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Evaluating the Impact of Display Light Settings on Circadian Rhythms, Visual Fatigue, and Cognitive Performance: A Comparative Study of Static and Dynamic Backgrounds

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Abstract

As displays become ubiquitous and increasingly integrated into daily life, their impact on human health is a major concern for academia and industry. The aim of this study was to investigate the effect of display backgrounds with different Correlated Colour Temperature (CCT) and Circadian Stimulus (CS) settings on human circadian rhythms and visual fatigue. Twelve participants underwent four 9-hour display lighting interventions over a 10-day period, including S1 (CCT at 4000K; CS from 0.29 to 0.15), S2 (CS at 0.2; CCT from 6500K to 4000K), S3 (CCT from 6500K to 4000K; CS from 0.30 to 0.15), and static S4 (CCT at 4000K; CS at 0.2). Participants' melatonin levels, visual fatigue, cognitive performance, sleep quality and 24-hour core body temperature were monitored. The results showed that S4 was the most circadian-friendly condition, with the least visual fatigue and the best sleep quality. In addition, the S3 intervention resulted in the lowest nighttime alertness. Therefore, static display backgrounds with low CCT and CS appear to be more beneficial for circadian health than dynamic display backgrounds. Furthermore, the results of several statistical tests showed that CS has a greater effect on rhythm than CCT.

1. Introduction

Display screens are an integral part of modern life, serving as essential tools for work, study, and entertainment. However, the extensive use of display screens has an impact on human health. Previous research has indicated that using electronic devices, such as smartphones, tablets, and computers, especially at night, could delay sleep onset, reduce sleep quality, and cause daytime sleepiness and fatigue [1, 2]. Excessive screen time could also lead to eye strain, dryness, and vision problems [3]. Given the limited amount of research in this field, it is important to investigate the effects of display screen parameters on circadian rhythms and visual fatigue.

The resetting effect of light on the human biological clock is a manifestation of non-visual effects [4, 5]. This effect is primarily mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina, which convert light signals into electrical signals and transmit them to the suprachiasmatic nucleus (SCN). The SCN then signals the pineal gland, influencing melatonin secretion and regulating the biological clock [6, 7]. However, research has showed that other visual photoreceptors are also involved in this process [8]. Therefore, it can be hypothesized that the regulation of circadian rhythms by display backgrounds has an effect comparable to that of light source, as the light can typically enter the eye at a very close distance.

Substantial research in the field of lighting and circadian rhythms focused on exposure duration [4], exposure timing [9], and spectral components [10, 11]. Studies indicated that the Correlated Colour Temperature (CCT) of light sources affected circadian rhythms, with higher CCT values causing greater circadian phase shifts and often leading to delays [12, 13]. Furthermore, CCT has also been widely used in mobile displays to precisely simulate light spectra through display technology, improving display quality and reducing eye strain [14, 15]. However, it remains unclear whether the principles governing circadian rhythms in ambient lighting apply equally to displays.

Several metrics were developed for quantifying the circadian impact of lighting. Lucas *et al.* introduced a model to report the effective irradiance experienced by each photoreceptor (*i.e.*, rods, cones, and ipRGCs) involved in non-visual responses [16]. Subsequently, the equivalent melanopic lux (EML) and melanopic equivalent daylight (D65) illuminance (m-EDI)[17] were developed and widely adopted. However, research results indicated that these models cannot accurately capture non-visual responses of subjects, such as melatonin suppression or circadian phase shifts [18]. To date, Rea *et al.* [8] proposed the only model, the circadian stimulus (CS), that accounts for both the spectral and absolute sensitivities of the circadian system and the relative contributions of each photoreceptor.

Studies have shown that daytime participants who are exposed to lighting conditions with high CS and CCT can experience significant improvements in sleep quality [19, 20]. Figueiro *et al.*'s research in 2019 have shown that dynamic lighting with high CS values can trigger higher levels of work performance [21]. In this study, the corresponding CCT and CS values were calculated based on display characteristics, in order to investigate whether these metrics are also applicable to displays and which metric has a greater effect on circadian rhythms.

