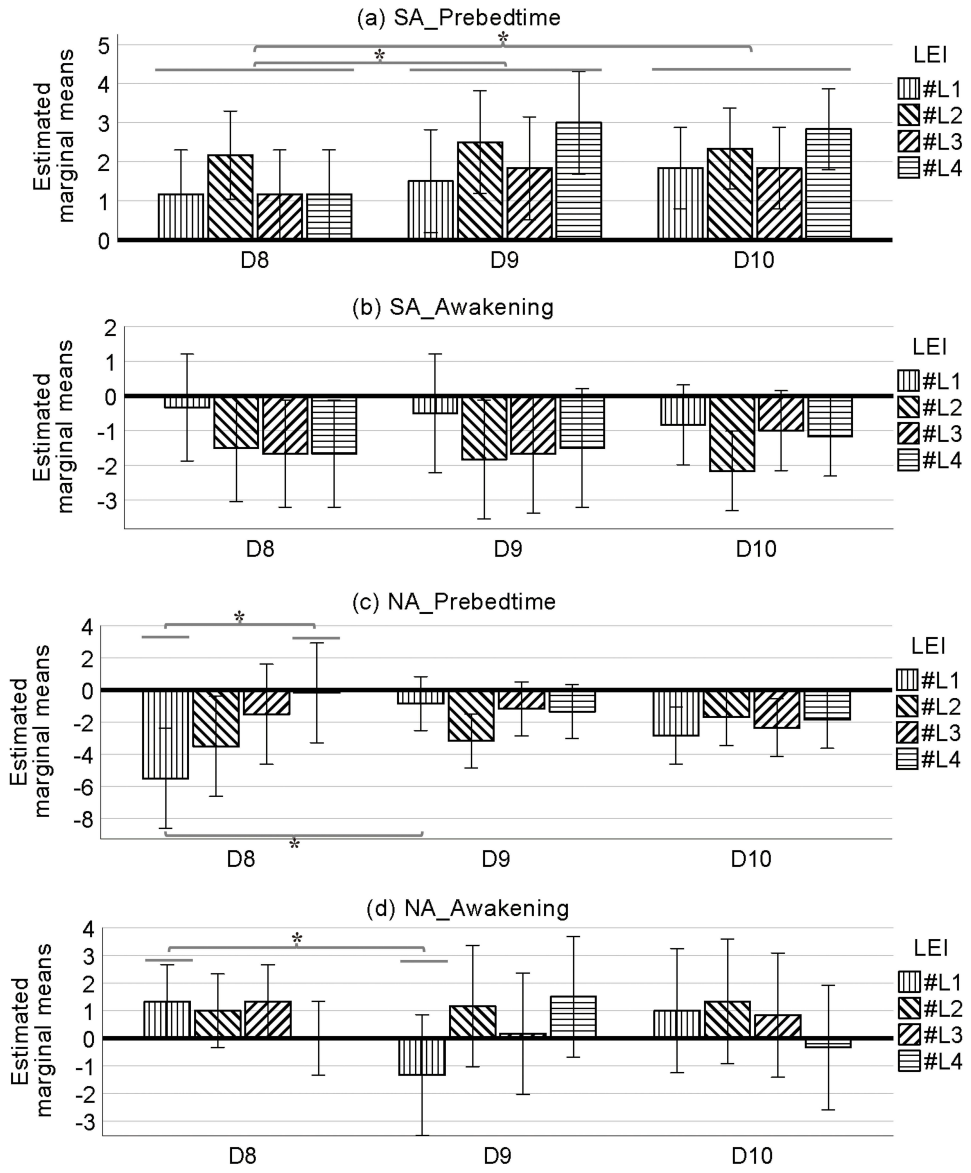

Figure 7 Estimated marginal means of the changes in subjective alertness: (**a**) before bedtime, (**b**) after waking up, and the changes in negative affect: (**c**) before bedtime, (**d**) after waking up. Error bars represent 95% confidence intervals. #L1 - #L4 indicate groupings from baseline to intervention distinguished by LEI. Significant is marked, *p < 0.05.

and #L3 at D10 (the mean PSQ difference of #L1 minus #L3 was 0.67, p = 0.059). The number of participants with insufficient sleep and poor sleep quality on D8 was higher than that on D9–10. Subjects with high illuminance and low CCT (#L3) were more likely to suffer from insufficient sleep. However, participants who underwent high illuminance intervention (#L1 and #L3) were less likely to have poor sleep quality.

