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Blue-light effects on saccadic eye movements and attentional disengagement

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Abstract

People are constantly exposed to high-energy blue light as they spend considerable amounts of time reading and browsing materials on electronic products like computers and cellphones. Recent studies suggest that the stimulation of intrinsically photosensitive retinal ganglion cells (ipRGCs)—a newly discovered type of photoreceptor shown to be particularly sensitive to blue light—activates brain regions related to eye movements and attentional orienting (e.g., frontal eye fields). It remains unclear, however, whether and how blue light affects eye movements and attention behaviorally. We examined this by adopting the gap paradigm in which participants made saccades to a peripheral target as quickly and accurately as possible while the fixation sign vanished (i.e., the gap condition) or remained visible. Participants were exposed to blue and orange light on two separate days. Faster saccade latency under blue light was found across two experiments, and the results indicate that blue light shortened saccade latency when attention and eye movements operate simultaneously. Our findings provide evidence for the blue-light facilitatory effect on eye movements and attentional disengagement, and suggest that blue light can enhance the speed of saccadic eye movements.

Keywords Attentional disengagement · Blue light · Eye movement · Gap effect · Saccade latency

We constantly use electronic products that usually contain high-energy blue light, such as computers and cellphones, and exposure to high-energy blue light has been shown to affect various aspects of human physiological and psychological functions. To name a few, blue light has been shown to delay the time we fall asleep at night and affect our circadian rhythms (Chang, Aeschbach, Duffy, & Czeisler, 2015; Daneault, Dumont, Masse, Vandewalle, & Carrier, 2016; Schmidt, Chen, & Hattar, 2011; Studer et al., 2019; Vandewalle et al., 2006), as well as affect cognitive functions such as alertness (Beaven & Ekström, 2013; Cajochen et al., 2005; Phipps-Nelson, Redman, Schlangen, & Rajaratnam, 2009; Souman, Tinga, Te Pas, Van Ee, & Vlaskamp, 2018), visuo-spatial attention (Newman et al., 2016), working memory (Daneault et al., 2018; Vandewalle et al., 2013; Vandewalle et al., 2007; Vandewalle, Maquet, & Dijk, 2009), and time perception (Yang, Tsujimura, Matsumoto, Yamashita, & Yeh, 2018). For instance, Phipps-Nelson et al. (2009) found that participants' reaction times (RTs) to the psychomotor vigilance task (PVT) were faster, and the authors attributed it to increased alertness under exposure to high-intensity blue-light, compared with dim white ambient light. Similarly, Newman et al. (2016) found faster RTs for detecting the coherence of randomly moving dots in the visual periphery under brighter than under dimmer blue light, which they attributed to enhanced covert attention under higher intensity of blue-enriched light. Daneault et al. (2018) showed that in the *n*-back working memory task, accuracy was higher

Public significance How blue light affects our browsing and reading behaviors becomes a critical issue as people are exposed to high-energy blue light through the use of electronic products every day. We examined whether blue light affects eye movements by using saccade latency as the index of eye movement performance. We found that blue light shortened saccade latency, which may be important given the large role of blue light in our contemporary lives.

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and RTs were faster under blue than orange light. Yang et al. (2018) adopted the oddball paradigm and found that blue light expanded the subjective duration of time compared with red light. Together, these findings of blue-light facilitatory effects on cognitive functions are compatible with the prominent role that blue light may play in our daily lives.

Despite the studies mentioned above suggesting that alertness and visual attention is enhanced under blue light, a closely related visual function, saccadic eye movements, has never been examined. Our goal here is to examine whether or not blue light affects saccadic eye movements and attention. Chen and Yeh (2019) was the first to examine the effects of blue light on eye pursuit by measuring the discrepancy between eye gaze and target location. They found that blue light, compared with orange light, enhanced *pursuit*. However, it remains unknown whether the behavior of human *saccadic* eye movements, another type of the eye-movement system, is also influenced by blue light. Saccadic eye movements are important during reading, since reading involves ample rapid saccades and short fixations while executing visual processing of written text (Liversedge & Findlay, 2000). Saccadic eye movements also allow us to better identify objects (Wolfe & Whitney, 2014). Moreover, visual attention and saccadic eye movements usually operate together (Hoffman & Subramaniam, 1995; Posner, 1980). According to the premotor theory of attention, attentional orienting toward a location occurs before the oculomotor programming for movement starts to execute (Rizzolatti, Riggio, Dascola, & Umiltá, 1987), which further guides the oculomotor system of saccades and fixations. Rizzolatti et al. (1987) compared participants' simple manual RT with a target that was either in the same or different hemifield of attentional allocation, and found longer RTs when the target was in the opposite hemifield as the initially deployed attention. This meridian effect was taken by Rizzolatti et al. (1987) to indicate that attention serves as a prior inducer of eye movements, since the response driven by the programming of eye movements to the target was influenced by the location of prior attention. The concept of the premotor theory was further supported by other studies adopting eye movements as measures (Deubel & Schneider, 1996; Sheliga, Riggio, & Rizzolatti, 1995), and this theory explains the reason foveation in everyday life is preceded by attentional orienting.

We adopted the gap paradigm (Saslow, 1967) and used saccade latency as the index of eye-movement performance to test the effects of blue light. Saccade latency indicates the time for transformation from fixation to saccade in the oculomotor system. Participants in the gap paradigm are required to make a saccadic response to the peripheral target as quickly and accurately as possible. By manipulating the disappearance (or not) of the central fixation before target onset in the periphery, typical results of *the gap effect* revealed shorter saccade latencies in the gap condition (where the fixation sign vanishes shortly before target onset) than those of the overlap condition (where the fixation sign remains visible even after target onset).

Two of the hypotheses proposed to explain the gap effect are examined here. The *attentional disengagement hypothesis* states that attention disengagement from the fixation sign is the prominent component of the facilitation (Jin & Reeves, 2009; Pratt, Lajonchere, & Abrams, 2006). Given that attention should be disengaged before shifting to the peripheral target (Posner, Walker, Friedrich, & Rafal, 1984), the removal of the fixation sign in the gap condition could facilitate the disengagement of attention from the central location. Second, the *oculomotor hypothesis* refers to the antagonism of saccade-related neurons and fixation-related neurons in the superior colliculus (SC; Fendrich, Demirel, & Danziger, 1999; Machado & Rafal, 2000; Reuter-Lorenz, Hughes, & Fendrich, 1991; Tam & Stelmach, 1993). Human saccade and fixation behaviors are mainly dominated by these two types of antagonistic cells in the SC (Dorris, Pare, & Munoz, 1997; Goffart, Hafed, & Krauzlis, 2012). Hence, when an organism is fixating on the central location and fixation-related neurons are activated, the saccade-related neurons are suppressed, causing longer RTs in the overlap condition than those in the gap condition.

Notably, blue light affects the critical factors that contribute to the facilitation of saccade latency. First, dynamic vision related to eye movements is enhanced by blue light (Chen & Yeh, 2019). Secondly, brain regions that are highly correlated with eye movements, such as frontal eye fields (FEF) and cerebellum, are influenced by blue-light sensitive intrinsically photosensitive retinal ganglion cells (ipRGCs; Hung et al., 2017). Thirdly, Ecker et al. (2010) proposed that ipRGCs are innervated to the SC, implying the possibility of the large role that blue light might play in eye movements. We hypothesize that blue light could modulate saccadic eye movements and attentional allocation through these pathways.

To examine this issue, we compared saccadic performance under blue-enriched light (which we will refer to as *blue light* hereafter) versus red-enriched light (the control condition, which we will refer to its appearance as *orange light* hereafter). Orange light was chosen as the control condition to minimize the stimulation of ipRGCs, short-wavelength cones, and rods, and also to avoid the contamination effect from using a color further down the spectrum, such as red, which might serve as a warning or stop signal that potentially carries stereotypical features (Chen & Yeh, 2019; Funke, 2010). A white-light background does not serve as an adequate control to the current study given that white light excites a wide range of S, M, L cones as well as ipRGCs, and thus causes difficulty in controlling underlying components and activations of each types of photoreceptors.

