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Alerting and orienting of attention without visual awareness

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ABSTRACT

Two types of the attentional network, alerting and orienting, help organisms respond to environmental events for survival in the temporal and spatial dimensions, respectively. Here, we applied chromatic flicker beyond the critical fusion frequency to address whether awareness was necessary for activation of the two attentional networks. We found that high-frequency chromatic flicker, despite its failure to reach awareness, produced the alerting and orienting effects, supporting the dissociation between attention and awareness. Furthermore, as the flicker frequency increased, the orienting effect attenuated whereas the alerting effect remained unchanged. According to the systematic decline in temporal frequency sensitivity across the visual hierarchy, this finding suggests that unconscious alerting might be associated with activity in earlier visual areas than unconscious orienting. Since high-frequency flicker has been demonstrated to only activate early visual cortex, we suppose that neural activation in early visual areas might be sufficient to activate the two attentional networks.

1. Introduction

In nature, organisms have evolved so as to be sensitive to environmental events which may reveal new information about the visual environment and require immediate action accordingly. Two types of the attentional network, alerting and orienting (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fernandez-Duque & Posner, 1997; Posner & Petersen, 1990; Raz & Buhle, 2006), cooperate and work together to help organisms maintain this sensitivity for survival in the temporal and spatial dimensions, respectively. Alerting refers to a state of enhanced response readiness in preparation for the imminent stimulus, whereas orienting is defined as the ability to selectively allocate attentional resources to a particular location of the visual field. Both the two attentional networks combine to influence the speed of responding to environmental events and then to produce an efficient and adaptive behavior.

An interesting question for understanding the relationship between attention and awareness is whether these attentional functions depend on visual awareness. In other words, when the attentional cue cannot be consciously perceived, is it still able to change the level of alertness and orient spatial attention to its location automatically? For the orienting aspect, previous studies regarding unconscious exogenous orienting have yielded mixed results (Mulckhuyse & Theeuwes, 2010). Some studies have shown that the subliminal cue can influence the distribution of spatial attention to a certain degree depending on the task relevance of the cue (Ansorge & Neumann, 2005; Ivanoff & Klein, 2003; McCormick, 1997). Some

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recent studies have shown that the subliminal cue is indeed capable of capturing attention in a stimulus-driven manner (Ansorge & Heumann, 2006; Bauer, Cheadle, Parton, Müller, & Usher, 2009; Mulckhuyse, Talsma, & Theeuwes, 2007). Other studies have shown that some specific stimuli that may be of ecological significance, such as erotic images (Jiang, Costello, Fang, Huang, & He, 2006) and threatening stimuli (Lin, Murray, & Boynton, 2009), can attract attention without reaching awareness. For the alerting aspect, however, no study to our knowledge has addressed the question of whether the subliminal alerting signal can produce an alerting effect. We reason that this blank might be due to the methodological limitation. Traditional methods used to manipulate visual awareness (Kim & Blake, 2005), such as interocular suppression and backward masking, usually introduce an inhibiting stimulus to erase a stimulus from awareness. Because the addition of alerting signals provides no additional benefit (Fernandez-Duque & Posner, 1997), the alerting effect induced by the invisible stimulus, if any, may be unlikely to be isolated from that induced by the inhibiting stimulus. Thus, to investigate unconscious alerting, a new method for subliminal stimulation is needed by which the stimulus cannot reach visual awareness itself and then does not need to be associated with an inhibiting stimulus.

Human perception of chromatic flicker is well known to be limited (De Lange, 1958; Kelly, 1971; Matin, 1968). When two equiluminant colors alternate at frequencies of 25 Hz or higher, observers perceive only one fused color. Recently, this imperceptible high-frequency chromatic flicker stimulation has been used to investigate subliminal processes of the visual system (Hoshiyama, Kakigi, Takeshima, Miki, & Watanabe, 2006a; Hoshiyama, Kakigi, Takeshima, Miki, & Watanabe, 2006b; Shady, MacLeod, & Fisher, 2004; Vul & MacLeod, 2006). In the present study, we applied chromatic flicker to manipulate visual awareness without involving an inhibiting stimulus and to investigate the ability of visual information to produce both the alerting and orienting effects in the absence of awareness. Furthermore, neurophysiological studies have shown that neurons in higher visual areas respond to a lower range of temporal frequencies than those in earlier visual areas, indicating a systematic decline in temporal frequency sensitivity across the visual hierarchy (Hawken, Shapley, & Grosof, 1996; McKeeff, Remus, & Tong, 2007). According to this characteristic of the human visual system, when the flicker frequency becomes higher, the neural activation evoked by the flicker stimulus may be assumed to take place at earlier stages, and the next ascending area in the visual hierarchy may not be activated. In the present study, we therefore varied the flicker frequency of the fused chromatic flicker stimulus systematically to explore the respective dependences of both the unconscious alerting and unconscious orienting effects on flicker frequency, which may be valuable for researchers to understand the mechanisms underlying the two attentional functions.

