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藍光背景顏色降低外因性視覺注意力轉移的速度

Blue-Light Background Color Impairs Visual Exogenous Attention Shift

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楊健群 先生所提論文 Blue Light Impairs Visual Exogenous Attention Shift

經本委員會審議， 符合 碩 士學位標準， 特此證明。

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摘要

照射藍光能影響認知功能；然而，視覺空間注意力方面的實驗結果卻不一致。這可能是因為過去的研究沒有對藍光裡可能造成影響的因素，如 S 視椎細胞的刺激量、內隱性感光節細胞（ipRGCs）的刺激量、與光的顏色等，進行嚴謹控制所導致的結果。因此，我們採用 Carlson、Hogendoorn、及 Verstraten （2006）所提出的時鐘派典並系統性地操弄背景光來估計藍光對外因性與內因性注意力轉移的影響。在時鐘派典中，受試者需看著一組轉動的時鐘，並回報外因性或內因性線索出現時提示時鐘上的指針方向。藉由比較真實及回報指針方向間的差即可算出注意力轉移速度。在實驗一，我們在藍光及綠光背景下進行實驗，並發現相比於控制組的綠光背景，藍光背景光會使外因性注意力轉移速度變慢卻不會影響內因性注意力轉移速度。我們更進一步使用多光源系統來操弄單一種感光細胞的刺激量變化並控制其他感光細胞的刺激量固定，用以檢視藍光敏感型感光細胞（如 S 視椎細胞與 ipRGCs）的影響。結果顯示藍光使外因性注意力轉移速度變慢並非來自 S 視椎細胞（實驗二）和內隱性感光節細胞（實驗三）的影響，而可能來自對藍色的聯想如藍光危害所造成的影響。我們的實驗結果提供證據顯示顏色對視覺注意力轉移的貢獻大於藍光敏感型感光細胞的貢獻。顏色對高階認知處理的影響不容忽視。

關鍵詞：視覺注意力轉移、藍光、S 視椎細胞、內隱性感光結細胞、對顏色的聯想

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Blue-Light Background Color Impairs Visual Exogenous Attention Shift

Chien-Chun Yang

Abstract

Exposure to blue light could influence cognitive functions; however, the findings were inconsistent, especially in visual spatial attention, probably due to the lack of decently controlling the factors involved in exposure to blue light such as S-cone stimulation, ipRGCs stimulation, and color. We adopted the clock paradigm (Carlson, Hogendoorn, & Verstraten, 2006) and systematically manipulated the background lights to estimate how blue light affects the speed of exogenous and endogenous attention shift. In the clock paradigm, participants viewed an array of moving clocks and reported the time on a target clock, which was indicated by an exogenous or endogenous cue. The speed of attention shift was estimated by the time latency between actual and reported cue-onset time. In Experiment 1, we conducted the experiment under blue and control (green) light background and found that compared to the control-light background, exposure to blue-light background slowed down the speed of exogenous visual attention shift but did not affect the speed of endogenous attention shift. To further clarify the contribution(s) of blue-light sensitive photoreceptors (i.e., S-cone, ipRGCs), we applied the multi-primary system that could manipulate the stimulation of a single type of photoreceptors without any stimulation change of other photoreceptors (i.e., the silent substitution method). The results showed that the stimulation of S-cone (Experiment 2) and ipRGCs (Experiment 3) did not contribute to the impairment of exogenous visual attention shift. Our results suggest that associations to blue color, such as the concept of blue light hazard, may cause the impairment of exogenous attention shift. Our findings provide evidence that contribution of blue color dominates over those of blue-light sensitive photoreceptors on visual attention shift, and suggests that the influence of color on higher cognitive processing should not be overlooked.

Keywords: visual attention shift, blue light, S-cone, ipRGCs, associations to colors

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1. Introduction

Blue light affects us in various ways. For example, exposure to blue light affects human physiology associated with circadian rhythm, such as delaying sleep onset time, suppressing melatonin secretion, increasing core body temperature, and raising heart beat rate (Cajochen et al., 2005; Chang, Aeschbach, Duffy, & Czeisler, 2015). In addition to physiology, blue light also influences human cognitive functions, such as alertness (Phipps-Nelson, Redman, Schlangen, & Rajaratnam, 2009; Viola, James, Schlangen, & Dijk, 2008), working memory (Alkozei et al., 2016; Vandewalle et al., 2013; Vandewalle et al., 2007; Vandewalle, Maquet, & Dijk, 2009), time perception (Yang, Tsujimura, Matsumoto, Yamashita, & Yeh, 2018), eye pursuit (Chen & Yeh, 2019), saccadic eye movement (Lee & Yeh, 2021), and dynamic vision (Chen & Yeh, 2019).

One of the most common findings among blue light studies is the facilitation effect of alertness-related cognitive functions, such as subjective alertness level and sustained attention (e.g., Phipps-Nelson et al., 2009; Viola et al., 2008; but see Souman, Tinga, Te Pas, Van Ee, & Vlaskamp, 2018), possibly contributed by the stimulation of the *intrinsically photosensitive retinal ganglion cells* (ipRGCs; see review in Cajochen, 2007). The ipRGCs are the third type of photoreceptors found in mammals' retinas in addition to cones and rods (Berson, Dunn, & Takao, 2002), and

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are most sensitive to the light ranging from 460 nm to 480 nm in the wavelength (Berson et al., 2002; Hankins, Peirson, & Foster, 2008). Unlike rods and cones, the ipRGCs contribute little to visual perception (Gooley, Lu, Fischer, & Saper, 2003). Instead, most ipRGCs project to the non-visual brain areas, such as the suprachiasmatic nuclei (SCN) and the locus coeruleus (LC): the SCN is the brain area controlling the circadian rhythm and alertness (Saper, Lu, Chou, & Gooley, 2005), and the LC is the brain area served as an alertness regulator (Aston-Jones & Cohen, 2005). Further, signals from ipRGCs passing through alertness-related subcortical areas eventually arrive at the cortex, suggesting that blue light or ipRGCs-stimulating lights could contribute to alertness-sensitive cognitive processing (see review in Vandewalle et al., 2009).

The subjective alertness level has been shown to affect the speed of visual spatial attention (Fimm, Willmes, & Spijkers, 2006; Matthias et al., 2010). For example, Fimm et al. (2006) conducted a sleep deprivation study to reveal how alertness level affected the performance of visual spatial attention. They asked participants to perform the visual orienting task every four hours over a 28-hour period. The results showed that the higher the subjective alertness level, the faster the speed of orienting task (Fimm et al, 2006). Similarly, Matthias et al. (2010) used the cueing paradigm to investigate whether temporal components of visual attention was influenced by

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changes in subjects' alertness level. They found that the speed of visual attention shift accelerated when participants' alertness increased (Matthias et al., 2010). Given that blue light can enhance alertness (Cajochen, 2007), it is expected that exposure to blue light could also speed up the shift of visual spatial attention.

However, past studies are inconsistent with respect to blue-light effects on visual spatial attention (Newman et al., 2016; Smolders & de Kort, 2017; Studer et al., 2019; Tonetti & Natale, 2019). For example, Smolders and de Kort (2017) used the Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) to investigate how blue light affects the three components of the attention system (alertness, orienting, and executive function) and found no effect of blue light on the performances of ANT. On the other hand, Studer et al. (2019) showed that compared to red light, blue-light exposure did not affect the reaction times (RTs) of ANT, but decreased the variability of RTs. Tonetti and Natale (2019) indicated that exposure to blue light facilitated the orienting network efficiency compared to being in the dark. In those studies, their lights were different in color, cone stimulation, and ipRGCs stimulation compared to the control lights. The lack of decently controlling the light may be the reason for the inconsistent results. Using series of experiments to isolate the influence of each factor involved in the exposure to blue light is a better way to understand how blue light affects human cognitive performances.

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Factors to be concerned with their potential contributions to the effect of blue light include ipRGCs stimulation, S-cone stimulation, and color/hue. First, the ipRGCs stimulation were found to facilitate several cognitive performances, especially alertness and sustained attention (Cajochen, 2007). We hypothesized that the ipRGCs stimulation could speed up visual spatial attention through alertness increment. Second, neural processing of S-cones is sluggish compared to other photoreceptors (Conway & Livingstone, 2006; Cottaris & De Valois, 1998) and could potentially slow down the speed of visual spatial attention. Last, blue background color could facilitate approach-related processing (Mehta & Zhu, 2009) as well as performance on a creativity task (Mehta & Zhu, 2009; Xia, Song, Wang, Tan, & Mo, 2016) and complex tasks (Soldat, Sinclair, & Mark, 1997; Xia et al., 2016). Although some studies suggested whether blue color improves or impairs human cognition depends on its contexts (Elliot & Maier, 2012; Elliot 2015), it seems that blue background color could improve task performances in general (Mehta & Zhu, 2009; Soldat et al., 1997; Xia et al., 2016). Despite these factors have shown their potential to influence the cognitive performances, how they each and combined to affect the effect of blue light on visual spatial attention shift remains to be elusive.