Four target locations (up, down, left, and right) were manipulated to investigate if blue light affects saccadic eye movements only in certain directions. Chen and Yeh (2019) have shown that

blue light, compared with orange light, enhanced dynamic visual acuity in the downward direction (targets moved from the upper portion of a screen to the lower portion), but not the upward direction (targets moved from the lower portion of a screen to the upper portion). In addition, the authors found that blue light enhanced eye pursuit accuracy in the vertical axis, but not in the horizontal axis. That is, blue-light effects vary for different eye movement directions. Moreover, Newman et al. (2016) have shown that covert shifts in attention toward the left hemifield is facilitated under blue-light exposure, but not the ones toward the right hemifield, suggesting that blue light might affect visual processing asymmetrically with respect to the deployment of visuospatial attention and eye movements.

Experiment 1

In Experiment 1, we aimed to examine the effects of blue light on eye movement using the classic gap paradigm (Saslow, 1967). In addition to examining different eye-movement directions, we also examined if the response times in the manual response task would be modulated by blue light (reported in Appendix 1). By comparing differences in background color, direction, and the gap condition in the saccadic response task, we could investigate which, if any, components of eye movements blue light influences.

Method

Participants The sample size was decided based on data from the first 12 participants. Since we hypothesized that blue light can influence eye movements and attention, we expected to see an interaction between background color and the gap condition. Based on the power analysis with Cohen's $f = 0.28$, we needed 19 participants to reach adequate power (0.8). We recruited 31 males, which is relatively more participants (50% additional) than theoretically needed to ensure that we have sufficient power to detect the effects of blue light on different conditions. Females were not included to avoid the possible interaction between the menstrual cycle and the influence of light exposure (Barron, 2007; Cowan et al., 2000). One participant was excluded for his inability to follow instructions due to drowsiness, and two other participants were excluded due to technical issues while recording eye-movement data. Hence, 28 valid participants remained (age range: 18–32 years old). All participants were free from psychological or neurological disorders, and with normal or corrected-to-normal vision. No participants wore blue-light-filter glasses or contact lenses during the experiment. Participants gave informed consent before the experiment and were given a monetary reward for their participation. Participants completed the experiment at the same time period for two consecutive days. The experiment was approved by the Research Ethics Committee at National Taiwan University and implemented in accordance with the subject guidelines.

Apparatus The monitor was an i-TECH 20-in. CRT that presented stimuli with a spatial resolution of 1,024 × 768 pixels. Participants' eye movements were recorded by the EyeLink 2000 eye tracker (SR Research, Mississauga, Ontario, Canada) at 1000-Hz refresh rate. Stimuli presentation and background colors were manipulated using MATLAB (The MathWorks) Psychtoolbox. The background colors were either blue (luminance: 12.00 cd/m^2, CIE: 0.1463, 0.0695) or orange (luminance: 14.70 cd/m^2, CIE: 0.5843, 0.3703), measured by Photo Research Inc's PR 655.[1] The two background colors were the same as the ones used in Experiment 1 of Chen and Yeh (2019) and the color spectra is shown in their Fig. 1.

Stimuli and design Participants were seated in a quiet room with their chin placed on a chin rest at a viewing distance of 57 cm. No other lighting was provided except for the background light from the monitor. They were instructed to fixate at the central black solid dot (1° in diameter) and press the space button to initiate a trial. After initiating the trial, a black fixation sign (a plus sign, extending 1° horizontally and vertically) would appear at the center for a certain duration (jittered from 1,000 ms to 1,500 ms). In the overlap condition, the fixation sign would remain on the screen for an additional 200 ms. The target, a small black dot (1° in diameter), would appear subsequently at one of four possible locations (up, down, left, or right) for 1 second. All targets appeared 8° from the center, a typical distance used in the gap paradigm (Saslow, 1967). In the gap condition, all settings were identical to the overlap condition except that the fixation sign would disappear earlier and the screen would be blank for 200 ms. Participants were instructed to make a saccade as quickly and accurately as possible to the target when it appears (see Fig. 1).

Procedure Participants were randomly assigned to one of the two counterbalanced factors: background color (blue or orange) and response order (saccade first or manual response first). Half of the participants were exposed to blue light on the first day and orange light on the second day, and the other half, the reverse order (orange before blue). All participants completed the tasks in the same order on both days: either the manual task followed by the saccadic task, or vice versa. Before the experiment, participants were exposed to a 5-minute light adaptation period (Chen & Yeh, 2019; Wong, 2012) during which they opened their eyes and looked at the monitor. Participants then went through a 9-point calibration

[1] The CIE luminance measurement is based on fast flicker that slow-wavelength cones respond poorly to, and so might underestimate the brightness of blue light. If the lights had been matched for brightness, the luminance difference would have been even greater. Nevertheless, this should not affect our conclusion.

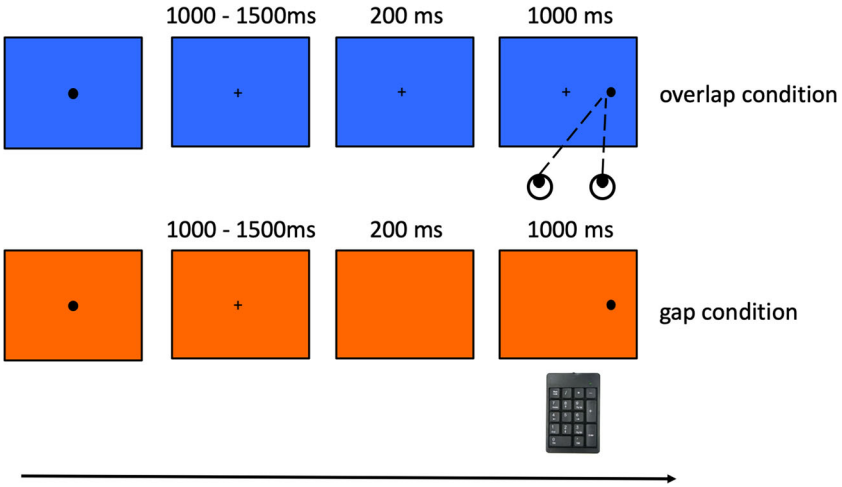

Fig. 1 Displays of the gap paradigm in Experiment 1. Participants were instructed to make saccade responses (upper panel) or manual responses (lower panel) to the target via number buttons on the keyboard. Note that saccadic responses and manual responses were conducted in different sessions. Both blue and orange backgrounds were used in each condition. The displays are not to scale

and validation procedure while the eye tracker recorded the eye movements of the right eye before the saccadic response task. If no errors exceeding 1° occurred during the validation procedure, participants would start their 10-trial practice session. To initiate each trial, participants fixated their eyes within 1° of the center and pressed the space button whenever they were ready. A total of five blocks per background color were conducted. Within each block, there were 10 trials per target location, half of which were either the gap or overlap condition. A total of 400 trials (200 per background color) were conducted for the response task.

Data analysis Saccade latency was calculated as the latency of the *first* saccade after target onset. Participants' saccades were detected by the EyeLink 2000, and saccades were defined as when eye velocity of the conjugate signal exceeded 35 deg/sec. Trials where the first saccade was in the wrong direction, toward the opposite side of the target (e.g., if the target was on the left and the onset of saccade started toward the right, regardless of the *y*-axis value), were excluded from further analysis (2.23% of trials). Saccade latencies shorter than 100 ms (2.3% of trials) and more than three standard deviations from the mean among all trials (0.8% of trials) were also excluded to avoid saccade anticipation and outliers. In total, 5.34% of trials were excluded from analysis.

