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Original Article

Gender Differences in the Effects of Adaptive Lighting on Heart Rate Variability and Cognitive Performance Among Night-Shift Nurses: A Between-Subjects Factorial Study

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Abstract

Introduction: Night-shift work disrupts circadian rhythms and exposes nurses to inadequate lighting, negatively affecting cognitive performance and physiological health. Circadian rhythm interventions, particularly those adapted to sex-specific responses, may help mitigate these risks. This study examined the effects of correlated color temperature (CCT), light intensity, and exposure duration on heart rate variability (HRV) and sustained attention in night-shift nurses, emphasizing gender differences.

Methods: Sixty-four nurses (32 men and 32 women) participated under controlled environmental conditions (22–24°C) with ergonomic seating. No randomization was performed for participant allocation, lighting condition, session timing, or condition sequence. Participants were allocated to eight experimental lighting conditions, with eight participants (four men and four women) in each condition. The lighting intervention consisted of eight conditions combining light intensities (500 and 1000 lux), CCT levels (3000 K and 6500 K), and exposure durations (10 and 20 minutes). The study used a $2 \times 2 \times 2$ between-subjects factorial design, and each participant was exposed to only one lighting condition. Experimental sessions were conducted between 11:00 PM and 1:00 AM. HRV indices and cognitive performance (2-back task, Psychomotor Vigilance Test) were measured before and after exposure. Changes from baseline to post-exposure were analyzed using three-way ANOVA to examine the effects of illuminance, CCT, and exposure duration, with appropriate non-parametric tests used for non-normally distributed outcomes. Statistical significance was set at $P<0.05$.

Results: Different lighting conditions elicited distinct autonomic responses according to sex. In women, CCT had significant effects on HR and SDNN, whereas in men, CCT significantly affected HR, SDNN, and RMSSD ($P<0.05$). In addition, several significant interactions among lighting parameters were observed for HRV indices($P<0.05$), with effect sizes (η^2) ranging from 0.17 to 0.45. Cognitive performance and sustained attention showed minor variations across lighting conditions; however, no significant main or interaction effects were observed for these variables ($P>0.05$).

Conclusion: These findings suggest that lighting characteristics may differentially affect autonomic responses during night-shift work according to sex. However, no significant effect on cognitive performance was observed, and larger studies are needed to confirm these findings.

Introduction

Night shifts constitute a critical component of healthcare systems as they ensure continuous patient care and maintain emergency preparedness. Nurses constitute the largest professional group involved in these shifts, accounting for approximately 30–40% of personnel working on rotating or permanent night schedules.[1,2] Working night shifts induce notable physiological alterations. These changes particularly affect the regulation of melatonin and cortisol, autonomic nervous system activity, and sleep-wake cycles. Numerous studies have documented elevated nocturnal cortisol levels, reduced heart rate variability (HRV), and

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increased sympathetic nervous system activity among night-shift nurses.[3-5] These physiological disruptions have been linked to impaired immune function, an elevated risk of metabolic and cardiovascular diseases, and may contribute to higher rates of occupational burnout within this population.[6-8]

Beyond physiological effects, night shift work significantly impairs cognitive functions. Nurses working night shifts frequently experience reduced alertness, diminished concentration, slower reaction times, and deficits in working memory and executive functions—factors that jeopardize patient safety.[9,10] Furthermore, chronic sleep deprivation resulting from insufficient restorative daytime sleep exacerbates these cognitive impairments, creating a vicious cycle of diminished performance and sustained physiological stress.[11,12]

Traditionally, hospital lighting has primarily addressed visual and operational needs, often overlooking the non-visual effects of light such as its influence on circadian rhythm regulation, alertness, mood, and cognitive function. Although bright, cool fluorescent lighting enhances clinical visibility, it can disrupt circadian alignment and adversely affect nurses' biological and psychological well-being.[13,14] Moreover, in many hospitals, patient room lights are dimmed or turned off around 11:00 PM to facilitate rest, resulting in ambient lighting levels at nursing stations falling below 100 lux. This inadequate illumination contributes to increased drowsiness, diminished concentration, and impaired cognitive performance among nurses, potentially compromising their responsiveness during emergencies.

Light plays a pivotal role in modulating mental workload, task performance, and physiological regulation, particularly in environments such as hospitals where demands are high.[15,16] Research indicates that exposure to bright and blue-enriched light can mitigate drowsiness, enhance alertness, and improve sustained attention factors essential for optimal cognitive performance during night shifts.[17] Furthermore, appropriate lighting during both daytime and nighttime can alleviate the adverse effects of sleep deprivation and mental fatigue, potentially boosting productivity.[18]

The effects of blue-enriched white light are contingent upon the timing of exposure. During the day, high correlated color temperature (CCT) lighting enhances alertness, cognitive function, and reduces evening fatigue.[19] However, nighttime exposure to blue-enriched white light suppresses sleepiness and disrupts melatonin secretion,[20] which may result in poorer sleep quality and increased fatigue.[21]

Findings on the influence of light intensity on cognitive performance remain inconclusive. For instance, Mohebian et al.[22] found that increasing illumination from 500 to 1500 lux enhanced attention and shortened reaction times, with optimal effects observed at 1500 lux. Similarly, Smolders et al.[23] reported that exposure to 1000 lux, compared to 200 lux, significantly reduced sleepiness, increased alertness, and improved mood, particularly under conditions of mental fatigue. However, while higher light intensities consistently improved alertness, other cognitive functions exhibited variable and occasionally adverse responses. In a field study conducted by Zare et al.[24] in a power plant control room, raising illumination from 200 to 400 lux decreased sleepiness, lowered mental workload, and reduced perceived effort, indicating enhanced cognitive performance. Additionally, Zhu et al.[25] found that lighting levels up to 1200 lux contributed to decreased sleepiness and improved cognitive function.

Research on the effects of color temperature has yielded inconsistent findings. For example, Motamedzadeh et al.[20] reported that exposure of petrochemical operators to blue-enriched white light with CCTs of 6,500 K and 17,000 K reduced sleepiness and enhanced cognitive functions such as working memory and sustained attention. Conversely, Zhu et al.[25] reported slower response times in attention and working memory tasks under 3,000 K lighting, but improved long-term memory performance with 6,500 K light during the afternoon. Similarly, Mills et al.[26] found that 17,000 K lighting increased vitality and decreased fatigue compared to 4,000 K lighting among office workers. In contrast, Knez[27] demonstrated superior short-term memory and problem-solving abilities under warm lighting relative to cool or daylight white lighting.

Findings on the effects of illumination duration and timing on alertness and cognition have been inconsistent. Smolders et al.[28] demonstrated that higher illumination levels enhance alertness, vitality, and heart rate irrespective of both exposure timing or duration. Similarly, Ye et al.[29] reported variations in alertness and cognitive performance with differing light intensities and color temperatures, while exposure duration showed no significant effect. Furthermore, Sasseville et al.[30] found that even a brief 30-minute exposure to light during nighttime, excluding blue wavelengths, can significantly increase alertness.

The observed cognitive and behavioral effects of light exposure underscore the necessity for further investigation into the underlying neurophysiological mechanisms. A comprehensive understanding of these processes is essential to elucidate how light modulates alertness and cognitive performance. The implementation of localized lighting systems with adjustable intensity and color temperature at nursing stations could effectively maintain alertness and mental readiness, thereby improving both safety and quality of healthcare delivery.

Neurophysiological research indicates that bright light exerts a significant influence on autonomic nervous system activity, which is primarily mediated by the suprachiasmatic nucleus (SCN) of the hypothalamus. This stimulation can elevate sympathetic nervous system activity while concurrently suppressing parasympathetic responses.[31] Lighting conditions that promote alertness, such as bright white or blue-enriched light, may mitigate the detrimental effects of mental workload on cognitive performance. Furthermore, short-term exposure to appropriate lighting could prevent long-term adverse outcomes associated with insufficient illumination, including retinal damage and eye strain.