The current study isolated the contributions of blue-light sensitive photoreceptors (i.e., S-cone and ipRGCs) to investigate how blue light affected the speed of two

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kinds of visual spatial attention: exogenous and endogenous attention (Jonides, 1981; Posner, 1980). Exogenous attention is an involuntary system that corresponds to an automatic orienting response to a location where sudden stimulation has occurred, whereas endogenous attention is the voluntary system that corresponds to our ability to willfully monitor information at a given location (see review in Carrasco, 2011). The temporal natures of these two types of attention are different; it takes about 75-175 ms and 300 ms to shift exogenous attention and endogenous attention, respectively (e.g. Carlson et al., 2006; Müller, & Rabbitt, 1989; Nakayama, & Mackeben, 1989).

We adopted the clock paradigm introduced by Carlson et al. (2006) to estimate the speed of exogenous and endogenous attention shift to investigate how blue light affected the speed of visual spatial attention. The clock paradigm consisted of three trial conditions: the baseline condition, peripheral-cue condition, and central-cue condition. There three conditions were intended to estimate the task performance without attention shift, of exogenous visual attention shift, and of endogenous visual attention shift, respectively. By comparing the three conditions under blue background light vs. a control light (green) in Experiment 1, we aimed to test whether blue light affected exogenous attention shift, endogenous attention shift, or both, by examining whether the time to shift exogenous attention in the peripheral-cue condition and/or

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endogenous attention in the central-cue condition differs under blue background light and control light. Compared to the baseline where supposedly no attention shift is needed, additional time takes in the peripheral-cue and central-cue condition can be used to estimate the shift time of exogenous attention and endogenous attention. We would see whether we can replicate the original findings as a sanity check but the main issue here is the comparison of exogenous-attention and endogenous-attention shift. How blue light can affect the speed of visual spatial attention was examined by presenting different background colors (blue vs. green) in Experiment 1 and using the silent substitution method (Estévez & Spekreijse, 1982) to see whether the influences of each blue-light sensitive photoreceptors (S cone and ipRGCs) also contribute to the speed of attention shift in Experiment 2 and Experiment 3, respectively.

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2. Experiment 1A

In Experiment 1, we investigated how blue light affected the speed of visual attention shift. Past studies showed that increased alertness speeded up the processing of spatial attention (Matthias et al., 2010), and thus blue light exposure should accelerate the speed of visual attention shift if blue light exposure increases alertness level. However, other factors such as colors, cone stimulation, and ipRGCs stimulation were also possible contributed to the results, which may make the results deviate from our expectation. In Experiment 1A, we would directly investigate the relations between blue light and the speed of spatial attention; in Experiment 1B, we would further control the individual differences of luminance perception and test the role of alertness served in the results of Experiment 1A.

2.1. Methods

2.1.1. Participants. The planned sample size in our study was set at 24. Twenty-six male participants (age range: 20-35 years old) were recruited for Experiment 1A. Females were not included to avoid the possible interaction between the menstrual cycle and the influence of light exposure (Barron, 2007). For each condition and background light, participants whose average latency deviated from three standard deviations of the average latency of all participants were excluded from further

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analysis as outliers. One participant was excluded as outlier; one participant dropped out during the experiment. The final sample size for Experiment 1A was 24.

All participants had normal or correct-to-normal vision and they did not wear the glasses with any blue light filter. They all gave informed consent before their participation and were naïve to the purpose of the experiment. All experiments were approved by the Research Ethics Committee at National Taiwan University.

2.1.2. Apparatus and stimuli. All stimuli were displayed on an LCD monitor with 60 Hz refresh rate controlled by a PC running Matlab (The MathWorks, Inc.), using PsychToolbox extensions (Brainard, 1997). The experiment was conducted in a room without any lighting, except that from the computer screen. The participants sat at a distance of 57 cm from the LCD monitor and placed their head on the chin rest to minimize their head movement during the experiment.

In the clock paradigm, each trial consisted of two sessions: the presentation session and the report session. In the presentation session, a black fixation point and 10 black clockwise-running clocks were presented on the screen in an imagery circle with a diameter of 7°. At the center was the fixation point (about 0.1° of visual angle) where the participants were asked to keep fixating at. Each presented clocks were 2.5° of visual angle in diameter and featured with a clock hand moving 360° per second. The initial position of the clock hand on each clock was randomly assigned in each

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trial.

In the report session, a clock identical to each clock in the presentation session was presented at the center of the screen. The initial position of the clock hand pointed to the top of the screen in each trial (the 12-o'-clock location). A number ranged from zero to 60 was presented below the clock as the clock time to indicate the orientation of the clock hand. Participants were asked to use the arrow keys to increase or decrease the clock time to report the orientation of the clock hand as accurately as possible. The left arrow key could decrease one unit of the clock time; the right arrow key could increase one unit of the clock time; the up-arrow key could decrease five units of the clock time; the down arrow key could increase five units of the clock time.

Blue and green background lights were used in the experiment. The spectra of the two background lights as measured by PR655 Spectroradiometer in Experiment 1A are illustrated in Figure 2A. The peak wavelength of the blue background light was 444 nm (CIE xy color coordinate (0.14, 0.08)) and the peak wavelength of the green background light was 532 nm (CIE xy color coordinate (0.45, 0.50)). The luminance values for the blue background light and the green background light were 19.55 cd/ m^2 and 10.23 cd/ m^2, respectively. The amounts of cone and ipRGCs stimulation are summarized in Table 1.

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Table 1

Stimulation of Cones and ipRGCs in the Experiments

Experiment	Background light	L	M	S	ipRGCs
Experiment 1A	blue	13.50	19.53	85.98	65.56
	green	10.55	8.38	0.53	4.24
	ratio	1.28	2.33	161.72	15.47
Experiment 1B	blue	14.31	21.03	83.37	78.78
	green	14.14	14.58	1.26	10.42
	ratio	1.01	1.44	66.32	7.56
Experiment 2	S-cone high	188.55	111.88	45.24	40.34
	S-cone low	196.31	118.25	13.01	34.76
	ratio	0.96	0.95	3.48	1.16
Experiment 3	ipRGCs high	201.22	124.11	28.34	54.74
	ipRGCs low	186.34	110.83	28.96	23.80
	ratio	1.08	1.12	0.98	2.30

2.1.3. Procedure and design. Participants were asked to join in the experiment at the same time of the day on three separate days to minimize the influence of the circadian rhythm. The procedure and the stimuli shown on the three days were identical except for the background lights. On the first day of the experiment, participants performed the task under grey background light as a practice to reduce the practice effect in the formal trials. On the second and the third days, participants performed the task under the blue and green background lights. The order of the blue and green background lights was counterbalanced between participants.

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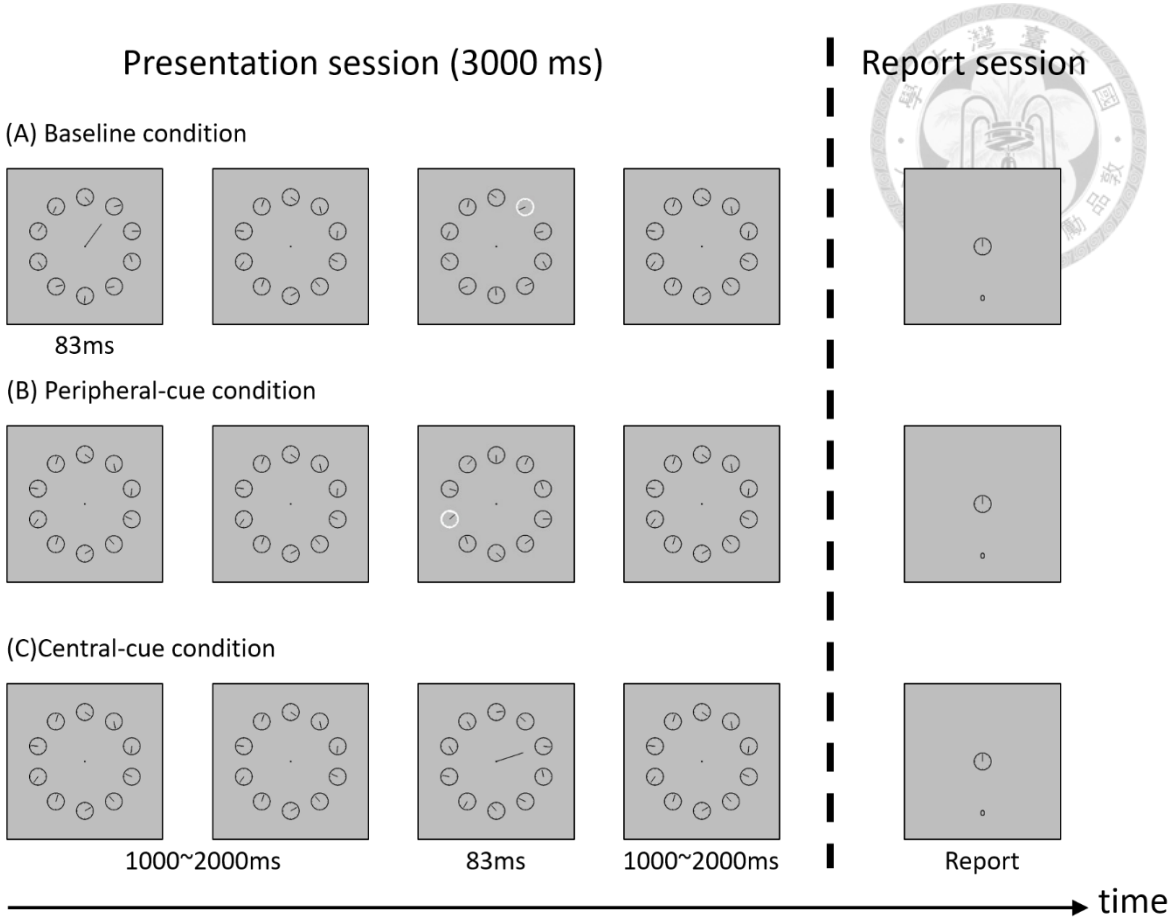