Results

Figure 2 shows the results of saccade latency under different conditions. A three-way repeated-measure analysis of variance (ANOVA) on saccade latency was conducted on the factors of gap (gap, overlap), color (blue, orange), and direction (up, down, left, right). The main effect of gap was significant, $F(1, 27) = 280.5$, $p < .001$, $\eta^2 = 0.91$; faster saccadic responses were found in the gap condition compared with those in the overlap condition, replicating the conventional saccadic gap effect. Additionally, there was a significant main effect of direction, $F(3, 81) = 53.96$, $p < .001$, $\eta^2 = 0.67$. Post-hoc analyses using Tukey's HSD test revealed that downward saccade was the slowest among all the directions (left-down: $p < .001$, $d = 1.8$, right-down: $p < .001$, $d = 1.72$, up-down: $p < .001$, $d = 1.52$), and that there were no significant differences between other directions ($ps > .1$). The main effect of color, $F(1, 27) = 5.18$, $p = .031$, $\eta^2 = 0.16$, and the interaction of color and gap, $F(1, 27) = 5.1$, $p = .032$, $\eta^2 = 0.16$, were significant. Paired t test revealed a significant difference of saccade latency between blue light and orange light in the overlap condition, $t(27) = -2.79$, $p = .019$, $d = 0.53$, but not in the gap condition, $t(27) = -1.34$, $p = .38$, $d = 0.25$ (under Bonferroni correction). No other significant interactions were found ($ps > .1$).

We further verified our results using an ANOVA based on the arsine-transformed saccade latency to avoid potential confounding of the heterogeneity of variance. The results were close to the analysis using saccade latency without transformation. Significant main effects of gap, $F(1, 27) = 324.3$, $p < .001$, $\eta^2 = 0.92$, direction, $F(3, 81) = 53.46$, $p < .001$, $\eta^2 = 0.66$, and color, $F(1, 27) = 5.24$, $p = .03$, $\eta^2 = 0.16$, were found. In addition, a marginal significant interaction between color and gap was found, $F(1, 27) = 4.06$, $p = .054$, $\eta^2 = 0.13$, but not gap and direction, $F(3, 81) = 1.1$, $p = .356$, $\eta^2 = 0.04$, or direction and color, $F(3, 81) = 0.71$, $p = .547$, $\eta^2 = 0.03$. No significant three-way interaction was found, $F(3, 81) = 0.2$, $p = .896$, $\eta^2 = 0.01$.

Discussion

Two main findings were obtained in Experiment 1. First, shorter saccade latencies were found under blue-light exposure compared with under orange-light exposure in the

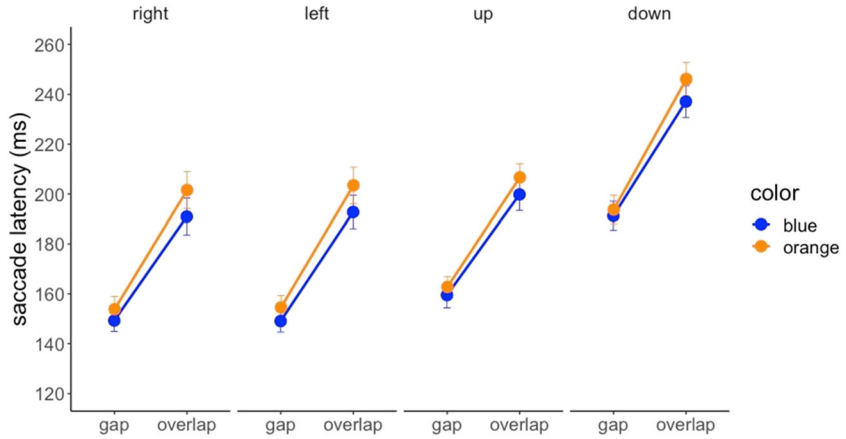

Fig. 2 Saccade latency of the saccadic response task in different directions under blue and orange light in Experiment 1. Error bars represent 1 SEM

saccadic response task. Second, the downward responses were the slowest compared with those of the other directions.

Why are we the worst at downward responses? Similar results were also found in the manual response task (see Appendix 1), and the results of the manual response task were further verified in another experiment (see Appendix 2). Abegg, Pianezzi, and Barton (2015) compared saccade latency in the upper and lower visual fields and found that saccade latency was slower in the lower visual field compared with that in the upper visual field. They proposed that this vertical asymmetry in saccades likely arises due to an advantage in oculomotor programming rather than faster visual information processing, given that upward antisaccades prompted by a cue in the lower hemifield also had faster latencies than downward antisaccades prompted by a cue in the upper hemifield. Despite better spatial and attentional resolution in the lower visual field (Fortenbaugh, Silver, & Robertson, 2015; He, Cavanagh, & Intriligator, 1996), these advantages seem to have a trade-off (i.e., slower saccade latency in the lower visual field). Alternatively, Vernet, Yang, Gruselle, Trams, and Kapoula (2009) proposed that because horizontal visual fields are used more often while reading, this leads to the optimization of horizontal saccades compared with vertical ones. However, Taiwanese readers are familiar with both horizontal and vertical reading directions (Bergen, Lau, & Ting, 2012; Chan & Bergen, 2005)—therefore, this explanation is insufficient for the participants in this current study who are all Taiwanese. Although no conclusive consensus has yet been reached, the present study excludes reading habits as the major role in this phenomenon based on cultural differences of reading habits. Future studies are needed to test the exact mechanism of the saccadic asymmetry.

What contributes to the general faster saccades under blue light compared with orange light? Furthermore, what contributes to the faster saccade under blue light only in the overlap condition? According to the literature on the gap effect, the difference of saccade latencies in the gap and overlap conditions can reflect the difference of involvement in attentional disengagement and fixation-related neurons in the SC (Jin & Reeves, 2009; van der Geest, Kemner, Camfferman, Verbaten, & van Engeland, 2001). To further examine this issue, we conducted Experiment 2 to investigate whether attentional disengagement and/or the oculomotor response contributed to the faster saccades under blue light.

Experiment 2

As our main interest lies in the effect of blue light on saccadic eye movements and attentional allocation, in addition to the original gap condition, we used a *no-gap* condition and a *parafoveal-gap* condition. In Experiment 2, we tried to dissect the contribution of attention and the oculomotor system. In the *gap* condition, after the fixation cross disappears, the screen would be blank for 200 ms before target onset. Therefore, both fixation and attention would be released from the central site. In the *no-gap* condition, the fixation cross turns into a solid circle before target onset, and thus both fixation and attention would be restricted at the center. In the *parafoveal-gap* condition, before target onset, the fixation cross would be replaced by four solid circles extending 4° from the center, forming an illusory square. Thus, attention was assumed to be locked at the center, but the saccade-related neurons in the SC was released from the inhibition of fixation-related neurons, as previous animal studies showed that the activity of the rostral pole fixation cells in the SC was significantly reduced or eliminated when the central fixation sign was removed (Dorris & Munoz, 1995; Munoz & Wurtz, 1993). By comparing pairwise contrasts of saccade latency in the gap, no-gap, and parafoveal-gap conditions under different color backgrounds, we can directly test the contribution of attentional disengagement and the oculomotor systems.

Table 1 summarizes the cognitive processes involved in each condition and each contrast (i.e., the pairwise contrasts of gap conditions) for the comparison between blue light and orange light to examine which component blue light facilitates. These

Table 1 Cognitive processes involved in each condition and contrast in Experiment 2

Condition	Attentional disengagement	Release of fixation-related neurons
Gap	o	o
No-gap	x	x
Parafoveal-gap	x	o
Contrast		
Gap vs. No-gap	o	o
Gap vs. Parafoveal-gap	o	x
No-gap vs. Parafoveal-gap	x	o

Note. The "o" indicates that the condition or contrast (specified in the row) involves the process (specified in the column), whereas the "x" indicates that the condition or contrast does not involve the process.

contrasts include the contrast between the gap and no-gap conditions, the gap and parafoveal-gap conditions, and the no-gap and parafoveal-gap conditions. These contrasts represent the combined effects of attention and fixation-related neurons (attention and fixation-related neurons are both restricted at the center in the no-gap condition. but are both unrestricted in the gap condition), the individual effect of attention (attention is locked at the center in the parafoveal-gap condition, but not in the gap condition), and the individual effect of fixation-related neurons (fixation-related neurons are activated in the no-gap condition but not in the parafoveal gap condition), respectively.