However, the interaction between light quality factors such as intensity, CCT, and exposure duration and outcomes such as mental workload, cognitive function, and physiological responses during night shifts remains poorly understood. Further research is required to establish optimal lighting strategies. Physiological measures, including HRV, offer sensitive, non-invasive indicators of fatigue, stress, and cognitive load.[32-35] Empirical evidence supports this notion; for example, one study [36] found that increased illumination reduces both heart rate and electrodermal activity, with heart rate showing particular sensitivity to lighting changes. Additionally, Jiang et al.[37] reported that higher CCT lighting (6300 K) elevated galvanic skin response (GSR) and decreased heart rate, whereas lower CCT lighting (2700 K) elicited the opposite physiological effects.

Although research on the physiological and cognitive effects of light exposure has expanded, substantial gaps remain. Most previous studies have been conducted in controlled laboratory, office, or industrial setting,[38-40] which fail to capture the complexity of real hospital environments where multiple stressors such as irregular work schedules, high workloads, and inadequate lighting simultaneously affect health and performance. Furthermore, existing hospital lighting standards primarily focus on visual requirements and often neglect the non-visual dimensions of light including its effects on physiological regulation and cognitive performance which directly impact nurses' well-being and patient safety.[41] Another critical limitation is that most studies have emphasized long-term light exposure,[42,43] while short-term effects of lighting interventions on objective physiological markers (e.g., HRV) as well as cognitive outcomes in nursing populations remain largely underexplored. Moreover, the majority of studies have relied on ambient lighting conditions,[44] whereas localized adaptive lighting, particularly at nursing stations, has received limited attention.

Although evidence indicates that men and women exhibit significant biological differences in circadian rhythm regulation and stress responses, the role of sex in light sensitivity has received relatively little attention. Women generally display shorter intrinsic circadian periods and earlier phases of both body temperature and melatonin rhythms compared to men,[45,46] and the amplitude of these rhythms may vary depending on age and menstrual cycle phase. These sex-related differences likely arise from variations in the output of the suprachiasmatic nucleus, which contains sex steroid receptors, as well as from downstream differences in circadian pacemaker pathway, [45] Additionally, melatonin and cortisol secretion patterns differ between sexes, with women often showing greater susceptibility to circadian disruption.[47,48] Autonomic nervous system activity, including sympathetic and parasympathetic responses to stress, may also vary by sex,[49] potentially leading to distinct physiological and cognitive outcomes under different lighting conditions. These findings underscore the importance of considering sex as a moderating factor in lighting interventions.

Accordingly, the present study adopts a novel and integrative approach to examine the short-term effects of localized adaptive lighting with variations in intensity and CCT on physiological stress and cognitive performance in night-shift nurses. Furthermore, by exploring gender-based differences, this research aims to identify optimal lighting strategies that not only enhance nurses' occupational health but also improve the overall quality and safety of healthcare delivery. The findings are expected to provide evidence-based guidance for hospital lighting design that is practical, effective, and tailored to the diverse needs of healthcare workers.

Methods

Experimental condition

This experimental study was implemented using a Between-group design. Participants were recruited from the nursing unit of the hospital using convenience sampling based on the predefined inclusion criteria and their willingness to participate in the study. Each participant was evaluated only once during the study. The experiment was conducted in a room within the nursing station of a hospital. The room's walls were painted cream, and the ambient temperature was maintained between 22 °C and 24 °C. Ergonomic chairs were provided to ensure a calm and comfortable environment for participants. Experimental sessions were scheduled between 23:00 and 01:00, with each participant evaluated at a different time within this window. This time frame was chosen to coincide with the onset of melatonin secretion, as previous studies have reported the onset in salivary samples at approximately 22:30 ± 22 minutes and in plasma samples at approximately 21:50 ± 16 minutes. [50,51] Furthermore, this period corresponded to the midpoint of the participants' work shift, a time when fatigue and reduced alertness are typically at their peak.

The experiment was designed as a $2 \times 2 \times 2$ factorial design, between-subjects design, resulting in eight distinct experimental conditions. Each condition represented a unique combination of light intensity, color temperature, and exposure duration (as shown in Table 1). This experimental design enables the analysis of the main effects of each factor as well as the examination of their interactions. Consequently, it allowed for a precise evaluation of the independent and combined effects of these variables on dependent variables, including cognitive and physiological parameters.

Participants

In this study, 64 night-shift nurses (32 men and 32 women) who met the predefined inclusion criteria, including age under 60 years, normal or corrected vision, no history of severe ocular diseases or cardiovascular or other systemic disorders, at least two years of night-shift work experience, abstinence from nicotine, alcohol, or stimulants during the 24 hours before testing, and absence of self-reported sleep problems, psychological distress, or acute stress were recruited from the participating hospital units. All eligible nurses were invited to participate, and all agreed

Table 1. The eight-cell matrix of experimental conditions and Lighting parameters of different intervention scenes

CCT(K)		3000		6500	
Illuminance (Lux)		**500**	**1000**	**500**	**1000**
Time (min)	10	A	C	E	G
	20	B	D	F	H

*Time = exposure duration

to participate; therefore, there were no refusals during recruitment. A formal a priori sample-size calculation was not performed; the final sample size was based on the number of eligible nurses available and the feasibility of recruitment.

The mean age of participants was 40.91 years, with a standard deviation of 5.24 years. Following selection, participants were assigned to eight groups of 8 individuals each, with an equal gender distribution in each group. The general health status of all participants was assessed through self-report questionnaires, confirming the absence of any physical illnesses, psychological disorders, or sleep issues. Participation in the study was entirely voluntary, based on written informed consent. This research protocol was approved by the university's ethics committee under the code IR.SUMS.SCHEANUT.REC.1402.152, and all procedures were conducted in compliance with established ethical guidelines to fully protect the confidentiality and privacy of participants' personal information.

Intervention

The intervention consisted of eight distinct lighting conditions, with each participant exposed to only one lighting condition during a single experimental session (Table S1). In this study, localized lighting provided by a custom-designed light box was employed to assess the effects of lighting conditions on the dependent variables. The light box was constructed from medium-density fiberboard (MDF) with dimensions of measuring $40 \times 40 \times 50$ cm. It was designed to allow adjustments of light intensity and CCT. The box was structured as a closed unit, with only one side open toward the display surface, while the remaining sides were fully enclosed. This design ensured that light was focused solely on the work surface, preventing dispersion or leakage into the surrounding environment. Consequently, controlled and concentrated localized lighting conditions were established, enabling precise evaluation of their impact on participants' cognitive and physiological indices.

The light box used in this study was equipped with two Surface-Mounted Diode (SMD) lamps, with color temperatures of 3,000 K and 6,500 K, capable of producing light intensities ranging from 500 to 1,000 lux, as required by the experimental conditions. According to the standards of the Illuminating Engineering Society of North America (IESNA), the recommended illuminance level for nursing stations ranges from 300 to 500 lux. In this study, 500 lux was selected as the upper limit of this range, and 1,000 lux was chosen as a higher level, typically used in high-traffic areas such as emergency departments.[52] Additionally, the lamps had a Color Rendering Index (CRI) of 85, consistent with hospital lighting standards, ensuring accurate color representation. The selection of these illuminance levels and CRI was based on ergonomic requirements, technical considerations, and energy efficiency metrics to create a standardized, uniform, and feasible lighting environment.[53] Furthermore, the light box was equipped with a dimmer and control switches, enabling precise adjustment of light intensity and indirect light direction. Finally, the designated illuminance levels (500 and 1,000 lux) were accurately measured and verified at the work surface using a calibrated lux meter (Model EC1).

The light intensity was precisely measured at the work surface using a calibrated lux meter. The primary source of ambient lighting was a ceiling fluorescent lamp, with a CCT of 2700 K, providing a background illuminance of approximately 70 lux. The only differentiating factor in participants' light exposure was the localized lighting provided by the light box. This lighting was uniformly applied at a fixed distance of 50 cm from the work surface for all individuals, the distance was selected based on the experimental setup conditions to achieve the target illuminance level while minimizing visual glare. This localized lighting was adjusted to illuminate only the work surface, thereby preventing direct glare or intrusive light from affecting the participants' eyes. Thus, while adhering to ergonomic principles and ensuring visual comfort, this experimental setup allowed for a precise evaluation of the effects of lighting conditions on dependent variables.