Figure 1. The procedure of the clock paradigm. Each trial of the clock paradigm consisted of two sessions: the presentation session and the report session. The presentation time of each trial was 3000 milliseconds (ms) in total. The cue was presented once for 83 ms during 1000~2000 ms after each trial began. There were three conditions: (A) Baseline condition: a cueing line was presented as a probe at the beginning of the trial for 83 ms. Afterwards, the rim of the target clock changed from black to white for 83 ms as a cue. (B) Peripheral-cue condition: the rim of the target clock changed from black to white for 83 ms as an exogenous cue. (C) Central-cue condition: a line was presented for 83 ms as an endogenous cue. After the presentation, the participants needed to report the time of the target clock by using the arrow key to adjust the orientation of the clock hand on the clock presented at the center of screen.

All experiments started with a 20-minute light adaptation. After the initial light adaptation phase, participants needed to complete the practice phase with 30 trials (10

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trials for each condition) to remind them of the experimental procedure. During the experiment phase, each condition contained 50 trials, resulting in a total of 150 trials across three conditions. The three conditions were mixed and assigned in a pseudo-random manner across the entire experiment phase. The experiment last about 40 to 60 minutes.

The procedure of the clock paradigm is illustrated in Figure 1. Each trial consisted of two sessions: the presentation session and the report session. In the presentation session, participants were asked to fixate at the fixation point during the trial and start the trial by pressing the space key. The presentation time of each trial was 3000 ms in total. The cue was presented once for 83 ms during 1000~2000 ms after each trial began. In the baseline condition, a 4-degree-long black cueing line extending from the fixation point to the target clock was presented as a probe at the beginning of the trial for 83 ms. Afterwards, the rim of the target clock changed from black to white as a cue. By this way, we can measure the performance without the time cost of attention shift since the spatial attention has been deployed on the target clock when cue was presented. In the peripheral-cue condition, the rim of the target clock changed from black to white as an exogenous cue. In the central-cue condition, a 4-degree-long black cueing line extending from the fixation point to the target clock was presented as an endogenous cue. In the report session, a clock was presented at

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the center of the screen. The participants needed to report the time of the target clock (when either the exogenous or the endogenous cue was presented) by using the arrow keys to adjust the orientation of the clock hand on it. The speed of attention shift was estimated by the time latency between true and reported cue-onset time:

(1) Attention shift latency (in ms)＝ [reported cue-onset time － true cue-onset time] * 1000/60

In Experiment 1A, a 2 (Background Light with blue and green levels) x 3 (Condition with baseline condition, peripheral-cue condition, and central-cue condition) within-subject factorial design was adopted to analyze the estimated attention shift latencies.

2.2. Results

We excluded the trials that the estimated latencies were deviated from three standard deviations of the average latencies under each condition (1.29% trials were excluded). The remaining trials were averaged and illustrated in Figure 2B. The estimated latencies of remaining trials were analyzed using a two-way repeated measures Analysis of Variance (ANOVA). The ANOVA revealed a main effect of

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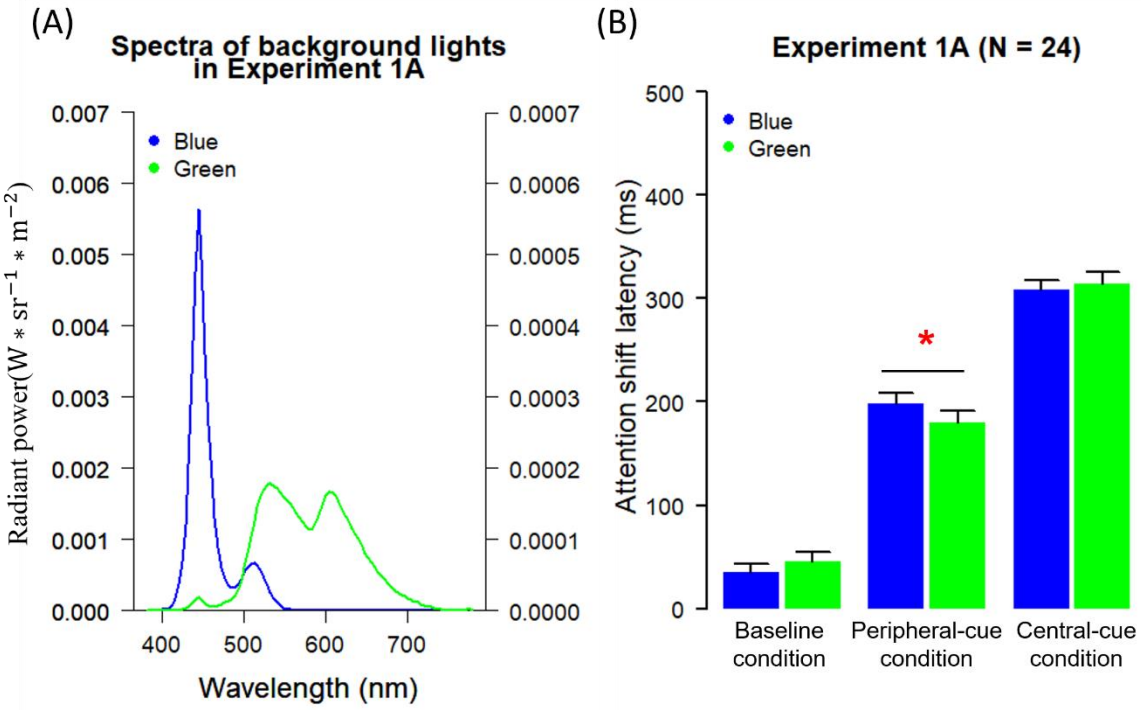

Figure 2. (A) Spectra of background lights in Experiment 1A. The spectra of blue and green background lights were presented by wavelength (x-axis) and radiant power (y-axis). The left y axis presented the radiant power of blue background light whereas the right y axis presented the radiant power of green background light. (B) Attention shift latencies in different conditions under blue and green background lights in Experiment 1A. The post-hoc test indicated that the average latencies of the peripheral-cue condition under blue background light were slower than for the ones under green background light. Error bars depict standard errors of the mean. The symbol* indicates a significant difference between the blue and green background lights (Holm adjusted $p < .05$).

Condition, $F(2, 46) = 424.60$, $p < .001$, $\eta_p^2 = .95$. The main effect of Background Light was not significant, $F(1, 23) = 0.06$, $p = .808$, $\eta_p^2 < .01$. Critically, the interaction effect between the Background Light and the Condition was significant, $F(2, 46) = 4.75$, $p = .013$, $\eta_p^2 = .17$. The following post-hoc test for the effect of background lights of each condition indicated that the average latencies of the

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peripheral-cue condition under blue background light were significantly slower than for the ones under green background light, Paired $t(23) = 2.72$, Holm adjusted $p = .036$. There was no significant difference observed in the baseline and central-cue conditions, all Holm adjusted $ps > .05$.

2.3. Discussion

The results of Experiment 1A replicated the findings of Carlson et al. (2006) that the estimated latencies differed in each condition. Although the latencies estimated in our study were higher than those in Carlson et al. (2006; Baseline condition: 40.41 v.s. 8.5 (ms); Peripheral-cue condition: 189.16 v.s. 141.00 (ms); Central-cue condition: 311.16 v.s. 237.25 (ms)), they were in the range of values reported in earlier studies (e.g., Müller, & Rabbitt, 1989). Moreover, the results showed that exposure to blue background light, compared to green background light, slowed down the speed of exogenous visual attention shift, but there was no difference in the endogenous attention shift between blue light and green light conditions. Contradictory to our prediction, the results indicated that blue light did not improve the speed of spatial attention (Matthias et al, 2010). Instead, blue light was detrimental to the exogenous visual attention shift.