Table 5 Mean Difference and Significance of the Changes in Subjective Alertness Before Bedtime Between Different Times

Time (I)	Time (J)	Mean Difference (I-J)	p value
D8	D9	−0.79	**0.022**
D8	D10	−0.79	**0.044**
D9	D10	0.00	1.000

Note: A significant difference is indicated by bold labels, p < 0.05.

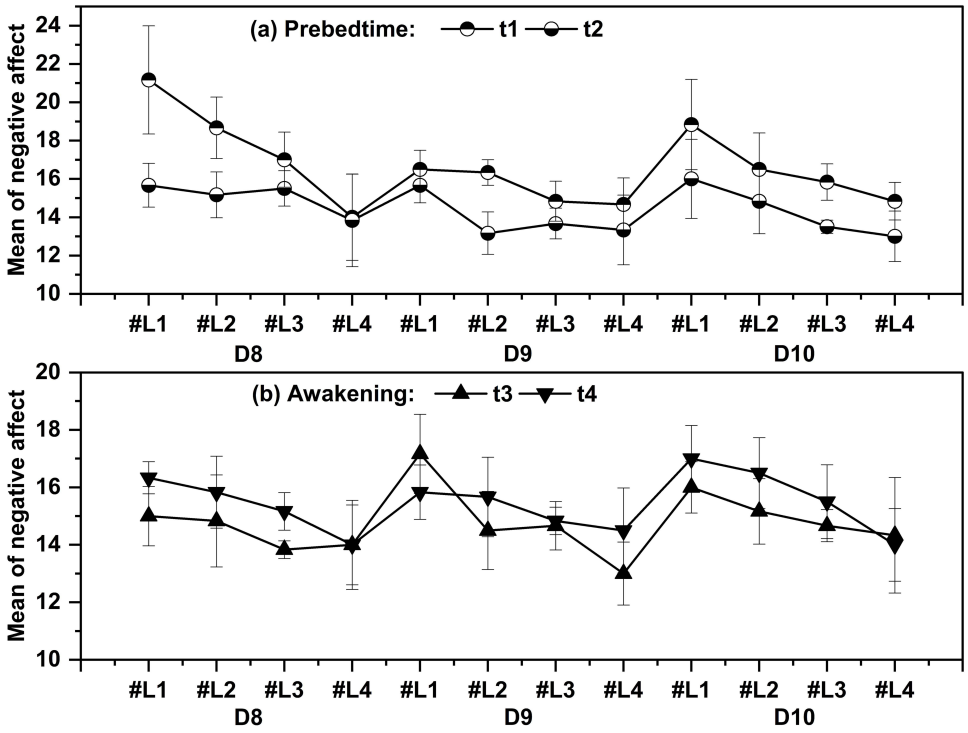

Figure 8 Mean of negative affect for (**a**) t1 and t2 at prebedtime, (**b**) t3 and t4 at awakening.

The five sleep parameter estimations under the four LEI groups are presented in Figure 10. When switching to low CCT lighting, the mean difference in TST between #L3 and #L4 showed that high illuminance at prebedtime significantly shortened sleep duration compared to low illuminance; specifically, the mean TST difference of #L3 minus #L4 was −0.70 hours (p = 0.019) at D8, while that of #L3 minus #L4 was −0.47 hours (p = 0.048) at D9. The mean TST difference of #L2 minus #L4 was significantly distinct (−0.47 hours, p = 0.047) at D9. For #L3, the TST outcome of post-intervention was distinguished from the baseline (the mean TST difference of D8 minus D9 was −0.37 hours, p = 0.036). As such, this result reminds us of the ability to acutely lower the color temperature and increase the illuminance (#L3) at prebedtime for enhanced sleep duration.

Figure 10b depicts the results of the SOL under different LEI groups. The SOL reveals whether the participants fall asleep normally. The SOL time for #L2 was longer than that for the other three groups, indicating more difficulty falling

Table 6 Mean Difference and Significance of the Changes in Negative Affect Before Bedtime and After Waking Up for #L1 Between Different Times

Time (I)	Time (J)	Mean Difference (I-J)	p value
Before bedtime			
D8	D9	−4.67	**0.006**
D8	D10	−2.67	0.090
D9	D10	2.00	0.087
After waking up			
D8	D9	2.67	**0.032**
D8	D10	0.33	0.809
D9	D10	−2.33	0.079

Note: A significant difference is indicated by bold labels, p < 0.05.