In this study, twelve subjects participated in four 9-hour display lighting interventions, including S1 (CCT at 4000K; CS from 0.29 to 0.15), S2 (CS at 0.2; CCT from 6500K to 4000K), S3 (CCT from 6500K to 4000K; CS from 0.30 to 0.15), and static S4 (CCT at 4000K; CS at 0.2). By measuring the participants' melatonin levels, visual fatigue, cognitive performance, sleep quality, and 24-hour core body temperature, the aim of this study was to recommend a display lighting design that was circadian-friendly and could minimize visual fatigue for users.

2. Methods

Subjects

A total of 12 students from Zhejiang University participated in this experiment, consisting of 9 males and 3 females, with an average age of 24.58 ± 3.23 years. All participants had normal vision, and did not suffer from any sleep-related disorders. Additionally, they did not engage in excessive alcohol consumption or frequent intake of coffee or tea. Participants were instructed to maintain a regular sleep schedule throughout the experiment. They were thoroughly briefed on the rules and procedures of the study. The experiment was carried out in four groups of three subjects each.

Experimental setup

The experiment lasted for 10 days, during which the participants underwent five experimental sessions, each spaced one

day apart to reduce the influence of the previous session. On the days of the experiments, the participants spent 10 hours in an office where they were exposed to certain light interventions and were then taken to a designated hotel to sleep at night. The hotel rooms were spacious and quiet, with ambient light of 3000 K and 50 lux for basic lighting. The 10-hour light intervention was conducted in a dedicated room measuring 6 metres in length, 3 metres in width, and 3 metre in height. The participants were instructed to maintain a viewing distance of approximately 45cm from the screen, with their line of sight basically perpendicular to the screen. This office was equipped with a ceiling panel light designed to simulate a real office environment. The room was sealed to prevent interference from external light sources. The experimental scene is shown in Figure 1.

Figure 1. *Experimental environment*

Stimuli

The ambient lighting in the office room was provided by a flat ceiling light source with a CCT of 4000 K and an illuminance of 500 lux. The ambient lighting chosen represent the typical lighting for normal work.

An Apple XDR display was used to implement the display light stimuli. The display has a resolution of 6016 × 3384 pixels. It took approximately 30 minutes to stabilize the colour characteristics of the display. The Gain-Offset-Gamma (GOG) model was used to characterize the display. Additionally, a total of 768 colours (256 colours for each RGB channels) were measured at the centre of the display using a Konica Minolta CS2000A spectroradiometer. The irradiance information at the position of the display panel was obtained from the measured radiance. The required CCT and CS values for the experiment were generated by exhausting all possible combinations of the RGB channels. Table 1 shows the four display background conditions (S1-S4) and their corresponding RGB values. The background duration spanned from 14:00 to 23:00 each day. In condition S1, the CCT remained at 4000 K throughout the day, while the CS value gradually decreased from 0.29 to 0.15. In condition S2, the CS value was fixed at 0.2, and the CCT gradually changed from 6500 K to 4000 K. In condition S3, both the CCT and CS values changed synchronously, with the CCT decreasing from 6500 K to 4000 K and the CS value decreasing from 0.30 to 0.15. In the three conditions above, the background colour changes stepwise rather than smoothly, which is a common way of displaying colour changes on current monitors. Condition S4 was the only one with a static and unchanging display background.

In addition to the four display background conditions, the experiment included a baseline condition in which the participants refrained from using any electronic devices throughout the day. From 18:00 to 23:00, participants engaged in activities such as listening to music or audiobooks in a room illuminated by a 4000 K, 50 lux light source. Previous studies suggested that low illuminance (less than 80 lux) did not suppress melatonin or induce significant changes in the circadian melatonin rhythm [22]. During this period, the use of electronic devices was strictly prohibited.

Table 1. The display background conditions and their corresponding RGB values

Stimuli	time	CCT	CS	R	G	B
S1	14:00	4080	0.29	255	213	174
	19:00	4029	0.25	238	199	160
	21:00	3939	0.20	210	175	140
	22:00	4043	0.15	188	161	123
S2	14:00	6481	0.20	133	129	129
	17:00	5965	0.20	141	134	130
	18:00	5469	0.20	151	139	131
	19:00	4965	0.20	168	152	135
	20:00	3953	0.20	221	187	144
S3	14:00	6496	0.30	172	168	166
	17:00	6009	0.30	177	165	164
	18:00	5517	0.30	192	179	168
	19:00	5049	0.25	183	164	151
	20:00	4029	0.25	238	199	160
	21:00	3939	0.20	210	175	140
	22:00	4034	0.15	188	161	123
S4	14:00-23:00	3939	0.20	210	175	140

Measurements

The present tests were primarily divided into three categories. The first category focused on circadian rhythms and included measurements of core body temperature (CBT), melatonin levels, and sleep quality. The second category assessed visual efficiency using the Critical Flicker Fusion (CFF) test and a visual fatigue questionnaire. The third category evaluated cognitive functions using the D2 Test of Attention and the Karolinska Sleepiness Scale (KSS).