However, it has been shown that alertness increment induced by blue light

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exposure impaired the accuracy in driving tasks (Rodríguez-Morilla, Madrid, Molina, & Correa, 2017; Rodríguez-Morilla, Madrid, Molina, Pérez-Navarro, & Correa, 2018). The alertness increment could improve the response speed but at the cost of accuracy (Posner, 1978). It is possible that blue light exposure did increase alertness on the one hand, but impaired the performance of exogenous visual attention shift on the other hand. Another explanation was that the blue light impairment we found was caused by other factors, like the stimulations of blue-light sensitive photoreceptors and the colors. To answer these questions, it was necessary to measure the alertness level directly and investigate how alertness level affected the speed of visual attention shift or not in the following experiments.

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3. Experiment 1B

In Experiment 1B, we aimed to replicate the previous results by making the luminance level equivalent in blue and green background lights to control the contribution of luminance on the temporal property of spatial attention (Chua, 2005) and also investigated whether blue-light exposure influenced the speed of exogenous attention shift through participants' alertness level. We applied the Karolinska Sleepiness Scale questionnaire (KSS; Åkerstedt & Gillberg, 1990) to measure participant's alertness level under different background lights. In addition, we also added a heterochromatic flicker photometry (HFP), which can create an achromatic circumstance to isolate the luminance contrast, to match the luminance between the blue and green background lights individually for a better control (e.g., Kaiser, 1988; Kelly & Van Norren, 1977; Lee, Martin, & Valberg, 1988). Also, we carried out linear mixed-effects model (LME) analysis to investigate how the stimulation of each photoreceptor, especially the blue-light sensitive photoreceptors such as S-cone and ipRGCs, contributed to the combined task performances of Experiment 1A and1B and predict possible results in the following experiments.

3.1. Methods

3.1.1. Participants. Twenty-seven male participants (age range: 20-34 years old)

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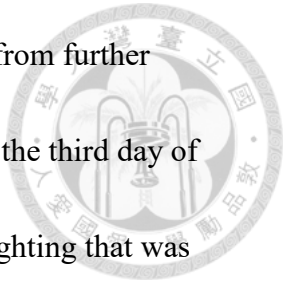

were recruited in Experiment 1B. Three participants were excluded from further analysis: (1) One participant wore the blue-light-blocking glasses in the third day of the experiment. (2) One participant happened to be exposed to the lighting that was out of our experimental planning during the experiment. (3) One participant did not follow the instructions. The final sample size for Experiment 1B was 24. All criteria were the same as in Experiment 1A.

3.1.2. Apparatus and stimuli. All the settings were the same as in Experiment 1A except for the following. First, the stimuli were displayed on a CRT monitor with a 60 Hz refresh rate. Second, the background colors were customized by the HFP to minimize the individual differences of luminance perception (Yaguchi, Kawada, Shioiri, & Miyake, 1993). In this experiment, the intensity of blue background light was kept at constant across the participants, and the intensities of the green background light were customized. The intensities of the green background lights were individually adjusted by HFP to match the luminance of the blue background light. The luminance-matched blue-green light pairs were used across the experiment. We used a PR655 Spectroradiometer to estimate the composition of blue and green background lights (see Figure 3A for the spectra). The peak wavelength of the blue background light was 452 nm (CIE xy color coordinate (0.14, 0.10)) and the peak wavelength of all green background lights was 528 nm (CIE xy color coordinate

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(0.31, 0.59)). The amounts of cone and ipRGCs stimulation are averaged and summarized in Table 1.

3.1.3. Procedure and design. Participants were asked to join in the experiment on three separate days. On the first day, participants completed a HFP to determine their equal-luminance point for green and blue background lights. Then, they performed the clock paradigm under grey background light (this was served as practice but they were not told about it). In the HFP, a filled circle (2° in diameter) was presented as a flicker at the center of the screen on a black background, and alternatively changed its color between blue and green with a frequency of 15 Hz. Since the temporal chromatic discriminability to this flicker was silenced, only the luminance difference of the blue and green background lights can be observed by the participant. The intensity of blue background light was kept constant (22.12 cd/ m^2) and the initial intensity of green background light was randomly assigned. Participants were introduced to adjust the intensity of green background light to make the two background lights fuse to a stable image as much as possible. Once the background lights fused, the luminance of green background light would be very close to that of blue background lights. The participants needed to complete the HFP five times, and the median intensity of the matched green background lights was used in the experiment in the green light condition.

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On the second and the third days, participants performed the formal tasks under the blue and green background lights matched by HFP. The order of the blue and green background lights was counterbalanced between participants. Before and after the clock paradigm, a KSS questionnaire was administered to participants to investigate their alertness level. For the KSS questionnaire, participants were asked to report the subjective alertness level by choosing one option whose description was closest to the alertness level they were at that moment. The options and their descriptions ranged from 1 (extremely alert) to 9 (very sleepy, great effort to keep alert, fighting sleep). The remaining procedure was identical to that used in Experiment 1A.

In Experiment 1B, a 2 (Background Light with blue and green levels) x 3 (Condition with baseline condition, peripheral-cue condition, and central-cue condition) within-subject factorial design was adopted to analyze data on the latencies of clock paradigm. These designs were the same as those used in Experiment 1A. Moreover, we also adopted a 2 (Background Light with blue and green levels) x 2 (Time with before the task and after the task level) within-subject factorial design to analyze the KSS scores. Additionally, we investigated the relations between the performance differences caused by blue light exposure. The relations between the blue-light effect on the attention shift latency of each condition and on the KSS scores

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before and after the task were analyzed by using linear regression model. The blue light effect on the attention shift latency and on KSS scores were used in the analysis:

(2) blue light effect on the attention shift latency ＝ average latency of the blue light condition － average latency of the green light condition

(3) blue light effect on KSS score ＝ KSS score of the blue light condition － KSS score of the green light condition

LME analysis were carried out to investigate how photoreceptors, especially S-cone and ipRGCs, contributed to the task performances by using the ‘lme4’ (Bates, Mächler, Bolker, & Walker, 2015) and ‘lmerTest’ (Kuznetsova, Brockhoff, & Christensen, 2017) packages with likelihood ratio tests from the statistical analysis software R. The data of Experiment 1A and 1B were combined in the analysis. The analysis comprised of three steps: (1) Compare the full and null models by using the likelihood ratio test to check whether the stimulation of the photoreceptors could predict the task performances of each condition or not. (2) Systematically reduce the fixed effects of the full model to prevent over-specification for the LME models. (3) Compute the slope of the determined models to provide parameters for the prediction

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of following experiments. The full and null models had the formula:

(4) Full model: latency ~ L + M + S + ipRGCs + (1|subject)

(5) Null model: latency~ (1|subject)

where L, M, S, ipRGCs are the amounts of stimulation for L-cone, M-cone, S-cone, and ipRGCs.

3.2. Results

We excluded the trials that the estimated latencies were deviated from three standard deviations of the average latencies under each condition (1.03% trials were removed). The remaining trials were averaged and illustrated in Figure 3B. The estimated latencies of remaining trials were analyzed using a two-way repeated measures ANOVA. Similar to the results reported in Experiment 1A, ANOVA revealed a significant main effect of Condition, $F(2, 46) = 456.10$, $p < .001$, $\eta_p^2 = .95$. The main effect of Background Light was insignificant, $F(1, 23) = 3.98$, $p = .058$, $\eta_p^2 = .15$. Critically, the interaction effect between Background Light and Condition was significant, $F(2, 46) = 3.96$, $p = .026$, $\eta_p^2 = .15$. The following Post-

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hoc test for the effect of background lights of each condition indicated that the average latencies in the peripheral-cue condition under blue background light were significantly higher than the ones under green background light, Paired $t(23) = 2.84$, Holm adjusted $p = .028$. There was no significant difference between blue light and green light exposure observed in the baseline and endogenous-cue conditions, all Holm adjusted *ps* > .05.

A two-way repeated measures ANOVA on the KSS scores revealed that there was neither interaction nor main effects of Background Light and Time, all *ps* > .05 (see Figure 4A). We also used linear regression analysis to investigate the relations between the effect of blue light on the attention shift latency of each condition and on the KSS scores before and after the task. The results showed that all the linear regression models were insignificant (all *ps* > .05).

The results of LME for the combined data (Experiments 1A and 1B) revealed that the stimulation of photoreceptors could predict the task performances of neither the baseline condition, $\chi^2(4, N = 48) = 2.45$, $p = .654$, nor the central-cue condition, $\chi^2(4, N = 48) = 8.63$, $p = .071$, but the peripheral-cue condition, $\chi^2(4, N = 48) = 13.96$, $p = .007$. After reducing other fixed effects, two models, S-cone model (model: latency ~ S + (1|subject)) and ipRGCs model (model: latency ~ ipRGCs + (1|subject)), were tested and determined. The goodness of fit of both models were

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significantly higher than the null model (S-cone model: $\chi^2(1, N=48) = 13.39$, $p < .001$; ipRGCs model: $\chi^2(1, N=48) = 13.03$, $p < .001$), and similar with full model (S-cone model: $\chi^2(3, N=48) = 0.58$, $p = .902$; ipRGCs model: $\chi^2(3, N=48) = 0.93$, $p = .818$). The slope of S-cone and ipRGCs models were 0.19 and 0.25, respectively.