The results of the calculated circadian stimulus (CS) under different lighting conditions are presented in Table 2. As shown, under warm light with a CCT of 2700 K, the CS value was 0.05, indicating a negligible effect on circadian rhythm. Under cool light with a CCT of 6500 K, an increase in illuminance raised the CS from 0.2 to 0.35, reflecting a moderate influence on melatonin suppression. Furthermore, at an intermediate CCT of 3000 K, CS values ranged between 0.2 and 0.3, suggesting a moderate effect of light in these conditions.

Experimental protocol

Prior to the commencement of the measurement procedure, participants spent 10 minutes in the testing room to acclimate to the experimental environment. During this period, they received detailed instructions regarding the experimental protocol and were connected to the equipment used for recording cognitive and physiological indices. Following the acclimatization and preparation period, baseline cognitive performance was assessed for 15 minutes. Subsequently, baseline HRV was recorded

Table 2. Lighting parameters of different intervention scenes

Variable	CCT(k)	Illuminance of Working Plane/lx	Vertical Illuminance at the Eyes/lx	Melanopic EDI/lx	Circadian Stimulus, CS
Room Light Source	2700	70.53	29.48	13.3	0.05
Light Source Under Test	6500	508.26	207.38	186.6	0.2
		1009.21	406.67	366	0.35
	3000	498.76	204.31	132.8	0.2
		1016.42	404.72	263.1	0.3

for 5 minutes. Each participant was then exposed to a specific combination of light intensity, CCT, and exposure duration, as detailed in Table 1. The exposure duration was determined by the experimental group to which the participant was assigned, with each participant undergoing either 10 or 20 minutes of light exposure. Immediately after the completion of the exposure period, cognitive performance was reassessed for 15 minutes, followed by a 5-minute HRV recording. Demographic and standardized questionnaires were administered to assess participants' initial state.

Figure 1 (Section A1) illustrates the workstation where participants performed the assigned tasks. Additionally, a schematic floor plan of the experimental room is provided to depict the spatial arrangement of the lighting equipment and workstation components (see Figure 1, Section A2).

Testing methods

Physiological Indices

The wireless Nexus-4 biofeedback and neurofeedback system, depicted in Figure 1, was employed to measure physiological variables, including HRV. HRV measures derived from electrocardiogram (ECG) recordings are widely recognized as valid and reliable indicators of autonomic nervous system activity and have been extensively validated in previous research.[54,55] HRV was selected as it provides a non-invasive and sensitive index of autonomic nervous system regulation, which is closely associated with both physiological and cognitive changes during experimental interventions.

In this study, the key HRV consisted of included heart rate (HR), standard deviation of normal-to-normal intervals (SDNN), root mean square of successive differences (RMSSD), percentage of intervals differing by more than 50 milliseconds (PNN50), and the low-frequency to high-frequency ratio (LF/HF). These HRV indices have shown strong validity and reliability in previous research.[56,57] HR, defined as the number of heart beats per minute, serves as a fundamental indicator of cardiovascular activity. SDNN reflects overall variability in heartbeat timing, providing a measure of autonomic nervous system balance. RMSSD quantifies short-term variations between consecutive heartbeat intervals, closely associated with parasympathetic nervous system activity. PNN50 quantifies the percentage of consecutive heartbeat intervals differing by more than 50 milliseconds, indicative of short-term variability and parasympathetic function. The LF/HF ratio, representing the relationship between low-frequency and high-frequency components, serves as a critical index for evaluating autonomic nervous system modulation.[58]

Electrodes were placed at specific points on the body to capture electrocardiogram (ECG) signals, and the data were processed and analyzed in real-time using BioTrace software. The software automatically identified and removed unwanted noise and artefacts from the recorded signals before to analysis. The IBI series were detrended and interpolated at 4 Hz for frequency-domain analysis. Spectral power was calculated using a 1024-point Fast Fourier Transform (FFT) over the 0–0.40 Hz frequency range. The frequency bands were defined as low frequency (LF: 0.04–0.16 Hz) and high frequency (HF: 0.16–0.40 Hz). This system enabled continuous and real-time monitoring and analysis of participants' physiological responses during the intervention. This system enabled continuous and real-time monitoring and analysis of participants' physiological responses during the intervention.

Cognitive ability test

Cognitive performance was assessed using the standardized 2-back test, which measures working memory,[59,60] and the Psychomotor Vigilance Test (PVT).[61] These cognitive tasks have been widely validated in previous studies, demonstrating strong evidence of both reliability and construct validity. [61-63] In the 2-back task, 120 stimuli (digits 1–9) were displayed on a screen with an inter-stimulus interval of 1500 ms. Participants compared each current digit with the one presented two trials earlier and, if the two matched, pressed a designated button as quickly as possible. The task lasted four minutes. Previous research has demonstrated the high validity and reliability of this test. [64] In accordance with the method proposed by Kim the learning performance index was calculated using the results from the n-back test. This index combined two key metrics accuracy and response time to produce an overall score integrating both speed and precision, thereby providing a more comprehensive measure of learning ability (Equation 1),[65]

Equation 1: $\text{Task performance} = \left(\sqrt{accuracy} \Big/ \sqrt{response\,time} \right) \text{^} 2$

where Accuracy is the proportion of correct responses (ranging from 0 to 1) and Response time is the mean response time (in seconds) for correct responses only. Higher values of this index indicate better overall task performance by integrating both speed and precision.

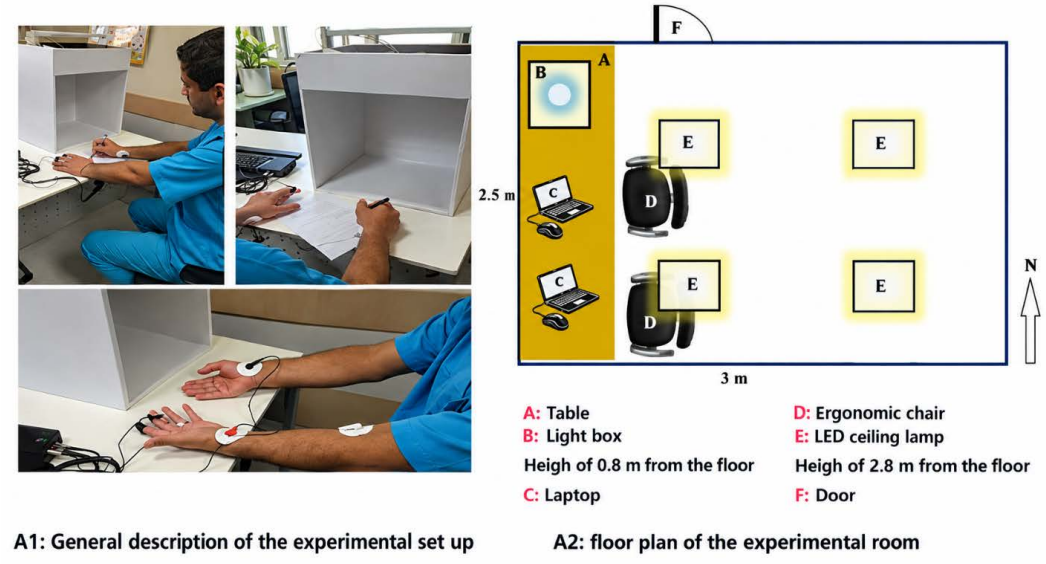


Figure 1. experimental set up

The PVT was used to measure alertness, sustained attention, and changes in cognitive function. [66,67] A duration of seven minutes was selected for the PVT. Pre-test results indicated that this duration provided an optimal balance between ensuring data accuracy and minimizing participant fatigue or loss of concentration, even though the software permitted durations ranging from four to ten minutes. During the task, red circles appeared on the screen at random intervals of 2 to 10 seconds. Participants were required to press the space bar with their dominant hand as quickly as possible upon seeing the target stimulus. If no response was recorded within 1750 ms, the next stimulus was automatically presented. Additionally, responses made within 120 ms or less were discarded, and an audible warning was played. This test has shown high reliability in previous studies for assessing performance, sleepiness, and fatigue.[68,69]

Statistical Analysis

All statistical analyses were conducted using SPSS version 21 and GraphPad Prism version 10. Initially, data normality was assessed using the Shapiro-Wilk test. Analyses were performed separately for males and females (stratified by sex). For each sex, changes before and after the intervention within each experimental condition were evaluated using paired t-tests for normally distributed data and Wilcoxon signed-rank tests for non-normally distributed data.