Initially, the core body temperature test was conducted. CBT rhythms are crucial indicators of human circadian cycles. The time at which the lowest body temperature occurs (CBTmin) is often used as a reference point to mark shifts in the circadian cycle [23, 24]. In this experiment, participants ingested a temperature-sensing capsule at 08:00 AM on the first day, and their body temperature was recorded every 30 seconds until 08:30 the next morning. During this monitoring period, participants were instructed to avoid caffeinated beverages such as coffee, tea, or cola.

Melatonin levels are influenced by circadian rhythms, and the direct use of its concentration can be inaccurate due to inherent delays. In this experiment, multiple saliva samples were collected from participants to determine the Dim Light Melatonin Onset (DLMO) time point [25]. This method, as employed in studies by Hou [26] and Parry [27], accurately assesses shifts in individual circadian cycles. Building on the methodologies of Hou and Parry, modifications were introduced in this experiment. The average melatonin concentration between 18:00 and 23:00 under four experimental conditions was used to determine the DLMO threshold. Based on the calculated results, 19:00 was identified as the time point when melatonin levels began to rise in most participants' results referring to the baseline condition. The DLMO time was defined as the time when melatonin levels increased twice in a row after light intervention. The closer DLMO time was to 19:00, the more it was deemed to align with normal conditions.

By integrating objective data from smart watch devices with subjective assessments from the Brief Assessment of Sleep Intensity and Quality Scale (BASIQS) [28] and General Sleep Quality Scale (GSQS) questionnaires [29], the study aimed to provide a comprehensive evaluation of sleep quality. The most important quantitative indicators of sleep quality are the Non-Rapid Eye Movement (NREM) sleep, sleep efficiency (SE), and total sleep time (TST). These indicators were provided by the smart watch. These tools were administered to participants upon awakening to

capture their personal experiences and perceptions of sleep. The BASIQS questionnaire focuses on immediate sleep experiences, such as sleep depth and restfulness, while the GSQS provides a broader evaluation of overall sleep quality, including factors such as sleep duration, latency, and disturbances.

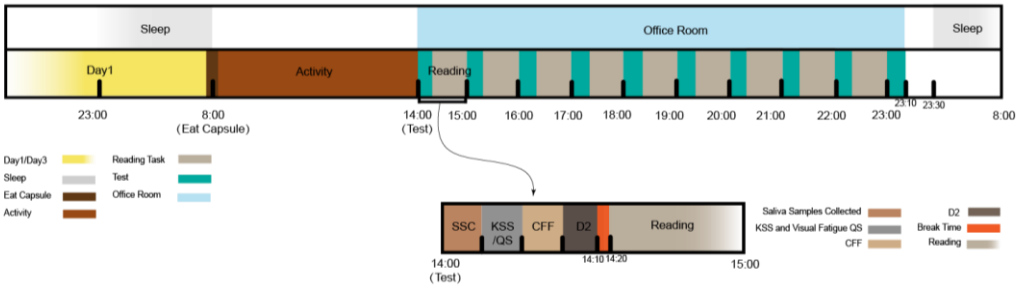

Figure 2. *The experimental procedure. Each condition underwent the same experimental process, with participants' activities taking place either in a hotel or an office. The time for the display background intervention was from 14:00 to 23:00, with a ten-minute test completed every hour.*

Cognitive performance is a crucial indirect measure of human alertness. In this experiment, the D2 test was utilized to assess short-term memory abilities. The D2 test is a time-constrained assessment of selective attention, widely recognized for its clinical applications. Participants were required to identify target objects swiftly, with 18 seconds allocated for each row. Detailed procedures can be found in Ref [30]. The Concentration Performance (CP) and error rates derived from the D2 test provided an evaluation of the participants' alertness levels.