2. Experiment 1

In this experiment, the invisible cue consisted of the red–green color alternation at various frequencies (42.5, 60, and 75 Hz). Under these circumstances, color alternations were no longer perceived as flicker but one fused yellow color, which was perceptually indistinguishable from its matched static control. By contrast, the visible cue consisted of the red–green color alternation at frequencies (all about 20 Hz) below the critical fusion frequency, resulting in the conscious perception of flicker. For each participant, both the invisible and visible cue stimuli were verified to be perceived as fused and as flickering, respectively.

2.1. Methods

2.1.1. Participants

A total of 126 students (85 females, 41 males; age range = 18–31 years) participated in this study (66 in Experiment 1a and 60 in Experiment 1b). All had normal or corrected-to-normal vision and provided informed consent. This study was approved by the ethics committee in Department of Psychology, Peking University.

2.1.2. Perceptual equiluminance between red and green colors

Before the experimental session, each participant performed a luminance-matching test to equate the perceptual luminance of the red and green colors. Luminance matching was carried out using a variation of the flicker photometry technique. The participants viewed two colored patches (a square with 10° in width) that alternated at a frequency of 30 Hz in the center of the screen. While the luminance value of the red patch was fixed at 4.80 cd/m^2, the participants adjusted the luminance of the green patch by pressing one of two keys to dim or brighten it until they found the luminance value that produced the minimum flicker.

2.1.3. Both Experiments 1a and 1b

Stimuli were generated by using Matlab and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and were presented on a 19 inch Philips Brilliance 109P monitor. There were three monitor refresh rate conditions: 85 Hz, 120 Hz, and 150 Hz. The screen background was gray at a luminance of 1.52 cd/m^2. Two black square frames ($2^\circ \times 2^\circ$) were continuously placed 5° to the left and right of a central fixation point (center-to-center) throughout the entire trial. At the beginning of each trial, both the two square frames were filled with a uniform and static yellow color (CIE *x*, *y* chromaticity coordinates of .484/.450), which was set to be equiluminant with the fused yellow color for each participant. After about 500 ms, the chromatic flicker cue was presented for 376 ms (32 refresh frames in the 85-Hz monitor refresh rate condition), 400 ms (48 refresh frames in the 120-Hz refresh rate condition), or 373 ms (56 refresh frames in the 150-Hz refresh rate condition), respectively,[2] and then the static yellow color was resumed inside both the two square frames. After a variable interval, the target, a black line (0.5° × 0.15°) tilted either +45° or −45° from vertical, was randomly presented at the center of one of the two square frames for 200 ms. Subsequently, all stimuli disappeared but the two square frames remained until the participant responded. The stimulus onset asynchrony (SOA) between the cue and the target was approximately 450, 650, and 900 ms under each monitor refresh rate condition (see Table 1 for details). The chromatic flicker cue was produced by alternately filling the square frame with the red (CIE *x, y* chromaticity coordinates of .630/.344) and green (CIE *x, y* chromaticity coordinates of .280/.598) colors, which were matched for perceptual luminance. For the invisible cue, the flicker frequency was 42.5 Hz (in the 85-Hz monitor refresh rate condition), 60 Hz (120-Hz refresh rate), or 75 Hz (150-Hz refresh rate), respectively. Under these invisible flicker conditions, the red–green color alternation yielded one fused yellow color (CIE *x, y* chromaticity coordinates of .485/.449). For the visible cue, the flicker frequency was 21.25 Hz (in the 85-Hz monitor refresh rate condition), 20 Hz (120-Hz refresh rate), or 18.75 Hz (150-Hz refresh rate), respectively. The accuracy of the presentation frequency and timing was confirmed independently using a photosensitive resistor circuit and an oscilloscope. The participants' task was to discriminate which of the two targets was present on each trial. They were instructed to maintain fixation throughout the entire trial and to respond as quickly as possible while maintaining accuracy. Reaction times (RTs) were measured from the onset of the target. Only the correct RTs within three standard deviations from the mean were submitted to analysis, resulting in the removal of less than 2.7% of the trials for both Experiments 1a and 1b. The analyses of error rates revealed no significant effect.