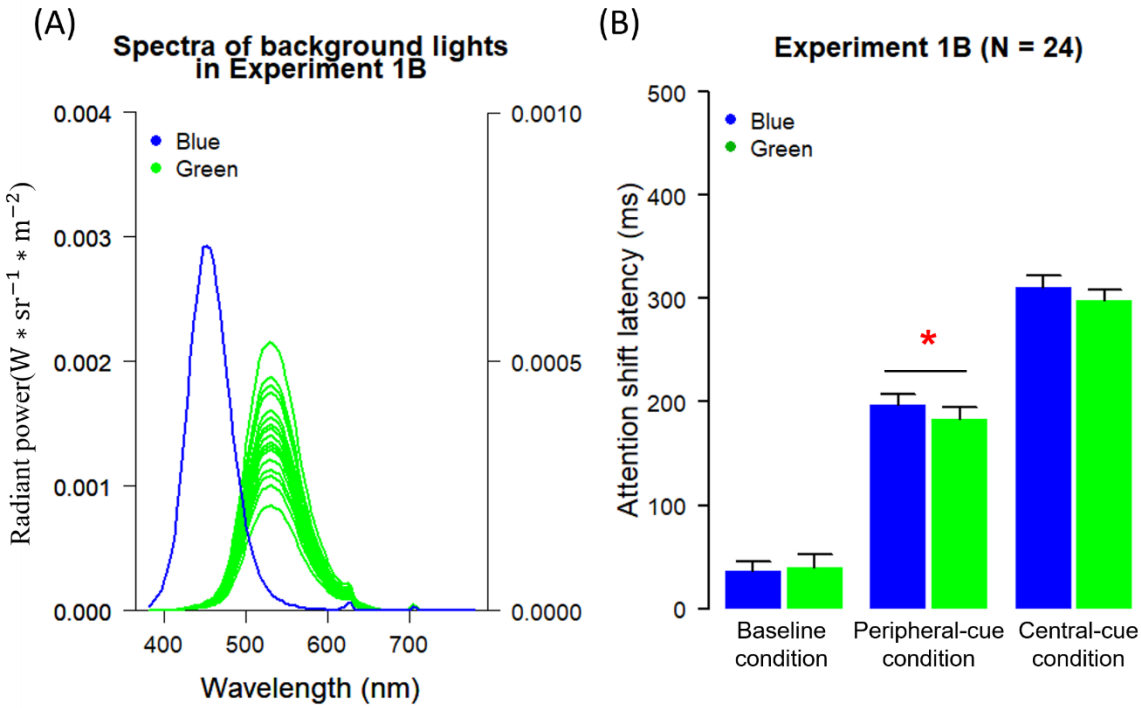

Figure 3. (A) Spectra of background lights in Experiment 1B. The spectra of blue and green background lights were presented by wavelength (x-axis) and radiant power (y-axis). The left y axis presented the radiant power of blue background light whereas the right y axis presented the radiant power of green background light. (B) Attention shift latencies in different conditions under blue and green background lights in Experiment 1B. The Post-hoc test indicated that the average latencies of peripheral-cue condition under blue background light were significantly higher than the ones under green background light. Error bars depict standard errors of the mean. The symbol * indicates a significant difference between the blue and green background lights (Holm adjusted $p < .05$).

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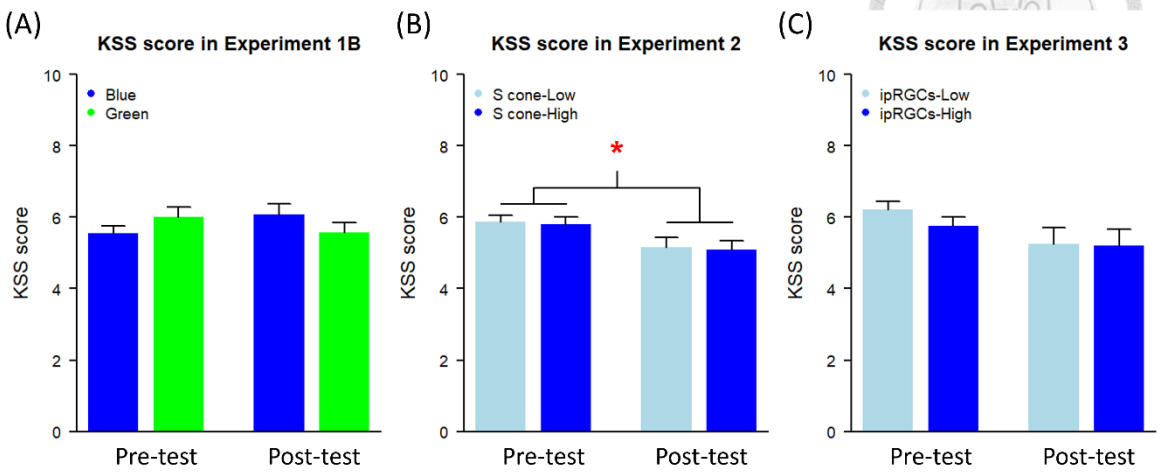

Figure 4. KSS scores in different time points under different background lights in (A) Experiment 1B, (B) Experiment 2, and (C) Experiment 3. Error bars depict standard errors of the mean. The symbol * indicates a significant difference between different time points in Experiment 2 ($p < .05$).

3.3. Discussion

Experiment 1B replicated the results of Experiment 1A, showing that the blue background light slowed down the speed of exogenous visual attention shift compared to green background light when the luminance of blue and green background lights was made equal for each individual participant. That is, the blue light impairment of exogenous attention shift was not due to the temporal property changes of spatial attention induced by the luminance level (Chua, 2005). More importantly, the impairment we found was independent to the participants' alertness level. That is, the blue-light impairment of exogenous attention shift was affected by the factors other than the alertness level; differences in color, cone stimulation, and ipRGCs

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stimulation were possible contributors to the results. The LME analysis further showed that the stimulation of S-cone and ipRGCs could be used to predict the blue light impairment of the speed of exogenous visual attention shift. We isolated these factors to tease apart what contributes to the blue-light effect on attention shift speed in the following experiments.

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4. Experiment 2

In Experiment 2, we investigated how the S-cone stimulation of background lights influenced the speed of visual attention shift. It has been found that the speed of exogenous and endogenous attention shift induced by S-cone contrast were slower than other cone and luminance contrasts (Anderson, Husain, & Sumner, 2008; McKeefry, Parry, & Murray, 2003). Thus, the S-cone stimulation of background lights was proposed in the literature to be the strongest candidate for the blue light impairment of exogenous attention shift due to the sluggish property of its processing (Conway & Livingstone, 2006; Cottaris & De Valois, 1998). We applied a multi-primary system that can manipulate the stimulations of three types of cones and the ipRGCs independently (Brown et al., 2012; Tsujimura & Okajima, 2015; Tsujimura, Ukai, Ohama, Nuruki, & Yunokuchi, 2010). By applying this system, we manipulated the stimulation of S-cone, and kept the stimulations of other photoreceptors at an identical level.

4.1. Methods

4.1.1. Participants. Thirty-one male participants (age range: 20-33 years old) were recruited for Experiment 2; one participant was excluded as outlier and six participants dropped out during the experiment. The final sample size for Experiment

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2 was 24. All criteria were the same as Experiment 1A.

4.1.2. Apparatus and stimuli. All stimuli were displayed on the multi-primary system with 60 Hz refresh rate. The participants sat at a distance of 30 cm from the display. All the stimuli in the clock paradigm were identical to those in Experiment 1B except for the background lights.

The multi-primary system consisted of three projectors and three interference filters. The lights produced from the projectors passed through the filters, and projected to the screen in front of the participant. The peak wavelengths of the four primaries were 455 nm, 530 nm, 580 nm, and 595 nm. By overlapping the images from the four primaries, the stimulation of each type of photoreceptors can be manipulated independently. In order to manipulate the stimulation of the S-cone, the multi-primary system was used to create two background lights corresponding to two conditions: S-cone-low and S-cone-high (see Figure 5A for the spectra). The peak wavelength in the S-cone low condition was 580 nm (CIE xy color coordinate (0.53, 0.41)) and the peak wavelength in the S-cone high condition was 580 nm (CIE xy color coordinate (0.47, 0.34)). The amounts of cone and ipRGCs stimulation are summarized in Table 1.