Additionally, the Karolinska Sleepiness Scale questionnaire was employed to assess subjective alertness. The KSS, developed by Åkerstedt and Gillberg [31], is a nine-point scale with higher scores indicating greater sleepiness. A score of "1" signifies "extremely alert", while a score of "9" denotes "very sleepy, great effort to stay awake, fighting sleep".

The Critical Flicker Fusion threshold is a crucial metric for evaluating visual fatigue. This threshold varies among individuals and is influenced by factors such as alertness and fatigue. CFF thresholds have been widely used in previous researches for assessing visual perception [11, 32]. In this experiment, subjects were asked to observe the white light with a frequency of 1-100hz, which varied from high to low and low to high, respectively. Finally, a fusion frequency value is given. Furthermore, subjective assessments of visual fatigue were also conducted. Participants completed questionnaires to report their experience of visual fatigue and discomfort. These subjective scores complemented the objective measurements (CFF), providing a comprehensive understanding of how different conditions affected the participants' visual and cognitive states.

Experiment procedure

Each participant first completed one baseline experiment, followed by four display light intervention experiments. The sequence of the four display stimuli was randomized over the remaining eight days, all following the same experimental procedure, as shown in Figure 2. On the day of the display intervention experiment, all 12 participants independently completed all tests. Participants checked into the hotel the day before the experiment to ensure adequate sleep and adherence to a consistent schedule with the experimental protocol. Upon waking at 08:00 the next morning, participants swallowed a capsule and filled out a questionnaire evaluating their sleep quality from the previous night. From 14:00 to 23:00, they entered the light intervention laboratory. The primary task during this period was to read on a display, where the text colour was black and the background colour matched the experimental light stimulus (specific CCT and CS values). Participants engaged in a 40-minute reading task followed by a series of hourly tests, for a total of ten sessions. Each testing session included the following steps: Saliva Sample Collection, Visual fatigue and KSS questionnaires, CFF Test and D2 Test.

Each testing session took approximately 10 minutes to complete, after which participants took a 10-minute break. After the final testing session at 23:10, participants were taken back to the hotel to prepare for sleep. The smart watch devices were used to monitor subjects' sleep parameters. To avoid interfering with CBT measurements, participants were not allowed to shower on the day of the experiment.

3. Results and Discussion

Statistical analysis was used to compare the effects of different display lighting conditions on circadian rhythms, visual performance and cognitive performance, and to analyse the consistency of results across different testing methods. The Repeated Measures Analysis of Variance (rm-ANOVA) was conducted at a 5% level of significance. All experimental data were analysed using IBM SPSS Statistics 22.

Circadian Rhythms

Circadian phase shift

CBT data were recorded for 12 participants over five cycles. However, the data from three participants were excluded due to data loss and anomalies. Consequently, the CBT data of nine participants were analysed. Initially, the raw CBT data required denoising and smoothing. Subsequently, the temperature curves were fitted using the Polynomial Curve Fitting Formula, as shown in Equation (1). The data processing of curve fitting was conducted by the curve fitting toolbox in MATLAB.

$$y(t) = x_1 \cos\big(2\pi(t - x_2)\big) + x_3 \cos\big(4\pi(t - x_4)\big) + x_5 \quad (1)$$

where $y(t)$ represents the CBT at time; x_1 is the amplitude of the first cosine term; x_2 is the phase shift of the first cosine term; x_3 is the amplitude of the second cosine term; x_4 is the phase shift of the second cosine term; x_5 is the baseline (offset) temperature.

Participants obtained a series of fitting curves for CBT, the example curves of one subject in four display background conditions are shown in Figure 3. The fitted curves were highly consistent with the original CBT curves, with Pearson correlation coefficients exceeding 0.95. Using numerical methods based on Equation (1), the minimum point of CBT and the corresponding time were calculated. When there was a significant difference between the predicted minimum point and the actual minimum point, manual data collection was performed, as illustrated in Figure 3d.

The Circadian Phase Shift (CPS) was then determined for four conditions by subtracting the baseline CBTmin from the experimental results.

A one-way rm-ANOVA was conducted on the mean CPS values of nine participants for four conditions. The main effect was found to be not significant ($F = 1.469$; $p = 0.242$), indicating that the four experimental conditions did not significantly affect the CBT phase shift. However, pairwise comparisons showed that the CPS value for condition S4 was significantly lower than that for S1 ($p = 0.087$) and S3 ($p = 0.071$). This suggested that, compared to S4, conditions S1 and S3 could significantly delay the circadian rhythm cycle. These findings implied that maintaining constant CCT and CS values on the display may be more conducive to circadian rhythm stability.