To examine the effects of the three independent factors (light intensity, color temperature, and exposure duration: 10 vs. 20 min), three-way ANOVA was applied to parametric data. Significant main effects or interactions were followed by post-hoc pairwise comparisons using Tukey's HSD test. For non-parametric data, the Kruskal–Wallis test (or Friedman test when appropriate) was used, and significant results were followed by Mann–Whitney U tests with Bonferroni correction to control for multiple comparisons. No primary endpoint was prespecified given the exploratory nature of the study.

Results

In order to assess the impact of various lighting patterns on the human body, three physiological and cognitive parameters were independently examined: psychomotor vigilance (PVT), working memory performance (N-back), and HRV. Analysis of the participants' demographic characteristics revealed no statistically significant differences among the study groups in terms of age, body mass index (BMI), years of shift work experience, or mental workload ($P > 0.05$). These findings indicate homogeneity across the groups with respect to these variables, ensuring that the observed changes in dependent variables were influenced by the intervention of independent factors rather than background variables or external confounding factors. Detailed statistical information regarding these indices is presented in Table 3.

Changes in Physiological Parameters Pre- and Post-Intervention

Tables 4 and 5 present the comparisons of the mean values of heart rate (HR) and HRV indices across different light exposure trials, before and after the intervention, in women and men, respectively. The results demonstrate statistically significant differences in certain trials, particularly among female participants.

Among women, significant changes were observed in HRV indices such as SDNN, RMSSD, and PNN50 under specific lighting conditions. In Trial 5 revealed significant decrease in SDNN ($P = 0.04$) and RMSSD ($P = 0.003$). The LF/HF ratio remained statistically unchanged across most trials ($P > 0.05$), although a decreasing trend was observed in Trial 8. Overall, these findings highlight that Trials 5,6 and 7 elicited the most notable physiological responses in women, suggesting that SDNN and RMSSD are particularly sensitive markers for evaluating the effects of light exposure in this group.

In men, although fewer statistically significant changes were detected compared to women, some notable alterations

Table 3. Basic information in the study groups

Study participants (Number)	Mean (SD)							
	Age (Years)		Working years of shifts (Years)		BMI (kg/m²)		Mental workload (NASA-TLX)	
	Women	Men	Women	Men	Women	Men	Women	Men
Trial (1): A	41.75(6.55)	39.66(2.08)	12(9.27)	9.33(4.93)	21.4(3.86)	25.33(1.52)	85.75(7.5)	87.66(2.1)
Trial (2): B	42.6(5.68)	42.5(2.7)	13.6(6.34)	17.5(2.7)	23.52(2.9)	27.34(1.9)	80.8(4.32)	89.5(2.12)
Trial (3): C	42.5(4.04)	42(3.6)	14.25(7)	10.33(3.2)	24.47(1.7)	23.66(3.05)	81.75(3.94)	80(2)
Trial (4): D	37(3)	3 9.5(6.36)	12.8(7.85)	13(4.24)	23.31(2.7)	23(1.41)	78(3.4)	87(4.24)
Trial (5): E	42.25(3.86)	40.33(4.04)	16.25(3.5)	10.66(2.1)	21.64(1.7)	23.35(1.56)	85.75(5)	79.66(3.78)
Trial (6): F	41.3(6.24)	38(3.53)	8(6.05)	16(4.04)	23.4(2.46)	23.2(0.83)	79.8(6.55)	85.6(4.82)
Trial (7): G	43(4.7)	42.7(7.4)	7(5.35)	16(4.58)	23(1.01)	22(1)	80.7(5.12)	89.7(6.5)
Trial (8): H	40.8(7.93)	40.6(7.5)	10.75(4.4)	12(2.64)	25.37(1.8)	24.66(1.53)	85.25(3.3)	87.33(3.51)
P-value*	0.17	0.12	0.31	0.15	0.29	0.22	0.5	0.26

Note: Each lighting condition included 8 participants, comprising 4 women and 4 men.
* One-way ANOVA

Table 4. Comparison of the Mean and Standard Deviation of Heart Rate Variables Across Different Trials, Before and After Intervention in Women

Variable (Unit)			Mean (SD)			Mean (SD)			Mean (SD)			Mean (SD)					
			HR (bpm)		*P* value	SDNN (ms)		*P* value	RMSSD (ms)		*P* value	Pnn50		*P* value	LF/HF (ratio)		*P* value
CCT (K)	Light (lux)	Time (min)	Before	After		Before	After		Before	After		Before	After		Before	After	
3000	500	10	66.21 (4.01)	63.07 (2.73)	0.14▼	162.4 (97.38)	109.14 (122.15)	0.054▼	154.67 (89.54)	100.16 (107.01)	**0.012▼**	39.25 (11.17)	26.56 (17.9)	0.37▼	4.78 (2.35)	4.23 (1.72)	0.67▼
		20	64.71 (4.16)	64.5 (1.91)	0.85 ▼	100.72 (98.5)	137.72 (95.77)	0.069▲	91.61 (92.66)	117.7 (77.39)	0.09▲	26.7 (12.59)	30.62 (19.71)	0.44▲	4.18 (1.52)	3.9 (1.22)	0.81▼
	1000	10	72.41 (3.87)	75.06 (5.74)	0.39▲	162.66 (116.74)	163.96 (26.83)	0.98▲	166.86 (115.75)	179.1 (12.55)	0.84▲	15.82 (12.28)	39.66 (14.38)	**0.001▼**	2.15 (1.59)	3.2 (1.76)	0.59▲
		20	71.65 (3.02)	74.08 (4.1)	0.23▲	168.42 (76.74)	117.58 (115.1)	0.08▼	205.72 (111.02)	130.16 (130.81)	**0.009▼**	45.6 (22.44)	33.27 (25.65)	0.08▼	1.52 (0.19)	2.5 (1.86)	0.33▲
6500	500	10	68.8 (1.66)	79.3 (8.55)	0.06▲	243.27 (124.9)	117.64 (106.82)	**0.04▼**	255.04 (128.45)	143.28 (131.84)	**0.03▼**	53.95 (19.29)	36.88 (19.98)	0.12▼	3.35 (2.86)	4.05 (2.18)	0.48▲
		20	69.3 (5.45)	74.37 (5.18)	0.13▲	179.64 (94.78)	107.4 (22.83)	0.16▼	219.22 (163.5)	100.86 (47.54)	0.13▼	60 (8.16)	45 (5.77)	**0.014▼**	5.65 (1.13)	8 (1.25)	0.14▲
	1000	10	69.31 (2.57)	74 (3.5)	**0.009▲**	260.56 (14.12)	201.62 (30.8)	**0.007▼**	307.78 (4.34)	258.72 (54.91)	0.18▼	66.84 (10.24)	66.83 (6.32)	0.93▼	2.15 (0.63)	3.08 (1.65)	0.2▲
		20	73.66 (2.19)	70.25 (3.56)	0.19 ▼	144.53 (74.47)	143.49 (87.21)	0.93▼	125.73 (87.35)	155.12 (89.83)	**0.026▲**	43.25 (5.27)	38.89 (6.68)	0.06▼	8.87 (3.71)	5.05 (1.1)	0.13▼

Change (Δ) = After Mean – Before Mean ▼ Decrease (Δ < 0) ▲ = Increase (Δ > 0)

Table 5. Comparison of the Mean and Standard Deviation of Heart Rate Variables Across Different Trials, Before and After Intervention in men