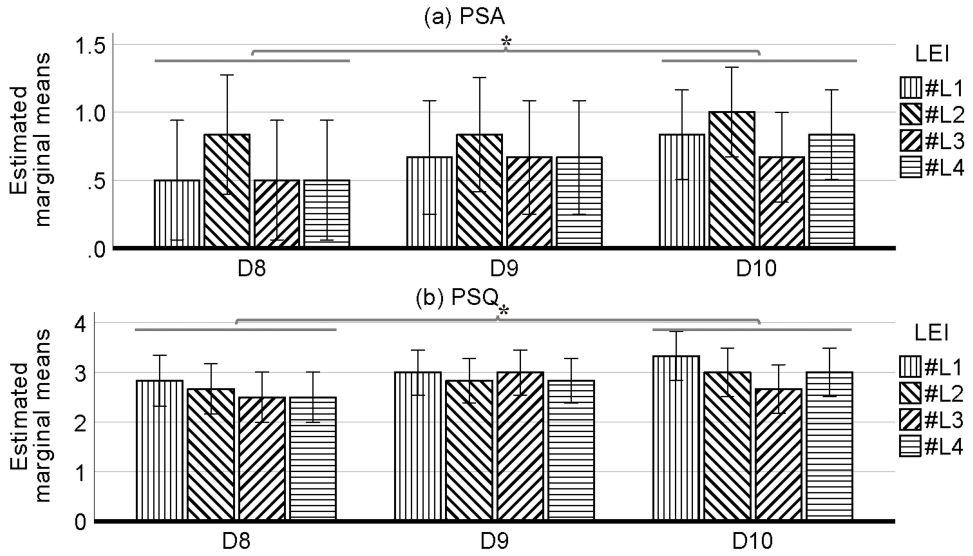

Figure 9 Estimated marginal means of (**a**) PSA, perceived sleep adequacy, and (**b**) PSQ, perceived sleep quality. Error bars represent 95% confidence intervals. #L1 - #L4 indicate groupings from baseline to intervention distinguished by LEI. Significant is marked, * $p < 0.05$.

asleep. However, from D8 to D10, the SOLs for #L2 were very higher. Particularly, #L2 significantly differentiated from #L1 (the mean SOL difference of #L2 minus #L1 was 9.39 minutes, $p = 0.007$) and #L4 (the mean SOL difference of #L2 minus #L4 was −8.33 minutes, $p = 0.014$) in Table 8. #L1 was marginally different from #L2 (the mean SOL difference of #L1 minus #L2 was −7.33 minutes, $p = 0.058$) at D9.

The WASO results are exhibited in Figure 10c. Compared to #L3, both #L1 (the mean WASO difference of #L1 minus #L3 was −28.17 minutes, $p = 0.045$) and #L4 (the mean WASO difference of #L3 minus #L4 was 38.00 minutes, $p = 0.009$) had a shorter awakening time after sleep onset at D8. Besides, as compared to #L4, #L1 (the mean WASO difference of #L1 minus #L4 was 28.00 minutes, $p = 0.051$) and #L3 (the mean WASO difference of #L3 minus #L4 was 27.67 minutes, $p = 0.053$) had longer awakening time after sleep onset at D9–10. Furthermore, regarding the SE in Figure 10d, the SE results exceed the normal threshold of 80%. #L3 significantly differentiated from #L1 (the mean SE difference of #L3 minus #L1 was −7.34%, $p = 0.031$) and #L4 (the mean SE difference of #L3 minus #L4 was −8.50%, $p = 0.014$) at D8, while #L2 (the mean SE difference of #L2 minus #L4 was −6.26%, $p = 0.046$) and #L3 (the mean SE difference of #L3 minus #L4 was −6.28%, $p = 0.045$) manifested lower SE values than #L4 significantly at D9. Lastly, the SFI variables did not show statistically significant at D9–10 in Figure 10e. Although the assessment of sleep disturbance theoretically depended on the SFI, its ultimate statistical result was insignificant.

Table 7 Mean Difference and Significance of Perceived Sleep Adequacy and Quality Between Different Times

Time (I)	Time (J)	Mean Difference (I-J)	p value
Perceived sleep adequacy (PSA)			
D8	D9	−0.13	0.359
D8	D10	−0.25	**0.042**
D9	D10	−0.13	0.099
Perceived sleep quality (PSQ)			
D8	D9	−0.29	0.063
D8	D10	−0.38	**0.006**
D9	D10	−0.08	0.534

Note: A significant difference is indicated by bold labels, $p < 0.05$.