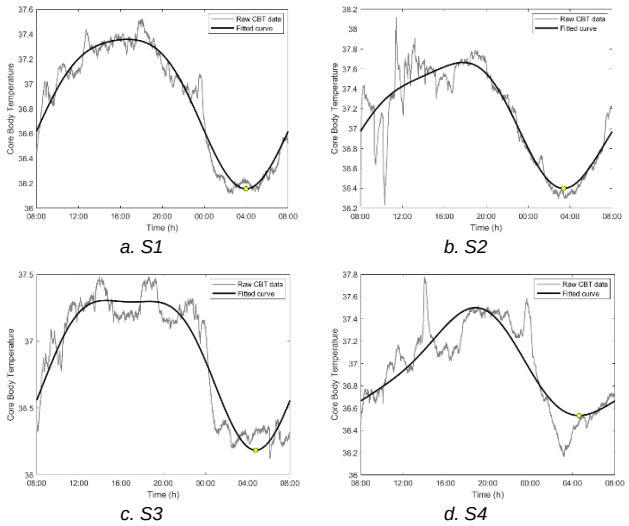

Figure 3. *Fitted CBT data and the CBTmin for one subject. The grey lines represent the original CBT data recorded by the capsule, while the black lines show the fitted curves. The yellow dots indicate the CBTmin.*

Melatonin onset

Melatonin was sampled 48 times during the experiment. The DLMO threshold was determined by calculating the average melatonin concentration between 18:00 and 23:00 for each subject in four experimental conditions, corresponding to a target time of 19:00. According to this target, the time point of the DLMO in the intervention data would be searched, as shown in Figure 4. The closer the average time point of the DLMO, the better is the adjustment. According to the mean values of the DLMO, the phase-advance shifts for four conditions are 21:26 ± 0.05 h, 20:00 ± 0.07 h, 20:23 ± 0.06 h, 19:07 ± 0.06 h, respectively. Thus, the DLMO adjustment result of S4 shows the best agreement with the target threshold.

Furthermore, a one-way rm-ANOVA was performed on the DLMO after the display light intervention under different conditions. The results showed that four conditions had significant effects on DLMO ($F = 3.080$; $p = 0.041$). According to the results of pairwise comparisons, the DLMO value of experimental condition S4 was significantly lower than that of S1 ($p = 0.005$). The result indicated that the static display background condition (S4) had the effect of the melatonin suppression, which was consistent with the CPS result.

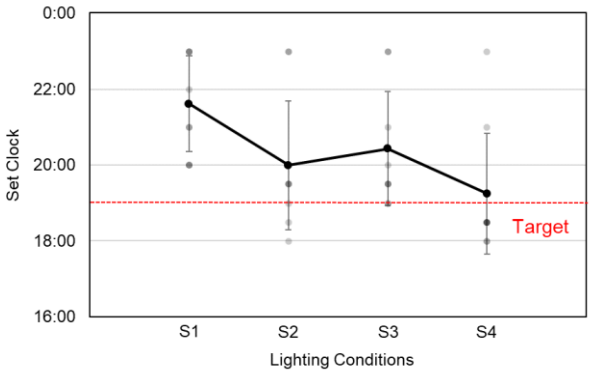

Figure 4. *DLMO of four display lighting conditions. Error bars represent standard deviation (SD).*

Sleep quality

In order to evaluate the sleep quality of the participants at night, they were required to wear the smart watch every night from 11:00 PM to 8:00 AM for sleep monitoring. The outcome measurements included TST, SE, and the duration of NREM and REM. The smart watch data were pre-processed by subtracting the baseline data from the intervention data to obtain the relative value of each indicator.

The BASIQS and GSQS sleep questionnaires were used to evaluate participants' sleep quality on the night following the experimental intervention. Lower questionnaire scores indicated better sleep quality. Figure 5 shows the scores of nine participants across four conditions on both sleep questionnaires. A strong consistency was found between two questionnaires, with a Pearson correlation coefficient of 0.98. The scores of both questionnaires were the lowest under condition S4, where the CCT and CS values remained static. This suggested that maintaining a constant and appropriate brightness and colour temperature of the display could be beneficial for sleep quality when using displays at night.