Variable (Unit)			Mean (SD)			Mean (SD)			Mean (SD)			Mean (SD)					
			HR (bpm)		*P* value	SDNN (ms)		*P* value	RMSSD (ms)		*P* value	Pnn50		*P* value	LF/HF (ratio)		*P* value
CCT (K)	Light (lux)	Time (min)	Before	After		Before	After		Before	After		Before	After		Before	After	
3000	500	10	75.81 (3.94)	78.62 (0.95)	0.27▲	74.03 (35.31)	78.44 (54.8)	0.7▲	61.67 (26.57)	81.61 (59.98)	0.4▲	14.16 (16.17)	12.28 (12.52)	0.81▼	3 (2.4)	2.27 (1.17)	0.61▼
		20	71.82 (2.58)	74.77 (2.99)	0.59▲	257.2 (216)	123.2 (109.9)	0.32▼	434.63 (445.71)	220.23 (231.34)	0.38▼	72.85 (50.48)	51.52 (21.46)	0.48▼	5.55 (7.13)	3.55 (3.89)	0.54▼
	1000	10	76.97 (3.54)	76.3 (3.02)	0.49▼	141.86 (84.76)	85.47 (27.15)	0.42▼	147.59 (89.52)	80.87 (48.09)	0.44▼	34.8 (15.76)	21.51 (15.12)	0.41▼	2.8 (2.38)	2.97 (2.24)	0.92▲
		20	73.75 (3.5)	72.95 (3.6)	0.07▼	137.42 (11.44)	66.97 (65.08)	0.31▼	163.3 (39.96)	83.72 (87.98)	0.25▼	30.68 (20.17)	20.77 (20.36)	**0.006▼**	1.55 (0.35)	2.45 (2.19)	0.61▲
6500	500	10	69.89 (6.48)	71.44 (1.4)	0.67▲	87.44 (40.47)	65.32 (56.83)	0.21▼	96.06 (57.18)	75.34 (71.82)	0.28▼	18.6 (10.69)	15.61 (13.29)	0.23▼	2.7 (1.55)	2.57 (1.11)	0.71▼
		20	76.15 (10.91)	71.1 (5.94)	0.14▼	53.91 (19.13)	107.16 (81.33)	0.17▲	57.08 (28.96)	97.67 (71.67)	0.25▲	22.92 (15.38)	26.96 (15.15)	0.59▲	2.72 (1.52)	4.54 (2.21)	0.23▲
	1000	10	84.77 (1.51)	73.72 (5.49)	0.11▼	88.18 (16.41)	162.42 (8.37)	**0.019▲**	120.26 (1.75)	213.84 (5.63)	**0.001▲**	41.4 (1.55)	57.61 (1)	**0.002▲**	6.3 (0.17)	1.07 (0.23)	<0.001▼
		20	75.53 (3.67)	70.26 (5.57)	0.42▼	169.93 (80.44)	160.8 (94.92)	0.68▼	156.38 (85.36)	185.21 (92.53)	0.06▲	45.97 (1.3)	39.5 (5)	0.12▼	12.4 (13.3)	6.37 (5.72)	0.3▼

Change (Δ) = After Mean – Before Mean ▼ Decrease (Δ < 0) ▲ = Increase (Δ > 0)

were observed. In Trial 7 resulted in a significant increase in SDNN ($P = 0.019$) and RMSSD ($P = 0.001$), PNN50 ($P = 0.002$) and a decrease in LF/HF ratio ($P < 0.001$), suggesting a shift toward sympathetic dominance under

this lighting condition.

In contrast, the HR variable did not exhibit significant changes in most trials for men, and the LF/HF ratio remained stable except in Trial 7. These findings suggest enhanced parasympathetic modulation or reduced sympathetic predominance under this lighting condition. SDNN, RMSSD, and PNN50 appeared to be the most responsive HRV indices in men.

The results of examining changes in physiological indices related to autonomic nervous system activity following short-term exposure to various lighting conditions revealed significant differences in the responses of female and male night-shift nurses. The heart rate index (ΔHR) showed an increasing trend in most female groups, indicating activation of the sympathetic branch of the nervous system, whereas males predominantly experienced a decrease in heart rate, which may suggest a calming effect on the cardiovascular system. In the SDNN index, a general measure of heart rate variability, males, particularly in groups 6 and 7, exhibited significant increases, while females in the middle groups experienced notable decreases. Additionally, RMSSD, an indicator of parasympathetic activity, showed an initial decrease followed by a recovery trend in males, whereas females generally displayed negative values. The PNN50 index increased in males, especially in the final groups. Finally, the LF/HF ratio, which reflects the balance of sympathetic to parasympathetic activity, decreased in both genders in the final groups, but the magnitude of this reduction was more pronounced in males. These findings suggest that males exhibit more stable and adaptive physiological responses to specific lighting conditions compared to females, highlighting the importance of considering gender differences in designing lighting interventions for night-shift work environments (Figure 2).

The results of the three-way ANOVA of pre–post change scores indicated differential effects of light intensity, color temperature, and exposure duration both individually and in interaction on heart rate variability indices among women and men. In women, the overall model was significant for HR, SDNN, RMSSD, and PNN50, while no significant effect was observed for the LF/HF ratio. Among the main effects, only color temperature showed a significant influence on HR ($P = 0.02$), whereas light intensity and exposure duration did not have significant main effects. However, the interaction between color temperature and light intensity (C × L) revealed significant effects on HR, RMSSD, and LF/HF, highlighting the importance of combined lighting characteristics in influencing cardiac autonomic regulation in women.

In men, the overall model approached significance for SDNN, RMSSD, and the LF/HF ratio. Color temperature had a significant main effect on HR ($P = 0.023$), SDNN ($P = 0.003$), and RMSSD ($P = 0.002$), while light intensity showed a marginal effect on HR ($P = 0.059$) but no significant effect on other indices. Importantly, the interaction between color temperature and exposure duration (C × L) significantly affected the LF/HF ratio ($P = 0.01$), and the three-way interaction (C × L × T) significantly influenced RMSSD ($P = 0.019$) and SDNN($P = 0.014$). Overall, these findings suggest that light intensity and color temperature particularly through their interactions play a crucial role in modulating autonomic and cardiovascular responses, whereas exposure duration alone does not exert a significant effect. Full results are presented in Table 6.

Post-hoc analyses using the Bonferroni adjusted means and 95% confidence intervals were conducted for the ΔHRV variables, including HR, SDNN, RMSSD, PNN50, and LF/HF Ratio. For female participants, Δ.HR significantly increased under the 6500 K condition (M = 4.08, 95% CI [1.74, 6.43], Bonferroni-adjusted $P = 0.028$). A significant interaction effect of (CCT × Lighting) was also found, indicating a significant increase in Δ.HR under the 6500 K and 500 lux condition (M = 7.54, 95% CI [3.78,

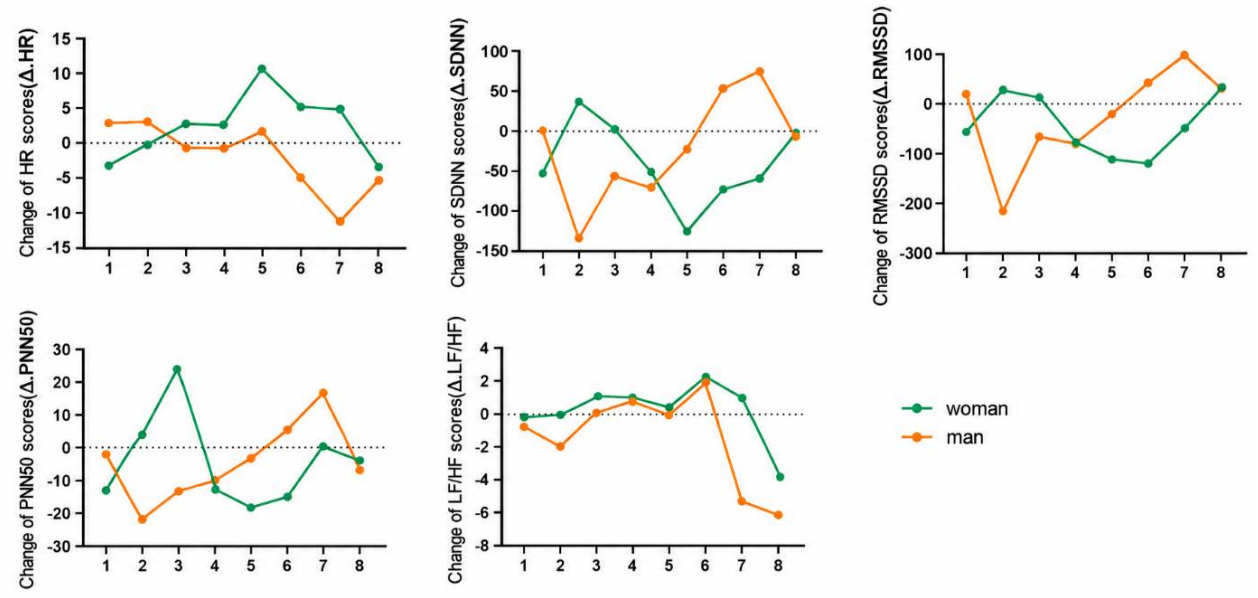


Figure 2. Changes in HRV scores under different lighting conditions during the experimental session