4.1.3. Procedure and design. Participants came to the lab on three separate days. On the first day, participants performed the task on an LCD screen under the

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grey background light. On the second and the third days, the participants performed the formal tasks for S-cone low and S-cone high conditions, respectively. The order of the S-cone-low and S-cone-high conditions was counterbalanced between participants. The remaining procedure was identical to that used in the second and third days of Experiment 1B.

In Experiment 2, A 2 (Background Light: S-cone-low, S-cone-high) x 3 (Condition: baseline, peripheral-cue, and central-cue) within-subject factorial design was employed to examine the latencies obtained from the clock paradigm. In addition, A 2 (Background Light with S-cone-low and S-cone-high levels) x 2 (Time with before the task and after the task level) within-subject factorial design was employed to examine the KSS scores. These designs were the same as those used in Experiment 1B.

Moreover, we calculated the expected and observed S-cone effect on the speed of exogenous visual attention shift to investigate whether the effect of S-cone stimulation and the impairment effect of blue light on exogenous visual attention shift were caused by the same mechanism. The slope of S-cone effect (0.19) calculated from the LME analysis conducted in Experiment 1B was used as the coefficient in the estimation of expected S-cone effect.

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(6) Expected S-cone effect on the speed of exogenous visual attention shift ＝0.19 * [S-cone stimulation of S-cone-high background light －S-cone stimulation of S-cone-low background light] = 6.26 (in ms)

(7) S-cone effect on the speed of exogenous visual attention shift ＝ average latency of peripheral-cue condition under S-cone-high background light － average latency of peripheral-cue condition under S-cone-low background light (in ms)

4.2. Results

We excluded the trials that the estimated latencies were deviated from three standard deviations of the average latencies under each condition (1.33% trials were remove). The remaining trials were averaged and illustrated in Figure 5B. The estimated latencies of remaining trials were analyzed using a two-way repeated measures ANOVA. A main effect of Condition was found, $F(2, 46) = 351.80$, $p < .001$, $\eta_p^2 = .94$. However, there was neither interaction effect between Background Light and Condition, $F(2, 46) = 0.26$, $p = .776$, $\eta_p^2 = .011$, nor the main effect of Background Light, $F(1, 23) = 0.02$, $p = .879$, $\eta_p^2 < .01$.

The result of one-sample *t* test revealed that the observed S-cone effect on the speed of exogenous visual attention shift did not significantly differ from the expected

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value, $t(23) = -1.48$, $p = .153$.

A two-way repeated measures ANOVA on the KSS sores revealed a main effect of the Time, $F(1, 23) = 9.73$, $p = .005$, $\eta_p^2 = .30$, which showed that participants' alertness level increased during the task. However, there was neither interaction effect between Background Light and Time nor the main effect of Background Light, all *ps* > .05 (see Figure 4B).

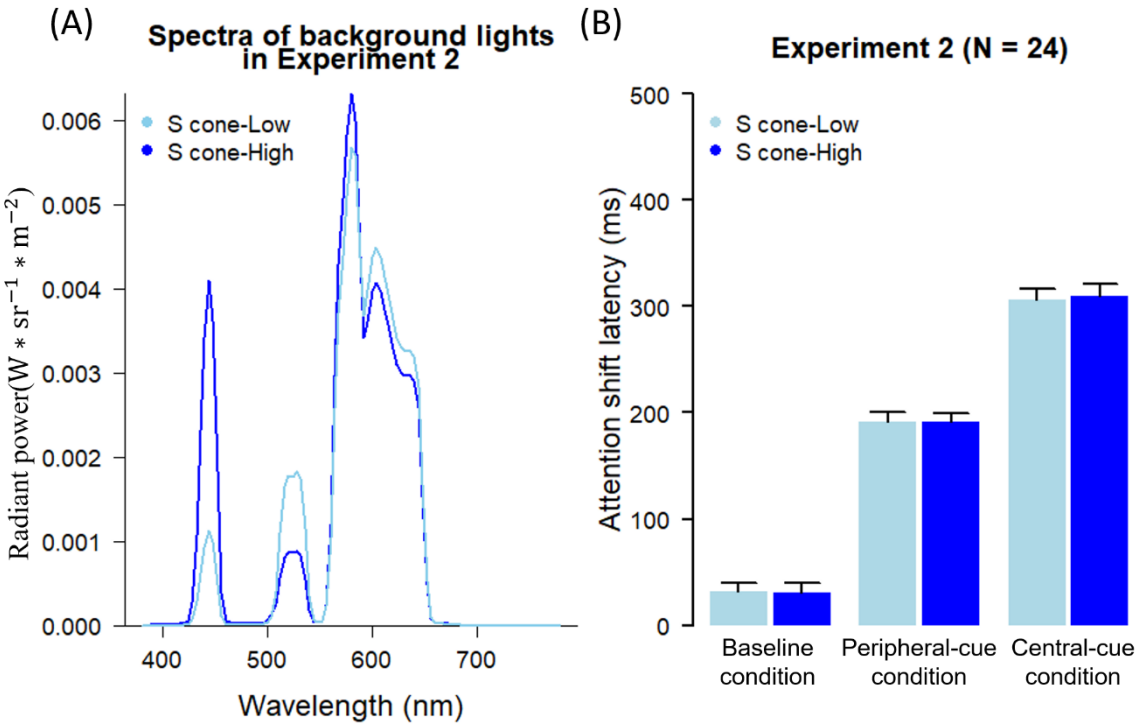

Figure 5. (A) Spectra of background lights in Experiment 2. The spectra of low and high S-cone stimulating background lights were presented by wavelength (x-axis) and radiant power (y-axis). (B) Attention shift latencies in different conditions under low and high S-cone stimulating background lights in Experiment 2. Error bars depict standard errors of the mean.

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4.3. Discussion

The results of Experiment 2 showed that the S-cone stimulation of background lights did not affect the speed of both exogenous and endogenous visual attention shift. However, the observed S-cone effect did not deviate from the expected value calculated from the results of Experiments 1A and 1B. Taken together, the absence to observe the effect of S-cone on the speed of visual spatial attention could be due to the insufficient manipulation of S-cone stimulation. Although participants' alertness level increased during the task since concentrating to the task, it was not influenced by the background lights. The results were consistent of the finding of Spitschan, Lazar, Yetik, and Cajochen (2019) which showed that S-cone stimulation did not contribute to both subjective and objective alertness.

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5. Experiment 3

In Experiment 3, we investigated if ipRGCs stimulation of background lights affected the speed of visual attention shift. By applying the multi-primary system, we manipulated the stimulation of ipRGCs, and kept the stimulations of other photoreceptors at an identical level. Two hypotheses were tested: (1) *ipRGCs impairment hypothesis*: the blue light impairment of exogenous visual attention shift was due to the ipRGCs stimulation of background lights, which predicted that the ipRGCs stimulation of background lights impaired the exogenous visual attention shift, and (2) *alertness increment hypothesis*: the ipRGCs stimulation could increase participants' alertness level (Cajochen, 2007) that would speed up the processing of spatial attention (Matthias et al., 2010), which predicted that the ipRGCs stimulation of background lights accelerated the speed of both exogenous and endogenous visual attention shift through alertness increment. In addition, some studies showed that the ipRGCs stimulation could directly improve the cognitive performances without changes of alertness level (Alkozei et al., 2016; Newman et al., 2016). We suggested that the ipRGCs stimulation speeded up both exogenous and endogenous visual attention shift without alertness increment could be a possible result.

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5.1. Methods

5.1.1. Participants. Twenty-seven male participants (age range: 20-34 years old) were recruited for Experiment 3; one participant was excluded as outlier, and two participants dropped out during the experiment. The final sample size for Experiment 3 was 24. All criteria were the same as Experiment 1A.

5.1.2. Apparatus and stimuli. The apparatus and stimuli used in Experiment 3 was identical to those in Experiment 2 except for the background lights.

In order to manipulate the stimulation of ipRGCs, we used the multi-primary system to create two background lights corresponding to two conditions: ipRGCs-low and ipRGCs-high (see Figure 6A for the spectra). The peak wavelength in the ipRGCs low condition was 580 nm (CIE xy color coordinate (0.50, 0.37)) and the peak wavelength in the ipRGCs high condition was 604 nm (CIE xy color coordinate (0.49, 0.39)). The luminance value for the ipRGCs low condition was 162.17 cd/ m^2 and the luminance value for the ipRGCs high condition was 178.64 cd/ m^2, respectively. The amounts of cone and ipRGCs stimulation are summarized in Table 1.