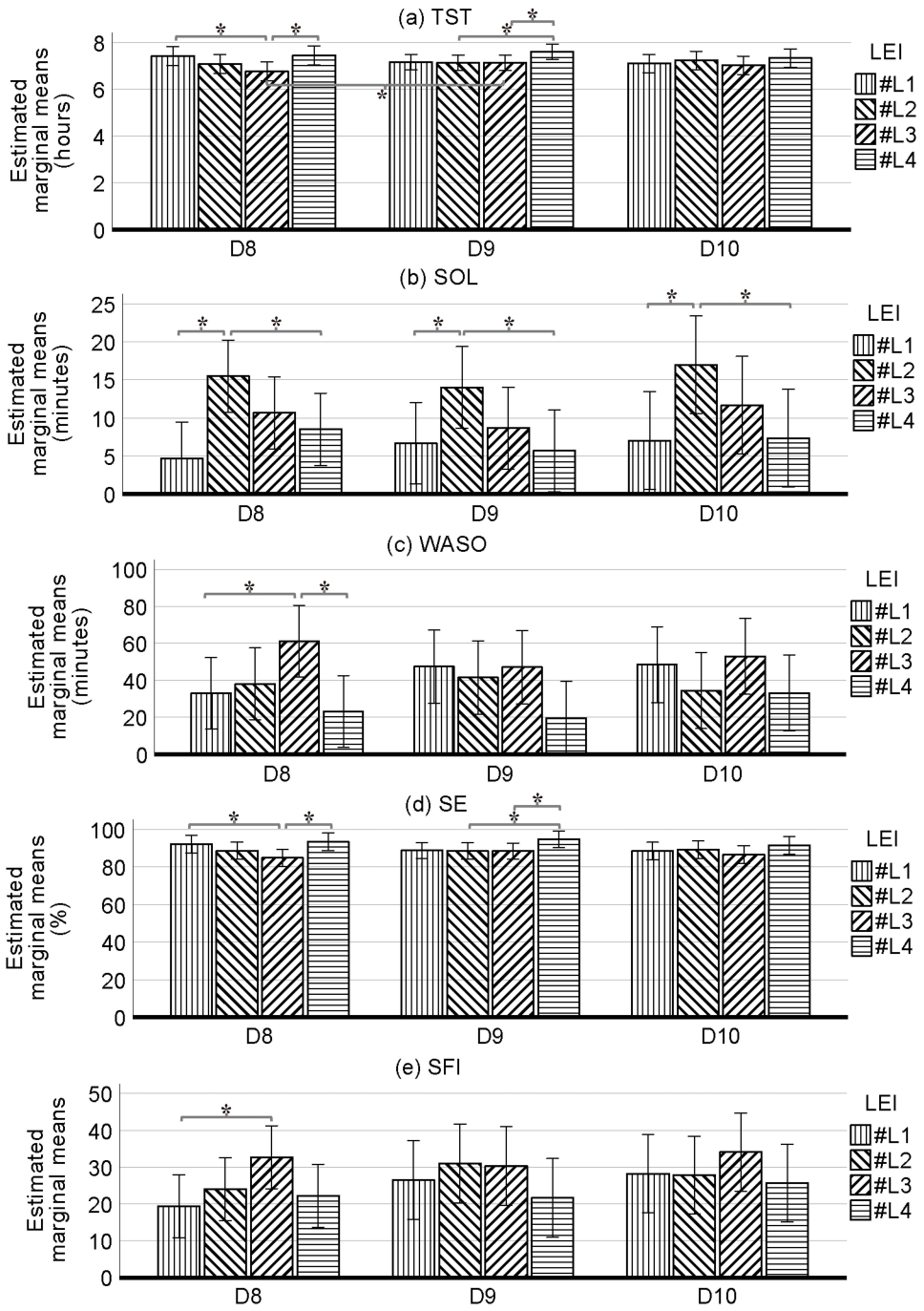

Figure 10 Estimated marginal means of sleep parameters: (**a**) TST, total sleep time; (**b**) SOL, sleep onset latency; (**c**) WASO, wake after sleep onset; (**d**) SE, sleep efficiency; and (**e**) SFI, sleep fragmentation index. Error bars represent 95% confidence intervals. #L1 - #L4 indicate groupings from baseline to intervention distinguished by LEI. Significant is marked, *p < 0.05.