If attentional disengagement contributes to the facilitation of saccade latency under blue light, we should see a larger difference of saccade latency in the contrast between the gap and parafoveal-gap conditions. If the activity of fixation-related neurons contributes to the facilitation of saccade latency under blue light, we should see a larger difference in the contrast between the no-gap and parafoveal-gap conditions. If, however, it is the combined effects of attentional disengagement and fixation-related neurons that contributes to the facilitation of saccade latency under blue light, we should see a larger difference in the contrast between the gap and no-gap conditions.

Method

Participants Twenty-six young males were recruited (age range: 18–30 years old). Other criteria were the same as Experiment 1.

Apparatus The background colors were either blue (luminance: 10.78 cd/m^2, CIE: 0.1481, 0.0674) or orange (luminance: 10.43 cd/m^2, CIE: 0.5753, 0.3758), measured by Photo Research Inc's PR 655 (see Fig. 9 in the Appendix 3 for the color spectra). Other settings were the same as in Experiment 1.

Stimuli, design, and procedure The settings were the same as in Experiment 1, except for the following. Participants were instructed to fixate at the central empty circle (1° in diameter and 0.04° in thickness) and press the space button to initiate a trial. After initiating a trial, a cross sign (extending 1° horizontally and vertically) would appear at the center for a certain duration (jittered from 1,000 ms to 1,500 ms). In the gap condition, after the fixation sign disappears, the screen would remain blank for 200 ms, then the target is presented. In the no-gap condition, instead of a blank screen, the fixation sign is replaced by a solid circle (1° in diameter) for 200 ms, followed by the target. In the parafoveal-gap condition, after the fixation sign disappears, four solid circles forming an illusory square would appear on the screen for 200 ms. The locations of the solid circles were 4° from the center (measured from center to center), which were the same as that used in Fendrich et al. (1999). The target, a small black dot (1° in diameter), appeared subsequently at one of four possible locations (up, down, left, or right) for 1 second. All targets were located 8° from the center. Participants were instructed to make a saccade as quickly and accurately as possible to the target when it popped out (see Fig. 3).

The experiment consisted of a total of five blocks per background color. Within each block, there were 12 trials per target location (left, right, up, and down), and one-third of the total trials were either the gap, no-gap, or parafoveal-gap condition. A total of 480 trials (240 per background color, with 4 locations × 12 repetitions × 5 blocks) were conducted in this experiment.

Data analysis Trials with the first saccade in the wrong direction (i.e., opposite from the location of the target) were excluded from further analysis (6.24% of trials). Saccade latencies shorter than 100 ms (5.32% of trials) and more than three standard deviations from the mean among all trials (0.88% of trials) were also excluded to avoid saccade anticipation and outliers. Trials with saccades that did not initiate within 4° of the center (0.7% of trials) were also excluded to ensure that participants followed the instructions to fixate at the center at the beginning of a trial. In total, 13.14% of trials were excluded from analysis.

Results

Figure 4 shows the results of saccade latency in different conditions under different background colors. A three-way repeated-measure ANOVA was conducted on the factors of gap (gap, no-gap, parafoveal-gap), color (blue, orange), and direction (up, down, left, right). There was a main effect of gap, $F(2, 50) = 91.78$, $p < .001$, $\eta^2 = 0.79$: Tukey's HSD test showed that saccade latency was the fastest in the gap condition, followed by the no-gap and parafoveal-gap conditions (gap–no-gap: $p < .001$, $d = 1.78$; gap–parafoveal-gap: $p < .001$, $d = 2.07$; no-gap–parafoveal-gap: $p < .001$, $d = 1.32$). In addition, there was a main effect of direction, $F(3, 75) =$

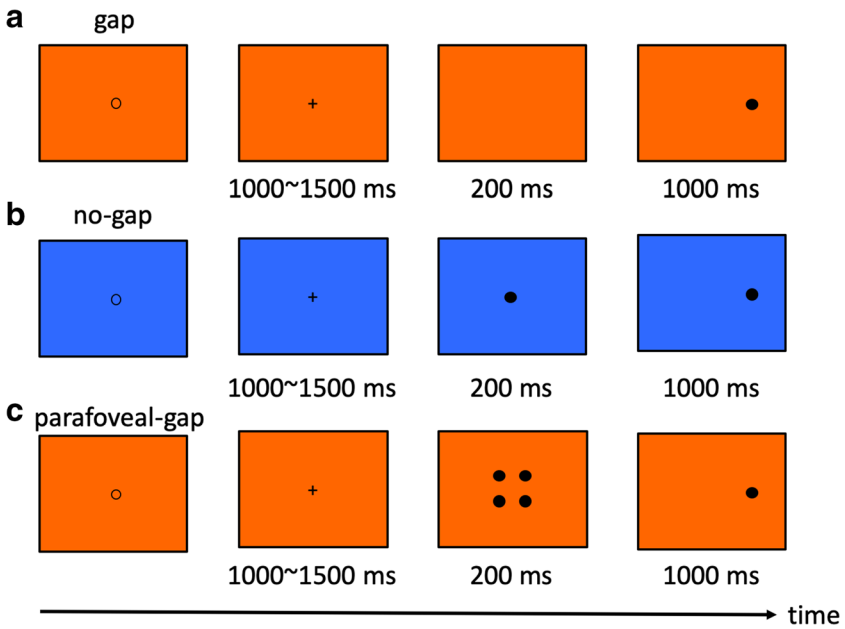

Fig. 3 Displays of the three conditions in Experiment 2. **a** Gap condition (an example under orange light). **b** No-gap condition (an example under blue light), the fixation would turn into a solid dot and disappear at the same time with the target onset. **c** Parafoveal-gap condition (an example under orange light), the fixation would turn into four parafoveal cues to release the inhibition of saccade-related neurons. The parafoveal cues disappeared when the target appeared. Both blue and orange backgrounds were used for each condition. The displays are not to scale

30.54, $p < .001$, $\eta^2 = 0.55$; post hoc analysis using Tukey's HSD test revealed that downward saccades were the slowest among all other directions (left-down: $p < .001$, $d = 1.24$, right-down: $p < .001$, $d = 1.27$, up-down: $p < .001$, $d = 0.84$), and upward saccades were slower than rightward and leftward saccades (right-up: $p < .001$, $d = 0.41$, left-up: $p < .001$, $d = 0.55$). No significant main effect of color was found, but a significant interaction between gap and color was found, $F(2, 50) = 3.77$, $p = .03$, $\eta^2 = 0.13$. Post hoc analysis revealed a marginally significant difference between blue light and orange light in the gap condition, $t(25) = -1.83$, $p = .08$, $d = 0.36$, but not in other conditions ($ps > .1$).

Since the contrasts between conditions reveal the cognitive processes (see Table 1) involved in the gap paradigm, we created three contrasts among the conditions and conducted an a priori analysis of the difference between contrasts under blue and orange light. Figure 5a shows the cumulative frequency of saccade latency across conditions, while Fig. 5b shows the comparisons of contrasts. Results showed a larger difference between the gap and no-gap condition ($p = .026$, $d = 0.57$) under blue light compared with orange light (under Holm correction), but no difference between blue light and orange light in the contrasts between the gap and parafoveal-gap conditions ($p = .153$, $d = 0.44$) and between the no-gap and parafoveal-gap conditions ($p = .359$, $d = 0.17$). We further verified our results using Wilcoxon Rank-Sum tests, to avoid that the heterogeneity of variance might confound the results. Similar results were obtained (difference between colors in the gap and no-gap conditions: $p = .061$; difference between colors in the gap and parafoveal-gap conditions: $p = .115$; difference between colors in the no-gap and parafoveal-gap conditions: $p = 1$, under Bonferroni correction).

One might expect that saccade latency in the no-gap condition would be the slowest compared with that of the gap and parafoveal-gap conditions, since fixation and attention were both restricted to the center in the no-gap condition while fixation was released in the parafoveal-gap condition. Specifically, the parafoveal-gap condition should have less processing compared with the no-gap condition (namely, without the process of releasing fixation). However, we observed that the parafoveal-gap condition was the slowest. This, however, was in line with the results of Jin and Reeves (2009), who found that the parafoveal-gap condition was slower than their white gap condition. The white gap condition used by Jin and Reeves (2009) is comparable to the no-gap condition in the current study. In their experiment, the fixation sign in the white gap condition turned from green to white for 200 ms before target onset, which was similar to our no-gap condition. It is possible that the solid dots extending 4° from the center were disposed around the fovea and potentially elicited a foveal control signal, which delayed the saccade latency in the parafoveal-gap condition (Jin & Reeves, 2009).