5.1.3. Procedure and design. The procedure was the same as in Experiment 2 and the experimental design was identical to those in Experiment 1B except for the following. First, the factor Background Light used in the analysis was with two levels: ipRGCs-low and ipRGCs-high. Second, the formula of ipRGCs effect was the same

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as that of blue light effect, but calculated by the task performances under different ipRGCs-stimulating background lights:

(8) ipRGCs effect on the attention shift latency ＝ average latency of the ipRGCs-high condition － average latency of the ipRGCs-low condition

(9) ipRGCs effect on KSS score ＝ KSS score of the ipRGCs-high condition － KSS score of the ipRGCs-low condition

Third, we calculated the expected and observed ipRGCs effect on the speed of exogenous visual attention shift to investigate whether the effect of ipRGCs stimulation and the impairment effect of blue light were caused by the same mechanism or not. The slope of ipRGCs effect (0.25) calculated from the LME analysis conducted in Experiment 1B was used as the coefficient in the estimation of expected ipRGCs effect.

(10) Expected ipRGCs effect on the speed of exogenous visual attention shift ＝0.25 * [ipRGCs stimulation of ipRGCs-high background light －ipRGCs stimulation of ipRGCs-low background light] = 7.65 (ms)

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5.2. Results

We excluded the trials that the estimated latencies were deviated from three standard deviations of the average latencies under each condition (1.36% trials were removed). The remaining trials were averaged and illustrated in Figure 6B. The estimated latencies of remaining trials were analyzed using a two-way repeated measures ANOVA. The main effect of Condition was significant, $F(2, 46) = 598.50$, $p < .001$, $\eta_p^2 = .96$. The main effect of Background Light was insignificant, $F(1, 23) = 3.62$, $p = .070$, $\eta_p^2 = .14$. Critically, the interaction effect between Background Light and Condition was significant, $F(2, 46) = 3.58$, $p = .036$, $\eta_p^2 = .13$. However, the post-hoc test for the effect of background lights of each trial condition showed that there was no significant difference between the ipRGCs low and the ipRGCs high conditions in all the conditions (baseline: Paired $t(23) = -0.54$, Holm adjusted $p = 1$; peripheral-cue: Paired $t(23) = 1.67$, Holm adjusted $p = .327$; central-cue: Paired $t(23) = 2.30$, Holm adjusted $p = .094$).

Although there was no significant difference between the ipRGCs low and ipRGCs high conditions in each condition, the interaction effect could be attributed from the contrast-contrast interaction (Kirk, 2013). The test of contrast-contrast interaction is to analyze the interactions between the contrasts of the two factors of interest. By testing the contrast-contrast interaction, we could get more precise

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information than post-hoc test for the further analysis of the significant interaction effect. We therefore tested the contrast-contrast interaction for the two factors: Background Light and Condition. On the one hand, one contrast was tested for the Background Light, $\hat{\varphi}_L$(ipRGCs low, ipRGCs high): $\hat{\varphi}_L$(-1,1). The $\hat{\varphi}_L$ represented the ipRGCs levels we defined above. On the other hand, according to our hypothesis, two contrasts were tested for Condition, $\hat{\varphi}_{T_i}$(baseline condition, peripheral-cue condition, central-cue condition): $\hat{\varphi}_{T_1}$(-1,2,-1), and $\hat{\varphi}_{T_2}$(2,-1,-1). The $\hat{\varphi}_{T_i}$ represented the contrast of two groups of conditions we defined. The $\hat{\varphi}_{T_1}$ represented the hypothesis that the ipRGCs stimulation of background lights impaired the exogenous visual attention shift whereas the $\hat{\varphi}_{T_2}$ represented the hypothesis that the ipRGCs stimulation of background lights accelerated the speed of both exogenous and endogenous visual attention shift through alertness increment. The results indicated that (1) the $\hat{\varphi}_{T_1}$ did not interact with $\hat{\varphi}_L$, $F(1,46) = 0.19$, $p = .664$, $\eta_p^2 < .01$, and (2) the $\hat{\varphi}_{T_2}$ significantly interacted with $\hat{\varphi}_L$, $F(1,46) = 6.27$, $p = .016$, $\eta_p^2 = .12$. The effect of ipRGCs stimulation for the peripheral-cue and central-cue conditions was significantly different from those for baseline condition. That is, compared to the baseline, the ipRGCs stimulation accelerated the speed of both the exogenous and endogenous attention shift.

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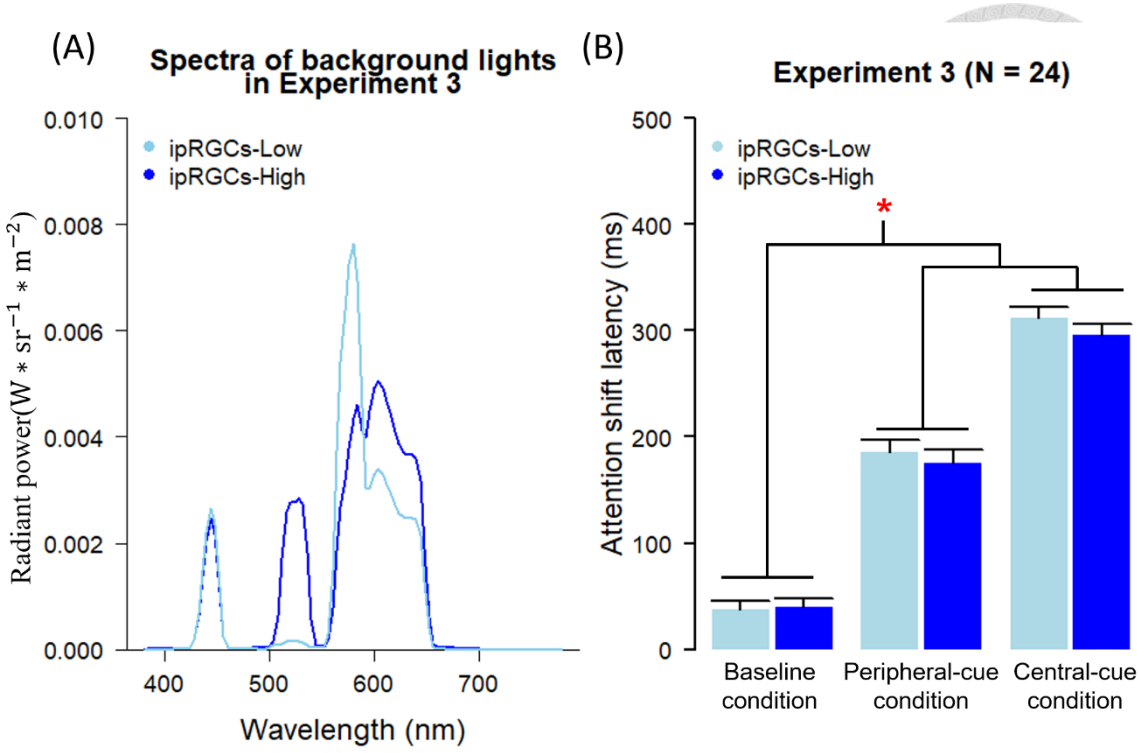

Figure 6. (A) Spectra of background lights in Experiment 3. The spectra of low and high ipRGCs stimulating background lights were presented by wavelength (x-axis) and radiant power (y-axis). (B) Attention shift latencies in different conditions under low and high ipRGCs stimulating background lights in Experiment 3. The contrast-contrast interaction revealed that the ipRGCs stimulation accelerated the speed of both the exogenous and endogenous attention shift. Error bars depict standard errors of the mean. The symbol * indicates a significant ipRGCs effect difference between the baseline condition, and peripheral-cue and central-cue conditions ($p < .05$).

The result of one-sample *t* test revealed that the observe ipRGCs effect on the speed of exogenous visual attention shift significantly differed from the expected value, $t(23) = -2.98$, $p = .007$, which suggested that the effect of ipRGCs and the impairment effect of blue light on exogenous visual attention shift were different mechanisms.

A two-way repeated measures ANOVA of the KSS scores revealed that there was

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neither interaction nor main effects of Background Light and Time, all *ps* > .05 (see Figure 4C). In addition, we use linear regression analysis to investigate the relations between the ipRGCs effect on the attention shift latency of each condition and on the KSS scores before and after the task. The results showed that all the linear regression models were insignificant in the analysis, all *ps* > .05.

5.3. Discussion

The results of Experiment 3 showed that the ipRGCs stimulation of background lights accelerated the speed of both exogenous and endogenous visual attention shift. The observed ipRGCs effect was deviated from the expected value calculated from the results of Experiments 1A and 1B, which suggested that the ipRGCs stimulation of background lights did not contribute to the blue light impairment. In addition, we found that participants' alertness level was independent of the effect of ipRGCs stimulation on the visual attention shift. The finding of this experiment indicated that the facilitation effect of ipRGCs was not due to the alertness increment.

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6. General Discussion

The current study examined whether and how blue light influenced exogenous and endogenous visual attention shift. We conducted the experiment under blue and green light background and found that exposure to blue light slowed down the speed of exogenous visual attention shift (Experiment 1A and 1B). To further clarify the contributions of blue-light sensitive photoreceptors (i.e., S-cone, ipRGCs), we applied the multi-primary system to manipulate the stimulation of a single type of photoreceptors without any stimulation change of other photoreceptors (i.e., the silent substitution method). The results showed that the stimulation of S-cone (Experiment 2) and ipRGCs (Experiment 3) did not contribute to the blue light impairment of exogenous visual attention shift. Taken together, we found a novel blue light impairment of exogenous visual attention shift that was caused by color, but not due to alertness, S-cone stimulation, and ipRGCs stimulation.