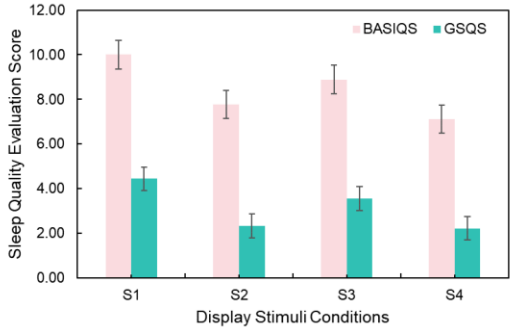

Figure 5. *The sleep quality evaluation score from the BASIQS and GSQS questionnaire, erspectively. Error bars represent anSD.*

Visual Fatigue

The CFF test and the eye fatigue questionnaire were administered hourly from 14:00 to 23:00. As shown in Figure 6a, participants' CFF scores showed a decreasing trend over the experimental period, indicating increasing eye fatigue. This finding was consistent with the results of eye fatigue questionnaire scores, as depicted in Figure 6c. Visual fatigue increased with prolonged display screen usage, suggesting a cumulative effect of display-induced eye strain over time. To quantify the increase in visual fatigue, we used the values from the first test at 14:00 as a baseline and subtracted these from those obtained at 23:00, resulting in ΔCFF (the absolute values were applied to facilitate comparison) and ΔF scores that representing the increase in visual fatigue. A two-way

rm-ANOVA was conducted on these growth values. The analysis revealed that changes in CCT and CS did not significantly affect the increase in visual fatigue, although the effect for CS (η_p^2 = 0.565) was larger than CCT (η_p^2 = 0.022), indicating that CS had a greater impact on the visual fatigue than CCT. The mean values of fatigue growth for the four display stimulus conditions are illustrated in Figure 6b and 6d. The ΔCFF and ΔF values indicated a ranking of fatigue growth from lowest to highest as S4, S3, S2, and S1. This alignment of subjective and objective measurements suggested that the static condition (S4) had the least impact on visual fatigue, while the condition with only CS variation (S1) resulted in a greater increase in visual fatigue. Moreover, these findings are consistent with the above results related to circadian rhythm, which showed that circadian-friendly display background would also result in subjects experiencing less visual fatigue.

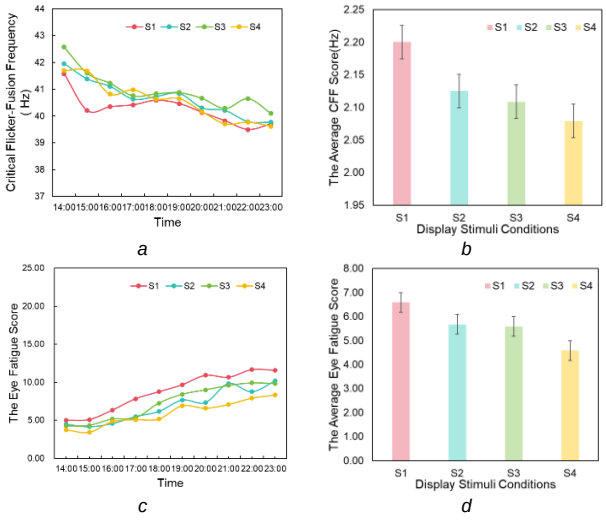

Figure 6. *The results of visual fatigue assessments, (a) CFF scores, (b) ΔCFF score, (c) Eye fatigue questionnaire scores and (d) ΔF scores. Error bars represent anSD.*

Cognitive Performance

The D2 test and KSS questionnaire were conducted hourly from 14:00 to 23:00. Previous studies indicated that lower nighttime alertness could facilitate better sleep onset and improved sleep quality [33]. Therefore, this experiment primarily focused on the CP, error rates, and KSS scores between 19:00 and 23:00. Both higher error rates and higher KSS scores indicate lower alertness, as well as lower CP scores. The two-way rm-ANOVA revealed that CCT significantly affected D2 error rates (F = 8.991, p = 0.012), while CS did not have a significant effect (F =0.339, p =0.572). Neither CCT nor CS showed significant influence on CP scores (CCT: F =1.185, p =0.300; CS: F =0.879, p =0.369) and KSS questionnaire scores (CCT: F =3.828, p =0.076; CS: F =0.314, p =0.587). However, based on the mean scores, CP scores, error rates, and KSS results consistently showed lower nighttime alertness under condition S3, whereas the other conditions did not exhibit a consistent pattern, as shown in Figure 7.