Another possibility is that the slowest saccade latency in the parafoveal-gap condition was due to the four solid dots (each extending 4° from the center) serving as temporary targets, which not only captured participants' attention but also triggered automatic saccades toward these cues even if participants were told to maintain their gaze at the center until target onset. The definition of whether fixation-related neurons were released is based on the existence of the central (foveal) target

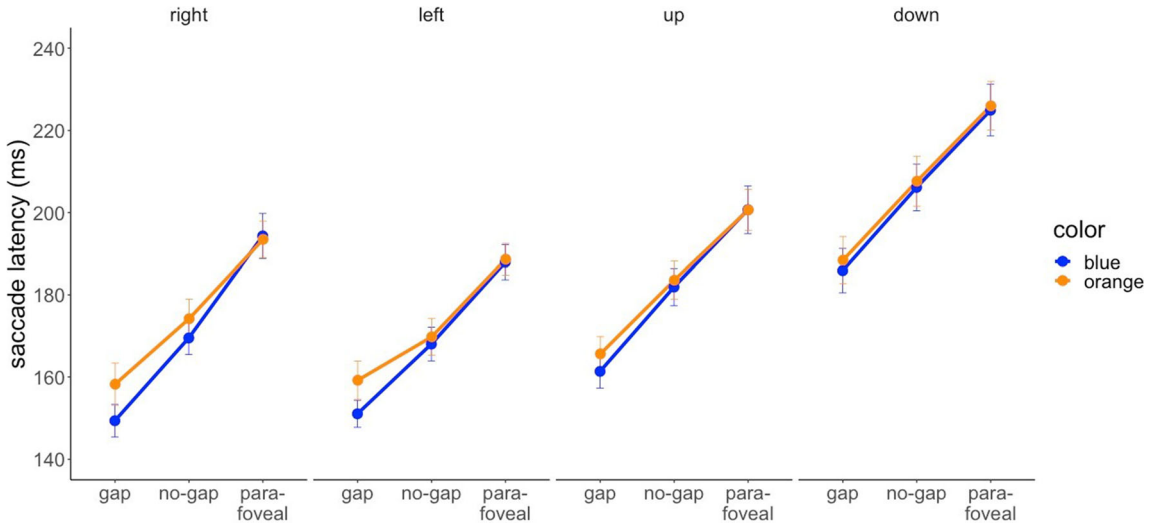

Fig. 4 Saccade latency of the saccadic response task in different directions under blue and orange light. Error bars represent 1 *SEM*

sign (Dorris & Munoz, 1995; Munoz & Wurtz, 1993). Therefore, even though participants had fixation behaviors in some trials of the parafoveal-gap condition, based on previous studies (Fendrich et al., 1999; Jin & Reeves, 2009), the fixation-related neurons might not be highly activated or activated at all. Hence, we speculated that it may be the parafoveal cues that captured participants' overt attention and induced eye movements that delayed the following saccadic responses.

To examine the hypothesis regarding the parafoveal cues capturing attention, we then separated the data from the parafoveal-gap condition into two subsets, *parafoveal-in*, where the first fixation after target onset was within 1° of the center, and *parafoveal-out*, where the first fixation was outside this region. Both types of trials (i.e., parafoveal-in and parafoveal-out) had more than 900 trials, providing enough trial number for statistical analyses.

A two-way repeated-measure ANOVA was conducted on the factors of gap (gap, no-gap, parafoveal-in, parafoveal-out) and color (blue, orange; see Fig. 6). We found a main effect of gap, $F(3, 75) = 67.71$, $p < .001$, $\eta^2 = 0.73$, but no main effect of color. In the post hoc analysis of the main effect of gap, significant differences between gap and no-gap, gap and parafoveal-in, gap and parafoveal-out, no-gap and parafoveal-in, and no-gap and parafoveal-out trials were found (gap–no-gap: $p < .001$, $d = 1.46$, gap–parafoveal-in: $p < .001$, $d = 1.9$, gap–parafoveal-out: $p < .001$, $d = 1.54$, no-gap–parafoveal-in: $p < .001$, $d = 1.27$, no-gap–parafoveal-out: $p < .001$, $d = 0.87$), but not the parafoveal-in and parafoveal-out trials ($p > .1$, $d = 0.13$). Importantly, a marginally significant interaction between gap and color was found, $F(3, 75) = 2.43$, $p = .072$, $\eta^2 = 0.09$. The difference of saccade latency among all conditions were tested here to examine the interaction. Six contrasts (i.e., gap vs. no-gap, gap vs. parafoveal-in, gap vs. parafoveal-out, no-gap vs. parafoveal-in, no-gap vs. parafoveal-out, and parafoveal-in vs. parafoveal-out) were rendered to examine the difference of saccade latency across colors. Again, a larger difference was only found between the gap and no-gap conditions ($p = .048$, under false discovery rate correction, $d = 0.57$), and no differences between blue light and orange light when comparing other contrasts ($ps > .1$).

We also separated trials from the no-gap condition into "no-gap-in" and "no-gap-out" trials based on the same procedure of differentiating the parafoveal-in and parafoveal-out trials to make a parallel comparison. The three-way repeated-measure ANOVA on gap (no-gap/parafoveal-gap), color (blue/orange), and fixation (in/out) showed a significant main effect of gap, where the saccade latency in the no-gap condition was faster than the parafoveal-gap condition, and no other significant main effect or interaction was found.

Discussion

In this experiment, we manipulated conditions that involved the potential engagement of fixation-related neurons and attention to investigate how blue light affects saccade latency to tease apart the respective contributions of the oculomotor system and attention. Results of the no-gap versus gap pairwise contrast indicated that the contrast under blue light was significantly larger than the contrast under orange light, but this did not apply to the gap versus parafoveal-gap contrasts and the no-gap versus parafoveal-gap contrasts. The important issue here is what these contrasts signify. The contrast between the no-gap and gap condition represents the combined effects of attention and fixation-related neurons, which indicates that blue light facilitated the integration of attention and the eye-movement system. However, no blue-light facilitation was found in either the gap versus parafoveal-gap contrast or the no-gap versus parafoveal-gap contrast, suggesting that when