Table 6. Three-way ANOVA results for changes in heart rate variables in women and men

Women	HR (bpm)			SDNN (ms)			RMSSD (ms)			PNN50(%)			LF/HF (ratio)		
Variable(unit)	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**
Corrected model	4.73	**0.002**	0.56	3.49	**0.009**	0.48	3.09	**0.016**	0.45	3.5	**0.009**	0.48	2.11	0.078	0.36
C	6.17	**0.02**	0.19	5.57	**0.026**	0.17	3.72	0.065	0.12	3.56	0.072	0.12	0.01	0.93	0
L	0.94	0.34	0.03	1.31	0.26	0.05	2.92	0.09	0.1	3.31	0.08	0.11	0.75	0.39	0.02
T	3.13	0.08	0.11	3.95	0.057	0.13	0.57	0.45	0.02	0.88	0.35	0.03	0.6	0.44	0.02
C*L	12.84	**0.001**	0.33	6.85	0.061	0.13	5.69	**0.025**	0.18	0.08	0.77	0.003	5.93	**0.022**	0.18
C*T	7.98	**0.009**	0.24	1.11	0.3	0.04	0.82	0.37	0.03	1.21	0.28	0.04	0.79	0.38	0.03
L*T	0.62	0.44	0.02	2.82	0.1	0.1	0.28	0.59	0.01	7.68	**0.01**	0.23	4.22	0.05	0.14
C*L*T	0.008	0.93	0	3.26	0.08	0.11	8.45	**0.007**	0.25	6.97	**0.014**	0.21	3.49	0.07	0.12
Men	**HR (bpm)**			**SDNN (ms)**			**RMSSD (ms)**			**PNN50**			**LF/HF (ratio)**		
Variable(unit)	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**	**F**	***P* value**	**η^2**
Corrected model	2.12	0.1	0.48	3.37	**0.021**	0.59	3.57	**0.016**	0.61	1.33	0.29	0.36	2.23	0.087	0.49
C	6.33	**0.023**	0.28	11.8	**0.003**	0.42	13.12	**0.002**	0.45	4.41	0.052	0.21	1.85	0.19	0.1
L	4.12	**0.059**	0.2	0.13	0.72	0.01	1.28	0.27	0.07	0.08	0.77	0.01	2.48	0.13	0.13
T	0.01	0.9	0.001	2.44	0.14	0.13	3.53	0.078	0.18	1.13	0.3	0.06	0.01	0.91	0
C*L	0.37	0.55	0.023	0.1	0.76	0.01	0.17	0.68	0.01	0.04	0.84	0.01	8.3	**0.01**	0.34
C*T	0.003	0.96	0	1.98	0.17	0.11	3.3	0.08	0.17	0.01	0.93	0	0.08	0.77	0
L*T	1.47	0.24	0.08	0.11	0.74	0.01	0.52	0.47	0.03	0.13	0.72	0.01	0.01	0.89	0
C*L*T	1.79	0.19	0.1	7.6	**0.014**	0.32	6.78	**0.019**	0.3	3.56	0.07	0.18	0.67	0.42	0.04

11.31], $P = 0.001$). Moreover, a significant interaction of (CCT × Time) emerged, such that Δ.HR significantly increased in the 6500 K and 10-minute condition (M = 7.57, 95% CI [4.77, 10.38], $P = 0.012$). No other effects were statistically significant.

In men, the results indicated that CCT had a significant effect on Δ.HR. Specifically, under lighting conditions with a color temperature of 6500 K, the mean Δ.HR was significantly reduced (95% CI: -8.28 to -1.62, Bonferroni-adjusted $P = 0.023$). These findings suggest that higher color temperature lighting can lead to a substantial decrease in HR.

In women, exposure to lighting with a color temperature of 6500 K resulted in a significant reduction in mean Δ. SDNN compared with 3000 K (95% CI: -96.15 to -33.10). In men, exposure to lighting with a color temperature of 3000 K resulted in a mean Δ. SDNN of -64.11 (95% CI: -105.58 to -22.64), which demonstrates a significant reduction. Furthermore, the interaction of CCT, light intensity, and time had a significant effect on Δ. SDNN ($P = 0.014$). Under 3000 K and 500 lux, the mean Δ. SDNN significantly decreased at 20 minutes (M = -133.99, 95% CI: -224.85 to -43.13). Conversely, under 6500 K and 1000 lux, the mean Δ. SDNN significantly increased at 10 minutes (M = 74.24, 95% CI: 0.05 to 148.43). No other conditions showed significant changes.

The effects of CCT, light intensity, and exposure duration on RMSSD were condition-dependent in both females and males. In females, the interaction between CCT and light intensity revealed that low-intensity cold light (6500K, 500 lux) significantly decreased RMSSD (Mean = -119.99; 95% CI = [-180.70, -59.29], $P = 0.013$), whereas other combinations showed no significant effects, indicating a negative impact of low-intensity cold light on parasympathetic cardiac activity. Additionally, the three-way interaction of CCT, light intensity, and exposure time showed condition-dependent effects, with low-intensity cold light significantly decreasing RMSSD at 10 and 20 minutes (Means = -111.27 and -128.72; 95% CIs = [-181.36, -41.17] and [-227.85, -29.59], respectively), and high-intensity warm light (3000K, 1000 lux) significantly reducing RMSSD at 20 minutes (Mean = -74.76; 95% CI = [-137.45, -12.07]). In males, warm light (3000K) significantly decreased RMSSD (Mean = -85.38; 95% CI = [-139.26, -31.50]), while cold light (6500K) had no significant effect. The three-way interaction revealed that only low-intensity warm light (3000K, 500 lux) at 20 minutes significantly decreased RMSSD (Mean = -214.41; 95% CI = [-332.45, -96.36]), with no other significant changes observed. These findings indicate sex-specific modulation of parasympathetic cardiac activity, with females showing heightened sensitivity to low-intensity cold light and males being primarily affected by prolonged exposure to low-intensity warm light.

The interaction between light intensity and exposure time on PNN50 in females revealed that low-intensity light (500 lux) at 10 minutes significantly decreased PNN50 (Mean = -14.87; 95% CI = [-25.74, -4.01]), whereas, in contrast, low-intensity light at 20 minutes and high-intensity light (1000 lux) at both 10 and 20 minutes exhibited no significant effects. Furthermore, the three-way interaction of CCT, light intensity, and exposure time indicated that high-intensity warm light (3000K, 1000 lux) significantly increased PNN50 at 10 minutes (Mean = 24.10;

95% CI = [8.74, 39.47]), but the same light significantly decreased PNN50 at 20 minutes (Mean = -15.97; 95% CI = [-29.71, -2.22]). Additionally, low-intensity cold light (6500K, 500 lux) significantly reduced PNN50 at 10 minutes (Mean = -16.56; 95% CI = [-31.93, -1.20]), while other combinations showed no significant effects.

The interaction between CCT and light intensity on LF/HF showed that, in females, none of the combinations of warm or cold light with low or high intensity (3000K and 6500K; 500 and 1000 lux) produced significant changes in LF/HF. This indicates a stable autonomic balance between sympathetic and parasympathetic activity under varying light conditions. In contrast, in males, only high-intensity cold light (6500K, 1000 lux) significantly decreased LF/HF (Mean = -5.63; 95% CI = [-8.60, -2.66]), whereas other combinations showed no significant effects. These findings suggest that autonomic responses to variations in color temperature and light intensity differ between females and males.