Although the results of D2 test and KSS questionnaire consistently indicated that condition S3 resulted in low nighttime alertness, the finding was not consistent with the results of the CPS, sleep quality, or DLMO. Based on these results, it can be hypothesized that the pathways influencing human cognition and circadian rhythms may differ, as the D2 test and KSS questionnaire are primarily related to cognitive performance. Therefore, such findings suggested that it may be possible to design display lighting that is circadian-friendly and does not adversely affect users' cognitive performance.

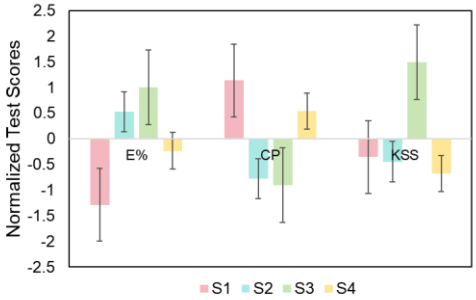

Figure 7. *The results of the normalized D2 and KSS test scores. Error bars repreent anSD.*

General Discussion

Three quantitative indicators directly related to circadian rhythms are CPS, DLMO, and sleep quality. This study employed five testing methods to statistically analyse these indicators. To compare the consistency of the results, the Pearson correlation coefficient was calculated for the mean values of the five testing methods under four display stimuli conditions. The results are shown in Table 2. The findings indicate significant consistency among the CPS, DLMO, and sleep quality results (p < 0.05). However, SE showed low consistency with the other indicators, suggesting the inaccuracy of SE measurements by the smart watch or the unreliability of SE as an indicator of circadian rhythms.

Table 2. The Pearson correlation coefficient between the five testing methods under four conditions

Pearson's *r*	CPS	SE	BASIQS	GAQS	DLMO
CPS		0.18	**0.95***	**0.89***	**0.99***
SE			0.12	0.01	0.14
BASIQS				**0.98***	**0.99***
GSQS					**0.95***
DLMO					

The significant results were mark with * (***p*** < 0.05) and in bold.

The results indicated that static backgrounds with low CCT and low CS combinations were more effective on circadian rhythm comparing to dynamic display backgrounds. Dynamic backgrounds were designed to mimic the natural variations in daylight, enhancing alertness during the day and reducing it at night. However, due to the cumulative effect of light exposure on circadian rhythms, the impact of high CCT and high CS conditions during the daytime in S1, S2, and S3 carried over into the evening[4, 9]. This result is consistent with the findings of lighting studies, as Hu et al. [5] studied the effects of dynamic light with a CCT ranging from 6500 to 12,000 K versus static light at 12,000 K in 2012 and found that dynamic light could induce more vigilance. Additionally, previous studies have shown that CCT value of the LED light source has a greater impact on circadian rhythm than CS [34]. However, the current display results are contradictory. This may be because displays are self-luminous devices with 3 narrow-band channels, unlike natural light or modern LED lighting sources. Furthermore, different CS values on the display correspond to different brightness levels. The change in CS value affects the luminance level of the display, leading to the hypothesis that the display's impact on circadian rhythms is primarily due to the brightness levels. This hypothesis will be tested in future experiments.

4. Conclusions

This study investigated the impact of display background settings on human circadian rhythms, visual fatigue and cognitive performance. Through a series of 9-hour display lighting interventions over 10 days, it was found that static background with low CCT and CS values (S4) are more conducive to maintaining circadian health and minimizing visual fatigue than dynamic display background. The S4 condition, characterized by a constant CCT of 4000K and CS of 0.2, consistently showed the best outcomes in terms of melatonin levels, core body temperature, and sleep quality. While dynamic light sources such as S3 were more effective in maintaining nighttime alertness, they were less circadian-friendly. This suggests that while dynamic lighting can enhance cognitive performance, it may disrupt circadian rhythms. Furthermore, the results of data analysis indicate that the CCT and CS settings of the display screens did not show statistical significance on circadian rhythms, visual fatigue, and cognitive performance. However, the effect of CS was higher than that of CCT, suggesting that future research should be more focused on the impact of the CS parameter of display screens on circadian rhythms and visual comfort.

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