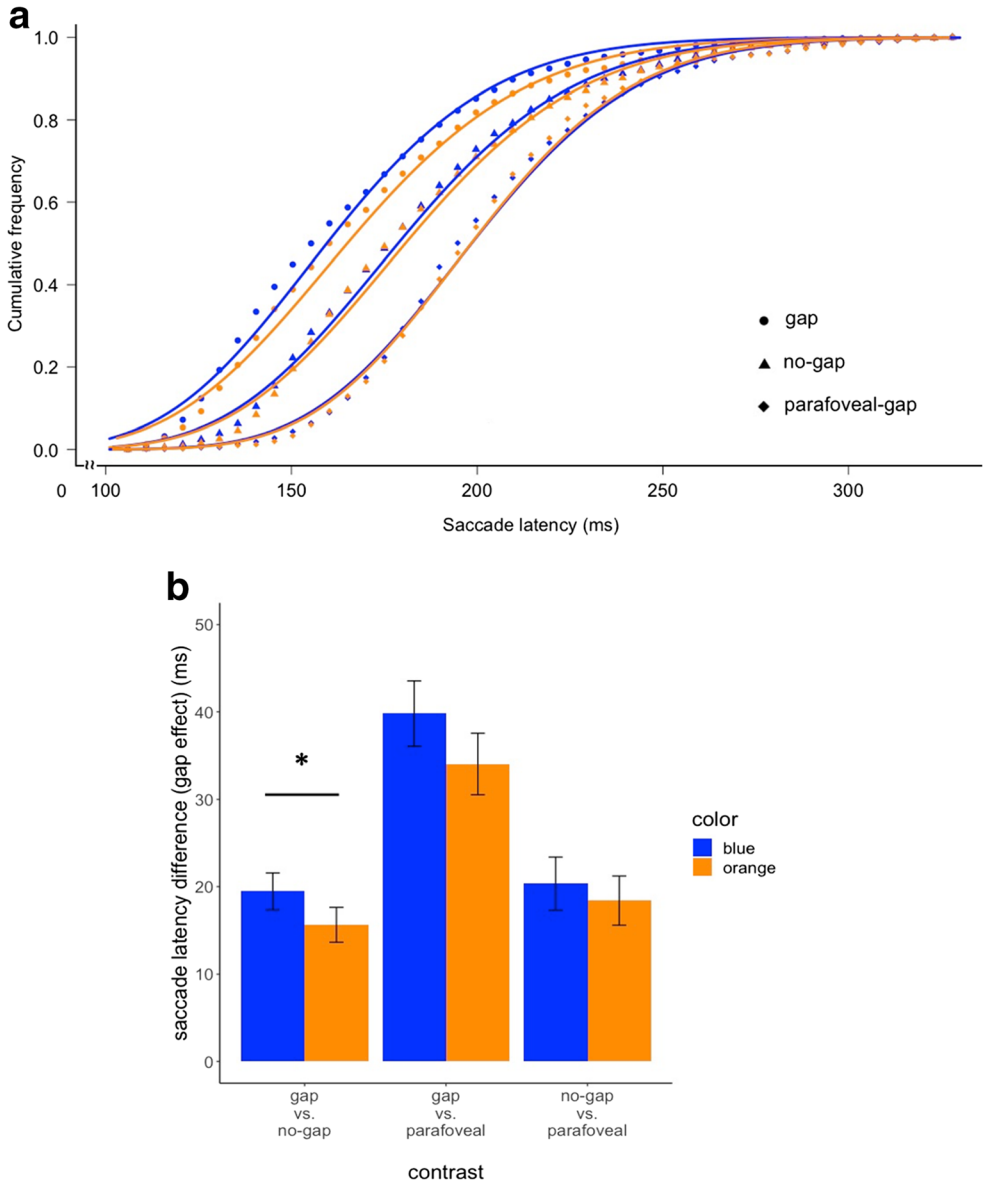

Fig. 5 **a** Cumulative frequency across conditions. **b** Pairwise contrasts between the gap, no-gap, and parafoveal-gap conditions. The *y*-axis represents the difference of saccade latency between two conditions. Error bars represent 1 *SEM*

separating attention and eye movement, the facilitating effect of blue light disappeared.

Our results also suggested that attention and eye movements work interdependently. The results that saccade latencies in both parafoveal-in and parafoveal-out trials were slower than those in the no-gap condition are in line with the premotor theory, since attentional shifting (or reorienting) has postponed saccade latency. The results suggested that attention serves as the prior induction of eye movements (Rizzolatti et al., 1987) and that attention and eye movements are inseparable (Deubel & Schneider, 1996; Pratt et al., 2006; but see Reeves & McLellan, 2020, showing that after hours of training, attention and saccades can shift in opposite directions). Neuroimaging studies also indicated that visuospatial attention and eye movements share the same cortical regions (Nobre, Gitelman, Dias, & Mesulam, 2000), mostly converging in the FEF, an area known to be responsible for the voluntary control of eye movements. If attention and the eye movement system were independent, we should have observed faster saccade latencies in the parafoveal-in trials than in the no-gap condition, since the shift of attention in the parafoveal-in trials should not influence saccadic eye movements. However, the opposite pattern was found. Even though participants continued to look at the center in the parafoveal-in trials, the saccade latency was still delayed compared with the no-gap trials by the disengagement and shift of attention, highlighting the dependency between attention and eye movements. In addition, for the six pairwise contrasts

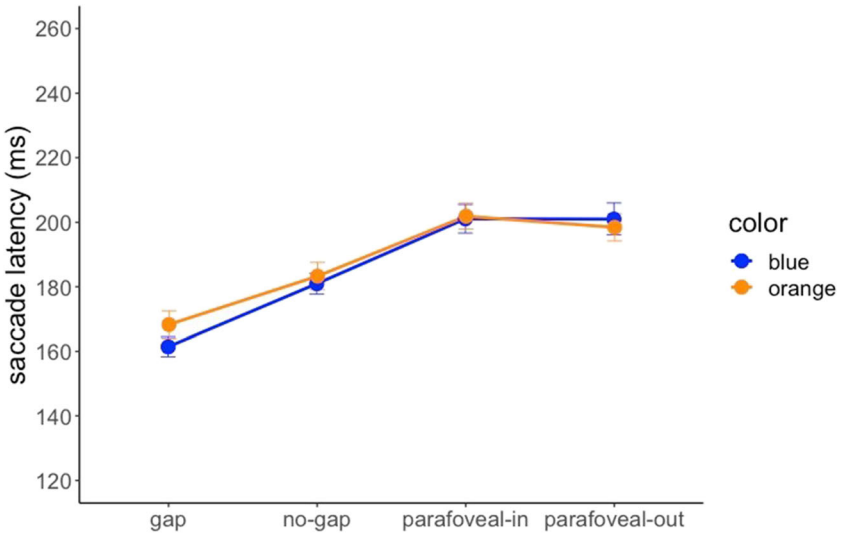

Fig. 6 Saccade latency of the saccadic response task when separating the parafoveal-gap condition into the parafoveal-in and parafoveal-out trials. Error bars represent 1 *SEM*

comparing the benefits of blue and orange light, only the gap and no-gap contrast was significant, and the difference in the underlying mechanism(s) between the gap and no-gap condition consists of both attentional disengagement and eye movements. Hence, we conclude here that when investigating the effects of blue light on saccadic behaviors, attentional disengagement and eye movements should be taken together to explain the obtained results. Indeed, there is essentially no precise separation or boundary between oculomotor and attentional processes as indicated in previous studies (e.g., Ikkai & Curtis, 2008; Pratt et al., 2006; Rizzolatti et al., 1987).

General discussion

In this study, we manipulated conditions that involve the potential engagement of fixation-related neurons and attention to investigate how blue light affects saccade latency, and tease apart the respective contributions of the oculomotor system and attention. Experiment 1 demonstrated the facilitation of blue light on saccadic eye movements. Experiment 2 further indicates that blue light only facilitated saccade latency when attention and the eye-movement system operated together.

A basic assumption in our experiment is that the detection threshold of the target (i.e., the small black dot) is the same across the two colors. If the difference of the detection thresholds in the two colors caused the difference in saccade latency, we would have observed the main effect of color across the experiment without interactions between color and other factors. However, in addition to the main effect of color in Experiment 1, an interaction between color and gap was found in both experiments. Hence, the influence of blue light on saccade latency is not due to the difference in the detection thresholds of the target under the two background colors.

The underlying mechanism

What is the underlying mechanism for the facilitatory effect of blue light on saccade latency found in the current study? We postulate that ipRGCs are responsible for the facilitation of saccade latency under blue light, given that they innervate to the SC (Ecker et al., 2010) and their activation also correlates with FEF activity (Hung et al., 2017). Although previous studies have shown that ipRGCs' responses are relatively sluggish (e.g., Wong, 2012) and mainly in charge of the tonic response (Sonoda, Lee, Birnbaumer, & Schmidt, 2018), the results we found here were at a postretinal adaptation level rather than at a retinotopic level. Thus, after the 5-minute light-adaptation phase we used in the current study, ipRGCs should continue to work and influence postretinal processing. Even though ipRGCs require strong light stimulation to be activated, previous studies have shown that M4 cells, one of the subtypes of ipRGCs, are relatively sensitive to light stimulation and have a faster acting response than other subtypes (Pottackal & Demb, 2018; Sonoda et al., 2018).