Sleep Performance in Relation to Human States

The paired correlation coefficients are used to characterize the relationships between all metrics in Table 9. The SA_Prebedtime was associated with PSA variable (r = 0.260, p = 0.028). The NA_Awakening correlated with the SA_Awakening (r = 0.247, p = 0.037). Notably, the PSQ was strongly correlated with the PSA (r = 0.633, p < 0.01). Sleep parameters were interrelated except for an insignificant correlation between SOL and SFI; for example, the TST was negatively correlated with the SOL (r = −0.450, p < 0.01) and the WASO (r = −0.946, p < 0.01).

Table 8 Mean Difference and Significance of Sleep Onset Latency (Minutes) Between Different LEIs

LEI (I)	LEI (J)	Mean Difference (I-J)	p value
#L1	#L2	−9.39	**0.007**
#L1	#L3	−4.22	0.189
#L1	#L4	−1.06	0.737
#L2	#L3	5.17	0.111
#L2	#L4	8.33	**0.014**
#L3	#L4	3.17	0.320

Note: A significant difference is indicated by bold labels, $p < 0.05$.

Table 9 Correlation Coefficient Calculation Results Among Different Variables

	1	2	3	4	5	6	7	8	9	10
1 SA_Prebedtime	–									
2 SA_Awakening	−0.014	–								
3 NA_Prebedtime	−0.151	−0.131	–							
4 NA_Awakening	−0.094	**−0.247***	0.051	–						
5 PSA	**0.260***	0.132	−0.133	0.094	–					
6 PSQ	0.024	0.123	−0.049	−0.007	**0.633****	–				
7 TST	0.043	0.064	0.158	0.050	−0.172	−0.066	–			
8 SOL	0.058	−0.208	−0.119	0.072	0.083	−0.074	**−0.450****	–		
9 WASO	−0.056	−0.025	−0.095	−0.032	0.188	0.133	**−0.946****	**0.243***	–	
10 SE	0.036	0.075	0.124	0.015	−0.191	−0.096	**0.980****	**−0.480****	**−0.967****	–
11 SFI	−0.062	−0.206	0.124	0.082	−0.006	−0.099	**−0.600****	0.188	**0.630****	**−0.616****

Notes: Significant differences are indicated by bold labels, two-tailed test; *Significant, $p < 0.05$; **Significant, $p < 0.01$.
Abbreviations: SA_Prebedtime, change in subjective alertness before bedtime; SA_Awakening, change in subjective alertness after waking up; NA_Prebedtime, change in negative affect before bedtime; NA_Awakening, change in negative affect after waking up; PSA, Perceived sleep adequacy; PSQ, Perceived sleep quality; TST, total sleep time; SOL, sleep onset latency; WASO, wake after sleep onset; SE, sleep efficiency; SFI, sleep fragmentation index.

For all datasets, four types of factors were obtained from the EFA method in Table 10. In most studies, ± 0.4 is adopted as the cutoff value for factor loadings.[71] Regarding the outcomes during different stages, it is thereby named as "Factor 1 - objective sleep", "Factor 2 - subjective sleep", "Factor 3 - awakening state", and "Factor 4 - prebedtime state", respectively. Herein, human states correspond to the prebedtime state and the awakening state. The four factors accounted for 72.4% of the cumulative variance contribution ratio as indicated by the calculated total variance. Each factor had an initial eigenvalue of greater than 1.0. To our knowledge, although subjective and objective sleep are correlated theoretically, the complexity of sleep phenomenon makes sleep parameters less interpretable than the self-reported sleep. SOL is assigned not only to Factor 1 but also to Factor 4, which indicates the fact that the SOL is an objective sleep parameter and infers a connection between SOL and the prebedtime state as well.

The path coefficient is one of standardized regression coefficients that indicates the direct effect of one variable on another. According to the estimated path analysis in Figure 11, the prebedtime state and SOL were negatively correlated ($t = 2.075$, $p = 0.038$) demonstrating that lowered alertness and reduced NA at prebedtime caused by light intervention are beneficial for a person to fall asleep as soon as possible. The SOL positively correlated with objective sleep assessments ($t = 2.740$, $p = 0.006$). Consequently, the SOL determines the level of objective sleep quality in the context of altered prebedtime light exposures. However, no immediate significant correlation was found between prebedtime state and either objective or subjective sleep (see Figure 11). The regression coefficient highlighted the statistical significance between subjective sleep and awakening state ($t = 2.508$, $p = 0.012$). A better subjective sleep rating corresponds to a better wakefulness state. Additionally, subjective sleep outcomes were close to correlate with objective sleep ($t = 1.750$, $p = 0.080$). Hence, in the course of participant interaction with lighting ergonomics factors, it developed