Changes in Cognitive Performance Pre- and Post-Intervention

Task performance test

Evaluation of participants' cognitive performance in task-based tests revealed that, in both female and male groups, a relative improvement in performance scores was observed following exposure to various lighting conditions. In the female group the largest increase in performance was recorded in trial 5. In the male group, while changes were more uniform and of lesser magnitude compared to females, a slight increase in performance was observed in most groups after light exposure, particularly in trials 5 and 6. However, these increases were not statistically significant, and the three-way ANOVA showed no significant main or interaction effects of CCT, light intensity, or exposure duration on task performance. For a visual representation of performance changes, refer to Figure 3. For a visual representation of performance changes, refer to Figure 3.

The results of the three-way ANOVA clearly indicated that the independent variables, including CCT, light intensity, and exposure duration, neither individually nor interactively had a statistically significant effect on participants' performance (task performance) ($P > 0.05$). In the female group, the overall model was not statistically significant (F (7, 26) = 0.841, $P = 0.564$), with an R^2 value of 0.185, indicating that only 18.5% of the variance in performance was explained by the model. Similarly, in the male group, no significant effects were observed (F (7, 16) = 0.757, $P = 0.630$), with the model accounting for 24.9% of the variance ($R^2 = 0.249$). Moreover, none of the main effects or interaction effects between the variables reached statistical significance in either group, suggesting that variations in lighting conditions and exposure time did not produce meaningful differences in participants' task performance under the present experimental settings.

Psychomotor Vigilance Test (PVT)

Analysis of participants' sustained attention performance based on the PVT results revealed that exposure to different lighting conditions led to noticeable changes in cognitive performance post-intervention. In the first part of the test, which measured the number of errors, a notable reduction was observed in the female group. In particular, trials 1 through 4 and trial 8 showed a clear decline in error count after light exposure, indicating improved accuracy and fewer attentional lapses. In contrast, the pattern among the male participants was more heterogeneous, with some groups showing increased errors while others showed reductions. Notably, Group 8 in the male group exhibited a sharp increase in error count post-exposure.

In the second part of the test, assessing mean reaction time (RT), different patterns emerged. Among women, a slight increase in RT was observed in most groups, particularly trials 6 and 8. This may suggest a more cautious response strategy following light exposure. In the male group, RT exhibited a general decrease, with the most pronounced reduction occurring in trials 4 through 6, indicating an overall enhancement in response speed following exposure to light.

Taken together, these findings suggest that short-term exposure to various lighting conditions can reduce attention-related errors, especially among female participants. However, its impact on reaction time appears more variable and may depend on specific lighting parameters and individual characteristics. Detailed results are illustrated in Figure 4.

A three-way ANOVA was conducted separately for male and female participants to examine the effects of CCT, light intensity, and time on sustained attention performance, measured by Δ.PVT (number of error). Among female participants, the overall model was not statistically significant, F (7, 16) = 0.584, $P = 0.760$, with a

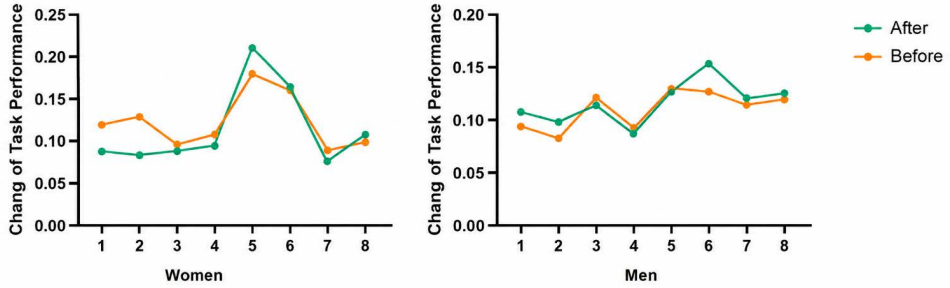


Figure 3. Changes of task performance

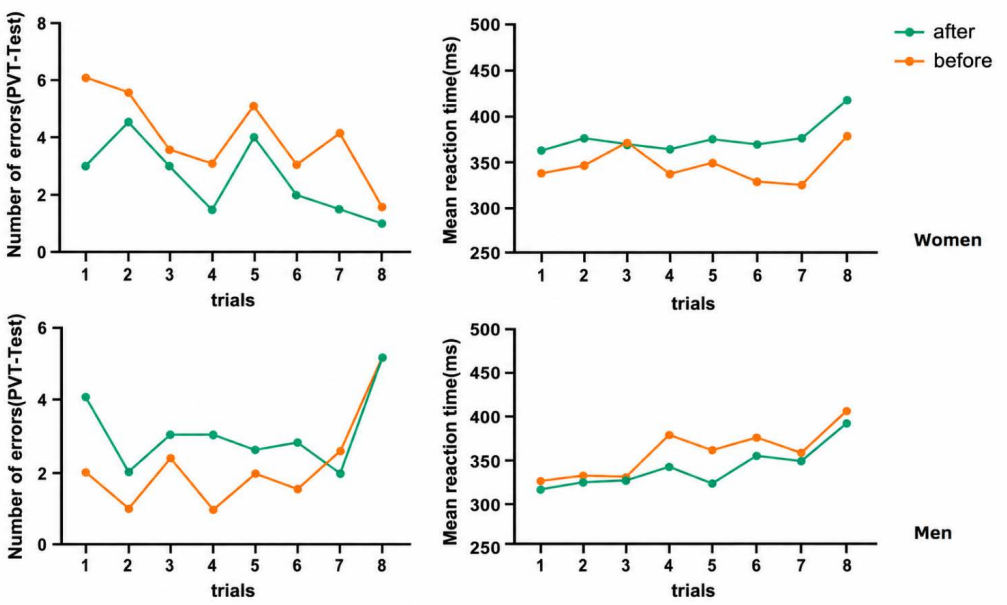


Figure 4. Changes in Number of error (Δ.PVT) scores and reaction time based on CCT were examined under different light intensities and exposure times in women and men

low proportion of explained variance ($R^2 = 0.203$). None of the main effects or interaction terms reached statistical significance, although the interaction between CCT and LIGHT approached marginal relevance (F = 2.552, $P = 0.130$, Partial $\eta^2 = 0.138$). Similarly, in the male group, the model also failed to reach significance, F (7, 16) = 1.153, $P = 0.379$, with $R^2 = 0.335$. All main effects and interactions were non-significant in this group as well, with the L × T interaction showing the lowest P-value ($P = 0.116$), yet remaining statistically non-significant. Overall, these findings suggest that under the experimental conditions of the current study, gender-specific differences in response to variations in lighting parameters did not result in meaningful changes in sustained attention performance.

Discussion

The present study aims to provide a comprehensive understanding of the combined effects of light on physiological rhythms and cognitive performance among night-shift nurses, with particular consideration of gender differences. The findings reveal that specific light parameters especially the combination of illuminance, correlated color temperature, and exposure duration induce distinct patterns of heart rate variability regulation in female and male nurses. These results highlight the importance of developing gender-sensitive lighting interventions in occupational health, emphasizing the critical role of tailored strategies for night-shift work environments.

Changes in HRV Variables

Results indicated that the combination of light intensity, color temperature, and exposure duration exerts differential effects on ANS regulatory indices, particularly HRV, between female and male subjects. These findings underscore the importance of designing sex-specific light interventions in occupational environments.

In female nurses, exposure to cool light (6500 K) at moderate intensity (500 lux) as well as warm light at high intensity (3000 K, 1000 lux) resulted in decreased parasympathetic HRV indices (RMSSD, SDNN, PNN50) alongside an increased LF/HF ratio, indicative of sympathetic dominance and parasympathetic withdrawal. This response may be attributed to the stimulatory effects of these lighting conditions on physiological stress systems, leading to heightened alertness and arousal. Conversely, exposure to warm light at lower intensity (3000 K, 500 lux) enhanced parasympathetic activity and reduced heart rate, reflecting a relaxation response and improved autonomic balance.

In males, responses to lighting conditions were more uniform and showed significant changes only under specific circumstances. For instance, warm light at low intensity (3000 K, 500 lux) induced an increase in heart rate, whereas higher intensities and longer exposures led to heart rate reductions. Moreover, exposure to high-intensity cool light (6500 K, 1000 lux) elevated parasympathetic indices and promoted a balanced, calming effect, suggesting a protective and soothing role of this lighting condition in males.