Some may argue that rods or luminance differences might have contributed to the facilitatory effect observed here; however, this is unlikely. Rods mainly work under 0.01 cd/m^2 at the scotopic level and under 3 cd/m^2 at the mesopic level, whereas the luminance in our study was over 10 cd/m^2. The slight difference in luminance between the orange and blue light should not be the main cause of the findings, since we did not only observe a main effect of color but instead also observed interactions. If luminance drove the effect, we should have seen the light with higher luminance induce faster saccade latencies (Horwitz & Albright, 2003). Yet no such effect was found in the current study. In addition, we combined the data in Experiments 1 and 2 while using high versus low

luminance as a within-subjects factor (based on their relative luminance) to examine whether luminance could modulate the saccade latency. In Experiment 1, the blue-light condition (12.00 cd/m^2) was coded as low luminance and orange-light (14.70 cd/m^2) was coded as high luminance, whereas in Experiment 2, the blue-light condition (10.78 cd/m^2) was coded as high luminance and the orange-light condition (10.43 cd/m^2) was low luminance. By comparing saccade latencies in high and low luminance conditions using a paired t test, no significant difference across luminance levels on saccade latency was found, $t(53) = -0.87$, $p = .386$. Therefore, we preclude the possibility for the luminance difference to influence our results.

The light spectrum that ipRGCs are most sensitive to highly overlaps with that of S cones, and partially overlaps with that of M cones. We calculated the activation levels of S, M, and L cones and ipRGCs, respectively (see Table 2). Do S cones contribute to the facilitation of saccade latency under blue light? Sumner, Adamjee, and Mollon (2002) have shown that distractors that were only visible to S cones in the periphery did not produce the saccadic distractor effect, suggesting that the SC did not receive input from the S cones. Their findings were in line with previous electrophysiological findings that S cones do not innervate to the SC (Marrocco & Li, 1977). However, a recent study conducted by Hall and Colby (2014) showed that the SC neurons respond differently to the high-S-cone contrast stimulus compared with the low-S-cone contrast stimulus. Yet no previous study has provided evidence regarding how high the luminance should be for S cones to activate the SC. Thus, although the luminance in the study of Hall and Colby (2014) was approximately 2 times the luminance in this study, we cannot completely exclude the possibility that S cones contributed to the saccadic performance to some extent. Future studies using S-cone specific stimuli are needed to resolve this issue.

The activation of M cones was slightly higher in the blue-light background compared with that in the orange-light background (see Table 2). Thus, it is possible that M cones played a role in facilitating the shorter saccade latencies that we observed, given their characteristic of high temporal resolution. Future studies can adopt the metameric pairs in a projector system (e.g., Yang et al., 2018) to probe into this issue and further clarify the role of M cones in the facilitatory effect of blue light on saccade latency.

Table 2 Stimulation of cones and ipRGCs in the experiments

Experiment	Background	L	M	S	ipRGC
Experiment 1	Blue	8.63	6.49	159.89	90.46
	Orange	12.63	3.21	1.93	5.84
	Ratio (blue/orange)	0.68	2.02	82.84	15.49
Experiment 2	Blue	7.78	5.73	139.08	78.64
	Orange	8.90	2.32	1.59	4.41
	Ratio (blue/orange)	0.87	2.46	87.36	17.85

Could orange light inhibit attentional disengagement and eye movements and be the main cause for the observed faster saccade latencies under blue light? Even though it is unlikely, since no previous studies have shown that orange light could influence attention or eye movements, future studies can directly test this notion by comparing attentional shift across colors of light in a different paradigm. Alternatively, could faster saccades under blue light be due to prolonged subjective time duration, as shown by Yang et al. (2018)? As participants subjectively feel that more time is passing by under blue light, they might feel pressured to respond faster, even though the time passed was identical to when performing the task under orange light. We doubt this possibility, as otherwise, faster saccade latency under blue light should be observed across conditions, and hence main effects in both experiments should have been observed. However, we found interactions in both experiments, and verified that the facilitation of blue light was influenced by attention and eye movements.

Saccade latency modulated by blue light

Although the general pattern of our findings across the two experiments points to a facilitation effect of saccade latency by blue light, blue light affected different conditions in each experiment. In Experiment 1, the blue-light facilitation effect mainly took place in the overlap condition, and in Experiment 2, the facilitation mainly occurred in the gap condition. How do we reconcile these seemingly inconsistent results given that the blue-light facilitation took place in different conditions across experiments? Even though the facilitation of blue light on the gap effect was due to a difference of color in different conditions, the pairwise contrasts across the experiments (see Table 1 and Fig. 5b) stand for the same cognitive processes. To be specific, the contrast between the overlap and gap conditions in Experiment 1 and the contrast between the no-gap and gap conditions in Experiment 2 both represent the combined effects of attentional disengagement and the oculomotor system. Both experiments showed that when considering attentional disengagement and the oculomotor system together, faster saccade latencies will be found under

blue light. By presenting these two experiments, we conclude that blue light affects both attention and the oculomotor system as attention and eye movement work interdependently. It is possible that the task difficulty will interact with the effects of blue light, as Experiment 2 had more than two kinds of gap conditions, and thus influenced where the facilitation of blue light took place. Future studies can systematically manipulate the difficulty of the task while examining if the facilitation effect of blue light will vary depending on task difficulty.

The benefits of blue light

In Fig. 4, the shorter saccade latencies in the rightward and leftward responses seemed to benefit more from blue light in the gap condition compared with the ones in the upward and downward responses. As the responses for the upward and downward saccades were generally slower than the ones for the rightward and leftward saccades, does this suggest that blue light only affect fast saccades (i.e., around 150 ms)? Based on Fig. 5a, the facilitation of blue light in saccade latency occurs from 100 ms along to 200 ms, which indicates that our results were not limited to fast saccades. Additionally, the blue-orange difference did not seem to vary across time series (see Fig. 5a). We hence concluded that the facilitation of blue light in saccade latency was not restricted in certain oculomotor response time period, but a general enhancement in saccadic response.

The current study is the first to demonstrate the facilitation effect of blue light on saccadic eye movements and attentional disengagement, and hints at the possibility that people should adopt light with shorter wavelengths when it comes to enhancing the speed of saccadic eye movements. In modern society, people are exposed to high-intensity blue light through electronic products such as laptops and cellphones every day; especially in this current period of time where most people work from home, people spend even more time on computers than when commuting was necessary. The amount of exposure to blue light from work is even longer than before, which further demonstrates the importance of our current findings. Namely, one beneficial effect of blue light is to enhance the speed of saccades, which could potentially help with gathering information when using modern technologies. Future studies can include a cognitive or spatial task to investigate how blue light influences the efficiency of reading or browsing, which requires a great quantity of saccades, to directly investigate blue-light effects on work efficiency and executive functions.

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Open practices statement The data in this study are available (https://osf.io/rsja8/). The experiment was not preregistered

Appendix 1 The manual response task in Experiment 1

Method

Stimuli and design The settings were almost identical as that of the saccadic response task, except that participants' task was to make manual responses to the target instead. Participants were instructed to respond to the target via pressing number buttons on a number pad, with their right index finger on 4, middle finger on 8, ring finger on 6, and thumb on 0. These four numbers were correspondent to the left, up, right, and down target locations, respectively.

Data analysis Trials with incorrect responses were excluded from further analysis (2.11% of trials). Responses shorter than 100 ms (0.02% of trials) and more than three standard deviations from the mean among all trials (1.57% of trials) were also excluded. In total, 3.71% of trials were excluded from analysis.

Results

Figure 7 shows the results of manual RTs under different conditions. A three-way repeated-measures ANOVA was conducted on the factors of gap (gap, overlap), color (blue, orange), and direction (up, down, left, right). Again, the gap effect was found, $F(1, 27) = 222.2$, $p < .001$, $\eta^2 = 0.48$, indicating faster manual RTs in the gap condition compared with those of the overlap condition. This result also replicated the manual gap effect (Jin & Reeves, 2009). A main effect of direction was also found, $F(3, 81) = 53.08$, $p < .001$, $\eta^2 = 0.66$: RTs in the downward direction was significantly slower than those of the other three directions (left-down: $p < .001$, $d = 1.42$, right-down: $p < .001$, $d = 1.85$, up-down: $p < .001$, $d = 1.21$). Moreover, both leftward responses and upward responses were slower than rightward responses (left-right: $p = .02$, $d = 0.45$, up-right: $p = .001$, $d = 0.4$). An interaction between gap and direction was found, $F(3, 81) = 3.03$, $p = .034$, $\eta^2 = 0.10$. Despite the seemingly slower RT in the blue background as shown in Fig. 7, no significant main

effect of color nor significant interactions of color with other factors were found (*p*s > .1). The null result of the color effect was further verified with nonparametric statistics with a Wilcoxon Rank-Sum test (p = .305) and the Bayesian factor (BF_{10} = 0.375), which was more in favor of the null hypothesis.