Table 10 Rotated Factor Loadings of All Metrics

	Factor 1 – Objective Sleep	Factor 2 – Subjective Sleep	Factor 3 – Awakening State	Factor 4 – Prebedtime State
SA_Prebedtime	0.122	0.134	0.052	**0.691**
SA_Awakening	0.093	0.204	**−0.767**	−0.024
NA_Prebedtime	0.073	−0.036	0.237	**−0.678**
NA_Awakening	0.048	0.174	**0.739**	−0.131
PSA	−0.106	**0.875**	0.048	0.241
PSQ	−0.025	**0.891**	−0.078	−0.050
TST	**0.970**	−0.060	0.030	−0.118
SOL	**−0.441**	−0.124	0.346	**0.468**
WASO	**−0.953**	0.139	−0.082	−0.023
SE	**0.978**	−0.090	−0.011	−0.106
SFI	**−0.738**	−0.099	0.192	−0.212

Note: A qualified factor loading with an absolute value greater than 0.4 is indicated by bold labels.
Abbreviations: SA_Prebedtime, change in subjective alertness before bedtime; SA_Awakening, change in subjective alertness after waking up; NA_Prebedtime, change in negative affect before bedtime; NA_Awakening, change in negative affect after waking up; PSA, Perceived sleep adequacy; PSQ, Perceived sleep quality; TST, total sleep time; SOL, sleep onset latency; WASO, wake after sleep onset; SE, sleep efficiency; SFI, sleep fragmentation index.

a chained pathway relationship of "prebedtime state - SOL - objective sleep - subjective sleep - awakening state" based on the aforementioned datasets.

Discussion

This study explored the time-dependent effects of altered prebedtime light exposure in enclosed spaces on sleep performance associated with human states using statistical analysis and process modelling. Our findings suggest that objective sleep parameters and subjective sleep assessments during sleep are associated with the SA and NA at prebedtime and awakening among young healthy adults.

In the current study, the LEI and the Time were considered as independent variables. For the experimental setup, illuminance and CCT as a fixed LEI factor provide four varying conditions. Compared with other studies, we set the illuminance in the medium threshold which is an intermediate between the higher (eg 5000 lx)[45] and low (eg 40 lx)[24] light intensity. Exposure to low illuminance and high color temperature (40 lx, 6500 K) in a previous study[24] resulted in enhanced SAs. The SAs of low illuminance and high CCT (#L2) at t1 and t2 were also observed to increase from

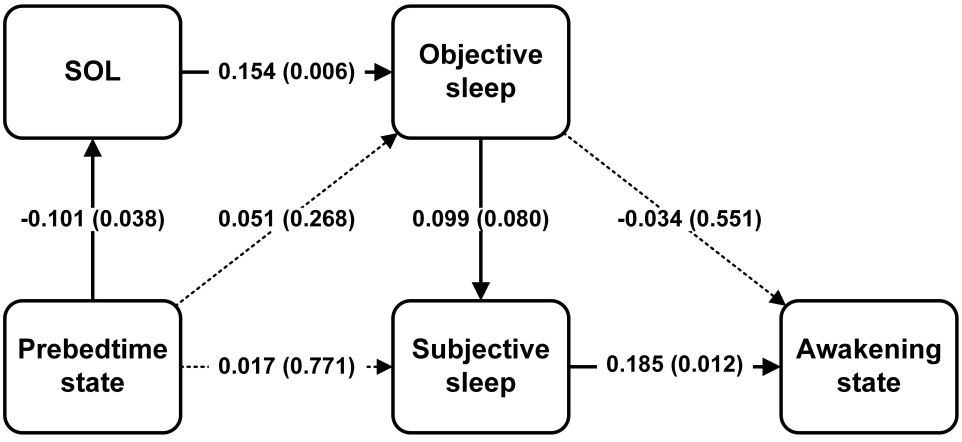

Figure 11 Results for standardized path analysis with a process model. Rectangles denote the latent variable, of which directed lines represent the value of path coefficients (p value).
Notes: Solid directed lines indicate statistical significance ($p < 0.05$), while dashed directed lines represent relationships that are not statistically significant.
Abbreviation: SOL, sleep onset latency.

baseline in Figure 6. The effect of 106 lx of illuminance for 4-h continuous exposure had little change on the SA (maintained KSS = 3), until 5.5 h when the KSS increased to 2 by Cajochen et al.[15] After 3-h light exposure, both #L2 and #L4 groups elevated the SA more than the other two, with the SA approaching 3 at the t2 timing of intervention, suggesting that the KSS-assessed SA outcomes were fairly reliable.