In the present study, the primary finding is that exposure to blue light slows down the speed of exogenous visual attention shift. After examining the potential candidates responsible to the impairment of blue light such as alertness increment, S-cone stimulation, and ipRGCs stimulation, we suggested that the blue color is the cause. When the stimuli were made to be metamers in Experiment 2 and 3 so that no color difference existed in the background lights but only different stimulation level

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of S cone (high vs. low in Experiment 2) and ipRGCs (high vs. low in Experiment 3), the blue light impairment effect on exogenous attention shift disappeared. It has been shown that color could selectively affect task performance in different cognitive domains (Elliot, 2015; Li, Chen, Pan, Wang, & Yang, 2021; Mehta & Zhu, 2009) through learned associations to colors (Elliot, 2015; Elliot & Maier, 2012). For example, Mehta and Zhu (2009) revealed how red and blue colors affected task performances. The authors argued that red color is associated with dangers and mistakes, and so red facilitates task performances related to hazard and compliance, whereas blue color is often associated with sky and sea, and so blue improves the performances associated with openness and peace. They found that the red background color facilitated the avoidance-related processing and enhanced the performance on a detail-oriented task, whereas the blue background color facilitated the approach-related processing and enhanced the performance on a creativity task (Mehta and Zhu, 2009). In sum, learned association to color could activate alternative motivations and thus influence specific cognitive performance.

However, according to the color-in-context theory, how color affects cognitive performance depends on its context (Elliot & Maier, 2012; Elliot 2015). For example, blue background color is related to openness, peace, and tranquility (Mehta & Zhu, 2009); blue stores and logos are associated with high quality and trustworthy (Alberts

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& van der Geest, 2011; Labrecque & Milne, 2012; Lee & Rao, 2010; Ridgway & Myers, 2014; Yüksel, 2009); blue food and drink are linked to unnatural and artificial in some cases (Spence, 2018). The same blue color can have different meanings and influence human cognitions in different ways depending on its context (Elliot & Maier, 2012; Elliot 2015).

In our study, we introduced and described the background screen colors as the background lights to the participants in the experiment. Thus, in this context, the blue screen background would be viewed as the light source of blue light. People may link the blue light with its damages on retina, the *blue light hazard* (BLH), because many media and worldly-known corporations claimed that exposure to the blue-enriched light sources such as LEDs may be harmful to the eyes (Lawrenson, Hull, & Downie, 2017; O'hagan, Khazova, & Price, 2016; Zhao, Zhou, Tan, & Li, 2018). Although the meta-analysis showed that the blue light filter lenses did not benefit on eye health (Lawrenson et al., 2017), it cannot stop people to keep wearing blue-light-filtered glasses and turning on the blue light filter mode when using the electronic devices such as cellphones and laptops (Singh, Anderson, & Downie, 2019). The panic of BLH is still spreading across the globe. The negative attitude toward blue light may activate the motivation to hold back and led to the impairment of task performance under blue background light.

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Past studies showed that exogenous attention is more sensitive to unconscious information than endogenous attention (McCormick, 1997). Moreover, it has been shown that the association to colors affected cognitive performances in an unconscious manner, which sometimes may be contradictory to participants' expectations (Mehta & Zhu, 2009). The sensitivity and susceptibility to unconscious information could be the cause why the association to blue light selectively affected exogenous visual attention shift shown in the current study.

Although we did not observe a significant S-cone effect on the speed of exogenous visual attention shift, the observed S-cone effect did not significantly deviate from the expected value calculated from Experiments 1A and 1B. It is possible that the manipulation of S-cone stimulation in Experiment 2 was too small to impair the speed of exogenous visual attention shift. Future studies are needed to investigate whether the stimulation of S-cone, with more than 66 times of manipulation, could impair the speed of exogenous visual attention shift.

Some may argue that differences in acuity, chromatic contrast, and luminance contrast between blue and green lights could contribute to the impairment effect of blue light on the exogenous visual attention shift; however, this is unlikely. Although the acuity of blue light is smaller at fovea and higher at high eccentricity compared with green light, they are similar at 2° to 15° eccentricity (Noorlander, Koenderink,

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Den Olden, & Edens, 1983). The processing of the exogenous cue and the target clock presented at 7° eccentricity in the current study would not confound with the acuity difference between blue and green lights. Past studies indicated that the chromatic and luminance contrast could influence the speed of visual spatial attention (McKeefry et al., 2003; O'Donell & Colombo., 2008); however, the effects of chromatic and luminance contrast survive only when the luminance contrast is under 30% (O'Donell & Colombo., 2008). In our study, the luminance contrast between the exogenous cues and the background lights were over 1000% across the experiments. Thus, the chromatic and luminance contrast should not affect the processing of exogenous visual attention shift.

We also showed that the ipRGCs stimulation of metameric background lights facilitated the speed of both exogenous and endogenous visual attention shift. However, the facilitation effect of ipRGCs was independent of participants' alertness level. Anatomical studies suggest that there are some brain areas, such as superior colliculus (SC), directly receive signals from ipRGCs without mediations of the alertness-related brain areas (Brown et al., 2010; Gooley et al., 2003). Through the SC–mediodorsal thalamus–frontal eye field (FEF) ascending pathway (Kirchner et al., 2009; Sommer & Wurtz, 2000), the signals, such as ipRGCs stimulation of background lights, could modulate the activities of FEF and further improve the

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performances of eye movements and covert attention (Thompson, Biscoe, & Sato, 2005). Functional Magnetic Resonance Imaging (fMRI) studies provide evidences that ipRGCs stimulation of metameric lights could increase the blood oxygen-level dependent (BOLD) responses of FEF (Hung et al., 2017). Furthermore, Lee and Yeh (2021) found that blue light exposure facilitated saccadic eye movements and attentional disengagement. Since they did not directly manipulate the stimulation of ipRGCs, our current study provides an empirical evidence that ipRGCs stimulation of background lights could facilitate cognitive performances related with FEF, such as exogenous and endogenous visual attention shift (Thompson et al., 2005).

Researchers often used blue light to investigate the effect of ipRGCs (e.g., Lee & Yeh, 2021; Tonetti & Natale, 2019) that blue light can stimulate ipRGCs dozens of times greater than other colored lights, but, by definition, it is with color which could be confounded with the effect of ipRGCs. However, only few studies conducted a series of experiments trying to understand how color and ipRGCs stimulation contribute to cognitive performances (Chien et al., 2020; Chen & Yeh, 2019; Yang et al., 2018). Yeh and colleges observed that the effect of blue light on subjective time expansion (Yang et al., 2018) was due to the ipRGCs stimulation of background lights, whereas the effects of blue light on multi-sensory integration (Chien et al., 2020) are contributed by effect of colors on the magnocellular processing. The

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relation between effect of color and of ipRGCs is still unclear. In our study, we observed the impairment effect of blue light on the exogenous visual attention shift and the facilitation effect of ipRGCs on both exogenous and endogenous visual attention shift. It is reasonable that the blue light used in our study also activated the facilitation effect of ipRGCs, but was cancelled by the effect of colors. Our finding provides evidence that the contribution of blue color dominates over that of blue-light sensitive photoreceptors on visual attention shift, and suggests that the influence of color on higher cognitive processing should not be overlooked.

Past studies investigating how blue light affected human attention have used the Attention Network Test (ANT; Fan et al., 2002) but obtained inconsistent results (Smolders & de Kort, 2017; Studer et al., 2019; Tonetti & Natale, 2019). Comparing the ANT paradigm and the clock paradigm we used, the biggest difference between the two paradigms is the way to estimate the speed of visual attention shift: the ANT requires participants to respond to the target as quickly as possible by pressing the keys, but the clock paradigm uses perception report and later report which asks participants to report the clock time they perceived after the presentation session. Whether using manual RT as the dependent variable or not could be important to observe the effect of blue light. Lee and Yeh (2021) showed that the effect of blue light observed in the saccadic RTs disappeared in the manual RTs perhaps due to

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manual RTs insensitivity to the blue light manipulation (Lee & Yeh, 2021). Thus, we suggest that conducting the experiment using perception report, later report, or physiological parameters is a better way than using manual RT (i.e. ANT paradigm) to investigate the effect of blue light on cognitive performances.

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7. Conclusion

Our study shows a novel blue-light color impairment effect on exogenous visual attention shift that was not caused by alertness, S-cone stimulation, and ipRGCs stimulation, indicating that the contribution of blue color dominates over that of blue-light sensitive photoreceptors on visual attention shift. The influence of color on higher cognitive processing, such as visual attention shift found here, should be more carefully examined, especially under the era of high exposure to blue light every day with the alarmist call of blue-light hazard.

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