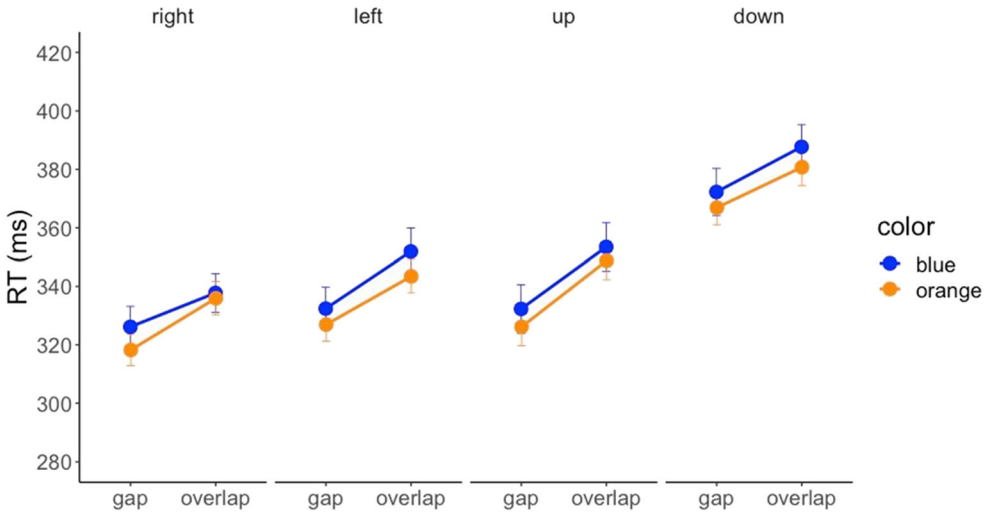

Fig. 7 Response time of the manual response task in different directions under blue and orange light in Experiment 1. Error bars represent 1 *SEM*

Discussion

In the manual response task, we did not observe a significant facilitation effect of blue light on manual response as the saccadic response task did. However, it is not surprising as previous studies have suggested that the manual gap effect and the saccadic gap effect are driven by different factors (Jin & Reeves, 2009; Ueda, Takahashi, & Watanabe, 2014), where the manual gap effect is mainly driven by the general warning effect (Jin & Reeves, 2009).

Interestingly, the slowest response was also found in the downward response as the saccadic response task showed. Before we explain this result, however, a possible confounding explanation for the pattern in the manual response should be addressed. After the experiment, two participants expressed that it was more difficult to press the number 0 button with the thumb compared with the other fingers in the manual response task. Therefore, the slowest response in the downward direction found in the manual response task might have been caused by the inflexibility of the thumb. Therefore, we conducted a supplementary experiment to verify the possible confounding of flexibility across different fingers in the manual response task by using the Microsoft gamepad as a response key (see Appendix 2). Again, we found the slowest response to be in the downward direction, although it was only significantly slower than the rightward direction and not the other two directions (leftward and upward).

Appendix 2 Supplementary experiment

Method

Participants Twenty-four males were recruited in the present study (age range: 18–31 years old). All criteria were the same as in Experiment 1.

Apparatus The apparatus was the same as that in Experiment 1. The background color was presented in white, since no interations between color and other factors were found in the manual response task in Experiment 1 (Appendix 1) and this experiment aimed to verify the possible confounding of manual responses in different directions.

Stimuli and design The settings were the same as Experiment 1, except for the background color. Participants were instructed to respond to the target with their thumb on the Microsoft gamepad. Participants were told to put their thumb in the central site of the gamepad. These four buttons corresponded to the left, up, right, and down locations.

Procedure The procedure was the same as Experiment 1 without color adaptation and the manipulation of color.

Data analysis Manual response time was calculated while excluding wrong responses. Response times within 100 ms and over three standard deviation among all trials were excluded. Hence, we ended up excluding 2.15% of trials in the analysis.

Results

Figure 8 shows the results of RTs in different conditions. A two-way repeated-measures ANOVA was conducted on the factors of gap (gap, overlap) and direction (up, down, left, right). We found a significant main effect of gap, $F(1, 23) = 101.4$, $p < .001$, $\eta^2 = 0.82$; faster manual response in the gap condition compared with the overlap condition. Significant main effect of direction was also found, $F(3, 69) = 3.64$, $p = .017$, $\eta^2 = 0.14$. Tukey's HSD tests revealed significant difference between the right and down directions ($p < .001$, $d = 0.6$, with Bonferroni correction). No other significant differences were found in the post hoc analysis ($ps > .1$).

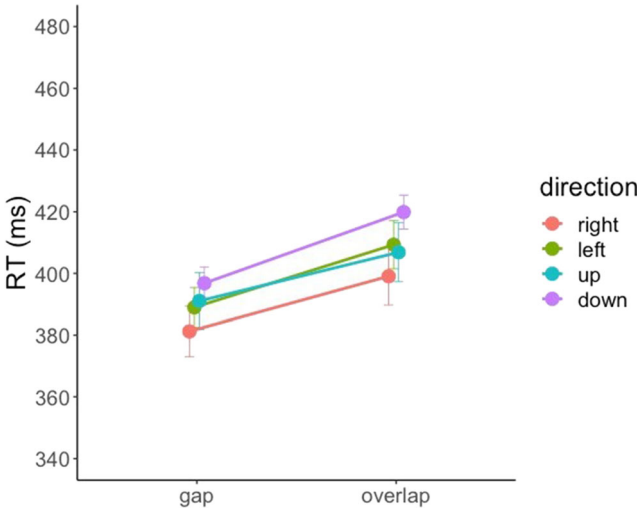

Fig. 8 Reaction times of the manual response task in different directions. Error bars represent 1 *SEM*

Discussion

The results in the supplementary experiment also showed that the downward response was the slowest among all directions. The responses here were free from the contamination of motor flexibility in the four directions for the following two reasons. First, we asked participants to put their thumb back to the central site of the gamepad after each trial, and so each trial started at the same point with response from the same finger (i.e., the thumb). Second, even if participants did not follow this specific instruction, the reaction time should not be biased toward the downward response because the location of the target was randomized across the experiment. Thus, if the target location of the previous trial is the initiating finger position of the next trial (which we assume did not happen), the bias of the reaction time should be randomized and equalized in each direction.

Appendix 3 Spectra of background colors in Experiment 2

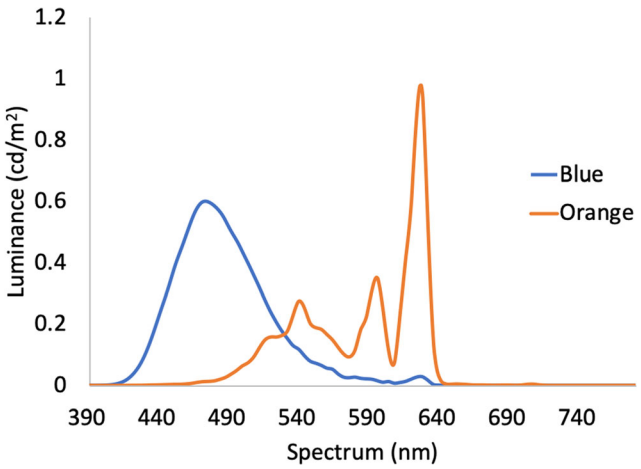

Fig. 9 Spectra of background colors. The spectra of blue and orange background were presented by wavelength (*x*-axis) and luminance (*y*-axis)

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