Luo's study[42] demonstrated that exposure to high-intensity blue-enriched light leads to increased sympathetic nervous system activity, such that time-domain HRV indices, including SDNN, RMSSD, and pNN50, were significantly higher under low-light conditions (200 lux) compared to high-light conditions (1200 lux). Moreover, Yoda et al.[70] observed in healthy individuals that exposure to blue light significantly increased the LF/HF ratio compared to red and green light. These findings suggest that blue light can simultaneously enhance both relaxation and alertness, a phenomenon likely mediated by the specialized photoreceptive retinal cells (melanopsin). In addition to

processing visual information, these cells are capable of influencing circadian rhythms and cardiovascular function. These results are consistent with reports by Schäfer[71] and Edelhäuser,[72] which highlight the role of blue and cold light in modulating autonomic nervous system activity and enhancing alertness, and they align with the findings of the present study.

The results of the present study differ in some aspects from previous findings reported by Noguchi,[73] Smolders,[23] and Araujo.[74] One of the main factors contributing to these discrepancies is the duration of light exposure. Additionally, studies by Yakoui[75] and Edelhäuser[72] have shown that both color temperature and light intensity can exert sex-dependent effects on HRV. The higher sensitivity of females to specific light conditions may be attributed to hormonal and physiological differences that influence autonomic nervous system regulation. In contrast, the more uniform responses observed in males are likely related to lower sensitivity of non-image-forming retinal photoreceptors and inherent physiological differences in autonomic nervous system function. These findings highlight the importance of considering individual variables and sample characteristics when examining the effects of light on cardiovascular and autonomic nervous system performance.

Cognitive performance

The findings of this study highlight gender differences in task performance under varying lighting conditions. Specifically, women exhibited greater fluctuations in performance following the intervention, whereas men demonstrated a more stable and consistent pattern. This difference may indicate a higher sensitivity of women to changes in light intensity and color temperature. Moreover, the present results are consistent with previous research showing that higher color temperature can enhance cognitive performance.[76,77] Previous studies, in contrast to the present findings, have reported that low light intensity combined with a cool color temperature enhances working memory performance, a result that differs from the pattern observed in this study.[78,79] However, some studies have reported conflicting results, indicating that changes in CCT have no significant effect on attention or short-term and long-term memory performance.[80,81] These discrepancies may be attributed to the influence of exposure duration or the complex effects of multisensory interactions on indoor environmental perception. These findings suggest that the effects of light on cognitive performance depend not only on its physical properties (intensity and color temperature) but also on individual and gender-related factors.

Regarding cognitive performance, although a relative improvement was observed in both sexes, statistical analysis revealed no significant independent or interactive effects of color temperature, light intensity, or exposure duration. This lack of significance may reflect the influence of psychological factors, fatigue, and individual differences that modulate cognitive outcomes. Sex-related differences in response patterns may also relate to physiological and hormonal variations.

Specifically, the Psychomotor Vigilance Task (PVT) results demonstrated that short-term exposure to varying lighting conditions significantly affected sustained attention, with distinct patterns in females and males. Females exhibited a significant reduction in errors, particularly under 3000 K and 6500 K at 1000 lux, indicating enhanced accuracy and attentional control, possibly due to greater light sensitivity and positive effects of illumination on concentration and alertness. In contrast, male response patterns were more heterogeneous; some groups improved following light exposure, while others especially those exposed to 6500 K at 1000 lux for 20 minutes showed a marked increase in errors. These fluctuations may be driven by individual biological and psychosocial variability within the male cohort.

Concerning reaction time, a slight increase in females suggests a more cautious response strategy post-exposure, notably under 6500 K at 1000 lux for 20 minutes, where error rates declined despite longer reaction times. Male reaction time changes were inconsistent, with some groups showing decreases and others increases, reflecting biological complexity or differing adaptation to lighting conditions.

In this regard, the study by Vimalanathan et al.[82] demonstrates that increased light intensity in work environments positively impacts individuals' cognitive performance. Specifically, a comparison between conditions with 500 lux and 750 lux lighting, and an environment with 1000 lux lighting, showed a significant improvement (19.91%) in reaction times during the tests. The study by Smolders[28] on the PVT test showed that response times were longer under 200 lux lighting compared to 1000 lux, which contrasts with the findings of the present study, where response times increased at higher light intensities. This novel finding suggests that the impact of light intensity on cognitive performance may not follow a linear relationship, but rather could depend on its interaction with color temperature and exposure duration. The observed discrepancies may be attributed to a variety of factors, including the nature of the tasks used, participant characteristics, the type of test, exposure duration, and the specific lighting conditions implemented in this study.

Silva-Urra[83] study also indicated that blue light can improve the PVT index (cognitive performance). However, in this study, response times increased under blue light, suggesting that the effects of CCT may be significantly influenced by factors such as task type, gender, individual differences, and light intensity. [84,85] Nonetheless, three-way ANOVA indicated that color temperature, light intensity, and exposure duration did not significantly influence sustained attention performance, independently or interactively. This reinforces the potential overriding effect of psychological factors, fatigue, and individual traits on cognitive function. Sex differences in response patterns likely stem from underlying physiological and hormonal mechanisms.

The limitations of this study include a relatively small

sample size and the absence of a formal a priori sample-size calculation, which may have limited the statistical power to detect small effects. Additionally, some eligibility criteria, including sleep status, psychological and emotional status, stress, stimulant abstinence, and systemic health status, were assessed based on self-reported information rather than objective clinical or laboratory measures, which may have introduced reporting bias. The study was also restricted to a limited selection of hospital wards, which may reduce the generalizability of the findings to other departments. Additionally, the short duration of exposure to lighting conditions may not fully capture long-term changes in cognitive performance or physiological parameters, and the lack of direct assessment of hormonal influences and circadian rhythms represents a notable shortcoming. Despite these limitations, the findings underscore the necessity of implementing multidimensional, sex-specific lighting interventions in healthcare settings. Intelligent lighting regulation has the potential to enhance physiological health and cognitive efficiency among night-shift nurses, mitigating stress and fatigue associated with suboptimal lighting. Therefore, policymakers and workplace designers should consider sex-specific responses to light in their strategies. Future research should involve larger samples, more ecologically valid work environments, and an exploration of hormonal effects, circadian influences, and long-term outcomes of light exposure. The development of personalized, sex-based lighting interventions may constitute a pivotal advancement in promoting occupational health and nurse well-being.

Conclusion

The findings of this study indicate that lighting conditions can significantly influence both physiological responses and cognitive performance in night-shift nurses. The results revealed sex-specific differences in responses to light, with female nurses showing greater sensitivity to variations in light intensity and color temperature, while male responses were generally more uniform. Although modest improvements in cognitive performance were observed in both sexes, no statistically significant independent or interactive effects of light intensity, color temperature, or exposure duration were detected. These results underscore the necessity of implementing multidimensional, sex-specific lighting interventions to enhance attentional performance and cognitive efficiency, while maintaining autonomic balance and mitigating the adverse effects associated with night-shift work. Considering that exposure to cool or warm light under certain conditions may improve cognitive performance and alertness, uncontrolled or prolonged exposure could disrupt circadian rhythms and reduce sleep quality. Therefore, targeted and intelligent adjustment of lighting in healthcare settings, particularly in hospitals, is essential to support occupational health, prevent chronic conditions, and minimize long-term negative outcomes. Given limitations such as a relatively small sample size and short exposure duration, future research should involve larger populations, longer intervention periods, and assessment of hormonal and circadian markers to provide a stronger scientific basis for optimizing lighting guidelines in clinical work environments.

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Competing Interests

The author confirms that there are no potential conflicts of interest regarding the research, writing, and/or publication of this article.

Ethical Approval

The study received ethical approval from the University Ethics Committee under the code IR.SUMS.SCHEANUT.REC.1402.152. All participants provided written informed consent prior to the data collection, and the study adhered to ethical guidelines, ensuring the protection of privacy and confidentiality of personal information.

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Supplementary files

Supplementary file 1 contains Table S1.

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