Different office light CCTs had significant main effects on SA, and the average KSS of 4000 K (= 5.41) was significantly higher than the other three higher CCTs, but the longer light exposure duration was only 90min.[72] In contrast, the baseline condition with 3-h light exposure in this study resulted in an inconsistent average KSS (= 6.33) at t2, which was higher than 5.41. In addition, various color temperatures in the office (4000, 6000, 8000, and 10,000 K at 300lx) had no significant effect on determined, annoyed, and anxious, while there was a significant main effect on happy, excited, inspired.[72] In our study, although no significant effect of the LEI on the NA was also observed, receiving LEIs from t1 to t2 caused the NA scores to decrease, which inferred that continuous exposure to bright light could alleviate NAs at prebedtime. Due to different ratios of male and female in Figure 3, a higher mean NA at the t1 of D8 was observed and some NA values of D9 has been excluded from the #L1 group. The result may be explained by the fact that these subjects require adaptation to enclosed spaces at the same time, and partly due to random assignment. In the case of the gender imbalance, higher NA values for an individual subject would likely result in larger mean of the calculated NA. Altered prebedtime light exposures might interfere with psycho-affective responses at awakening while ensuring adequate sleep (eg the mean PSQ was perceived as "fairly good" and the SE met over 80%).

The 3-h light exposure duration makes this study different from other studies, such as 1.5-h,[72,73] 1-h,[17,23] and 0.5-h[74] light exposure. These existing studies did not consider the time as a factor, but instead focused on spectral power-related light illuminance or CCT. After a 3-h continuous prebedtime light exposure, the main effect of the Time on the SA_Prebedtime and subjective sleep (refer to PSA and PSQ) was significant, which guided us to think about time-dependent relationships between human states and sleep performance. Additionally, an experimental study examined the diurnal effects of office lighting on alertness, mood, and cognitive performance,[12] but the time was set to daytime hours (10:00 h to 17:00 h). The experimental period of this study was approximately from 19:30 h to 9:00 h, and the human responses were differently mirrored on the timeline.

The calculated delta changes in human states (refer to SA and NA) from t1 to t2 (or from t3 to t4) are the relative values mapping psychophysiological responses. Subtle human state changes caused by shifts in the medium-intensity light exposure were observed at prebedtime (3-h) and awakening (1-h). During 3 consecutive laboratory days, we found that the measured changes in the SA at D9–10 nights were significantly different from that at D8 night (see Table 5). Figure 6a depicts that with continuous bright-light exposure overall alertness is keeping a trend of rising. The time-dependent significant effect of light exposure on SA changes at prebedtime disappeared upon awakening, but exerted a correlative impact on the SOL (see Figure 11). Furthermore, in the case of switching to the high illuminance and high CCT (#L1), the change in NA at prebedtime of D9 was obviously higher than that at prebedtime of D8, but the change in NA at awakening of D9 was lower than that at awakening of D8 within the same group. After experiencing 8-h sleep, NAs of participants in the #L1 group were observed to be disturbed at D9, yet the other three groups were less likely to be disturbed.

Through an EFA method, it was validated that subjective sleep consists of the PSA and the PSQ. For the PSA and PSQ, a significant increase of assessments was observed from D8 to D10. However, no such differences were found in the five estimated sleep parameters. The significant main effect of the LEI on the SOL was found and insignificant interaction effect between the LEI and time on sleep parameters was observed. Hence, we reasoned that as the time spent in the laboratory accumulated, the participants psychologically adapted to interacting with the LEIs and the enclosed space sleep environment.

Assessing sleep performance relies on subjective and objective sleep outcomes. Firstly, although the joint assessment of wrist actigraphy and sleep diaries has been validated by many previous studies (including a comparison between actigraphy and PSG),[75,76] baseline differences of sleep parameters between groups at D8 were observed in this study. This outcome may be rooted in some factors including: (1) the implicit presence of individual differences under the four groupings; (2) the psychological adaptation to the enclosed space environment; (3) the explicit existence of data differences in the proportion of males among subgroups (see Figure 3). The three factors pointed more or less to the

limitations of the experimental protocol. It was worth mentioning that these estimated sleep parameters at D8–10 were evenly compared, but the observed differences between the baseline and the intervention were partially significant. The SOL served as an essential outcome variable. In addition, the lower correlated color temperature with higher illuminance nocturnal light environment helped to improve sleep quality,[77] yet we did not find similar effects of high illuminance and low CCT (#L3) on the sleep parameters. The reason for this might be due to the difference in spectral energy emitted by LEDs. Second, strong correlations were found between five estimated objective sleep parameters. Meanwhile, an EFA revealed that the subjective and objective sleep were not be equivalent. Therefore, combining subjective and objective sleep outcome evidence is necessary.

To our knowledge, this is the first study to explore the association between sleep performance and human states at different stages from a holistic viewpoint in the contextual LEI environment. The sleep phenomenon is a form of periodic restorative activity that is difficult to decipher.[35] Importantly, the process modelling applied in this study helped to construct time-dependent relationships. Sleep performance and human states constituted a coherent and predictive pathway. Quantitative path regression coefficients provided a predictive basis for accurately judging individual sleep performance associated with human states at prebedtime or awakening. One key finding in this study was that the SOL became a mediating predictor for the prebedtime state and objective sleep. Moreover, subjective sleep served as a predictor for the awakening state. A precise chained pathway can be iterated through further data collection and model upgrades.

There may be several limitations in this study. Although this experimental protocol did not allow for the use of cell phones or tablets, exposure to similar or shorter wavelength lighting outside the laboratory is difficult to fully control.[67,78] The potential effects of age groups[79] and gender[80] were excluded. The sample size is modest (n=48), and thus a cohort-based big data collection[81] will be considered in the future. Moreover, only a limited set of sleep-related variables was considered, and actigraphy-derived sleep parameters had serious limitations.[76] When measuring individual sleep performances, other potential metrics are worth exploring, such as sleep architecture, sleep continuity, deep sleep, and slow-wave sleep. Importantly, the current study did not have accurate data on daytime light and work intensity, but no vigorous exercise was emphasized in the informed consent and 3 participants are excluded in Figure 3. Given previous research, the combination of subjective and objective measurements was the best option.[79] This study was done in the laboratory, but the construction of time-dependent relationships still relied on the actual human performance in a high-fidelity field environment. The effects of LEI on participants were complicated, and seasonal effects might be omitted throughout the experiment. In a real-world maritime context, the external conditions (eg sea state) under which the actual ship is traveling may have an effect.

Conclusions

Our study reveals that sleep performance is associated with human states at prebedtime and awakening in the context of exploring the time-dependent effects of altered prebedtime light exposure in enclosed spaces on sleep performance, the SA, and the NA. The Time has a significant effect on subjective sleep and changes in prebedtime alertness. The SOL, as a critical sleep metric, plays a mediating predictor between prebedtime state and objective sleep, which is linked to the awakening state through subjective sleep.

Abbreviations

ANOVA, analysis of variance; CCT, correlated color temperature; CRI, color rendering index; CS, circadian stimulus; EEG, electroencephalography; EFA, exploratory factor analysis; EML, equivalent melanopic lux; EMM, estimated marginal means; GLM, general linear model; HVAC, Heating, Ventilation and Air Conditioning; ipRGCs, intrinsically photosensitive retinal ganglion cells; IQR, interquartile range; KSS, Karolinska Sleepiness Scale; LED, light-emitting diode; LEI, light exposure intervention; LSD, least significant difference; mEDI, melanopic equivalent daylight illuminance; MEQ, Ostberg's Morningness-Eveningness Questionnaire; NA, Negative affect; NA_Awakening, change in negative affect after waking up; NA_Prebedtime, change in negative affect before bedtime; NSSQ, Next-day Self-assessment Sleep Quality; PAD, Pleasure-Arousal-Dominance; PANAS, Positive and Negative Affect Schedule; PSA, Perceived sleep adequacy; PSG, polysomnography; PSQ, Perceived sleep quality; PSQI, Pittsburgh Sleep Quality Index;

SA, Subjective alertness; SA_Awakening, change in subjective alertness after waking up; SA_Prebedtime, change in subjective alertness before bedtime; SE, sleep efficiency; SEM, standard errors of the mean; SFI, sleep fragmentation index; SOL, sleep onset latency; TST, total sleep time; WASO, wake after sleep onset.

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Disclosure

The authors report no conflicts of interest in this work.

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