2.1.4. Experiment 1a: unconscious alerting

The 66 participants were randomly assigned to one of three experimental groups based on the monitor refresh rate condition. For each group, there were three types of the chromatic flicker cue: invisible cue, visible cue, and no cue. For both the invisible- and visible-cue trials, the chromatic flicker cue with the respective flicker frequency was presented inside both the two square frames simultaneously (see Fig. 1). For the no-cue trials, the physically static yellow color remained inside both the two square frames during the cue period. Each participant performed a total of 360 trials that were equally distributed to each combination of cue type and SOA.

2.1.5. Experiment 1b: unconscious orienting

The 60 participants were randomly assigned to one of three experimental groups based on the monitor refresh rate condition. For each group, there were two types of the chromatic flicker cue: invisible cue and visible cue. For trials of each cue type, the chromatic flicker cue with the respective flicker frequency was presented inside one of the two square frames randomly whereas the physically static yellow color remained inside the other square frame (see Fig. 2). The cue, regardless of whether invisible or visible, was equally likely to be valid (i.e., the subsequent target appeared at the cued location) or invalid (i.e., the target appeared at the uncued location). Each participant performed 240 invisible-cue trials that were equally distributed to each SOA and 80 visible-cue trials only with the 450-ms SOA,[3] i.e., a total of 320 trials.

2.1.6. Perceptual equivalency between fused flicker and static control stimuli

Each participant underwent a two-alternative forced choice (2AFC) experiment under the respective monitor refresh rate condition to determine whether the fused chromatic flicker was perceptually indistinguishable from the luminance-matched static yellow color in a criterion-free way. Each trial began with the two square frames filled with the physically static yellow color. After about 500 ms, the chromatic flicker cue, regardless of whether invisible or visible, was presented inside one of the two square frames randomly for 376, 400, and 373 ms in the 85, 120, and 150 Hz monitor refresh rate conditions respectively, while the static yellow color remained inside the other square frame. After the offset of the flickering cue, the static yellow color was resumed inside both the two square frames for 71, 50, and 80 ms in the 85, 120, and 150 Hz monitor refresh rate conditions, respectively. Subsequently, only the two square frames remained until the participant responded. In brief, in each trial, the chromatic flicker cue was presented inside one of the two square frames randomly and was preceded and followed by the static yellow color, whereas the other square frame was filled with the static yellow color continuously. Note that this 2AFC experiment was the same as the 450-ms SOA condition in Experiment 1b (see Sections 2.1.3 and 2.1.5), except that there was no target period. With such design, we could test the visibility of any component of the chromatic flicker cue, including cue onset, cue offset, and chromatic flicker per se. The participants were instructed to indicate in which side of the

[2] In pilot experiments, we varied the cue duration systematically to establish the appropriate condition under which the invisible chromatic flicker cue could produce attentional effects. Under the short cue duration and short SOA condition (for example, the cue duration was about 141–150 ms and SOA was about 141–200 ms in some pilot experiments), no reliable effect was found. When the cue duration was long enough (as in the formal experiments), however, we observed reliable effects. Thus, for the invisible chromatic flicker cue, a long cue duration was required, leading us to employ relatively long SOAs in the present study.

[3] In pilot experiments of unconscious orienting, the three SOAs used in the invisible flicker condition had been used in the visible flicker condition. For the visible cues, however, we did not observe the IOR but facilitation effects at the 650-ms and 900-ms SOAs. We assumed that because the cue duration (373 ms and more) was normally too long to be appropriate for an exogenous cue, the visible cue with such a long duration might evoke endogenous orienting, resulting in facilitation effects even at the two longer SOAs. Since the facilitation effects of the visible cues at the two longer SOAs were neither appropriate to be compared with the corresponding IOR effects of the invisible cues nor relevant to the aim of our research, the two longer SOAs were therefore not used in the visible flicker condition of Experiment 1b.

Table 1
Cue duration, interval between cue offset and target onset, and the corresponding SOA between cue onset and target onset in each monitor refresh rate condition of Experiment 1 and in Experiment 2.

Monitor refresh rate (in Hz)	Cue duration (in ms)	Interval between cue offset and target onset (in ms)	SOA between cue onset and target onset (in ms)
Experiment 1			
85	376	71	447
		271	647
		529	905
120	400	50	450
		250	650
		500	900
150	373	80	453
		280	653
		527	900
Experiment 2			
85	94	71	165
	376	71	447

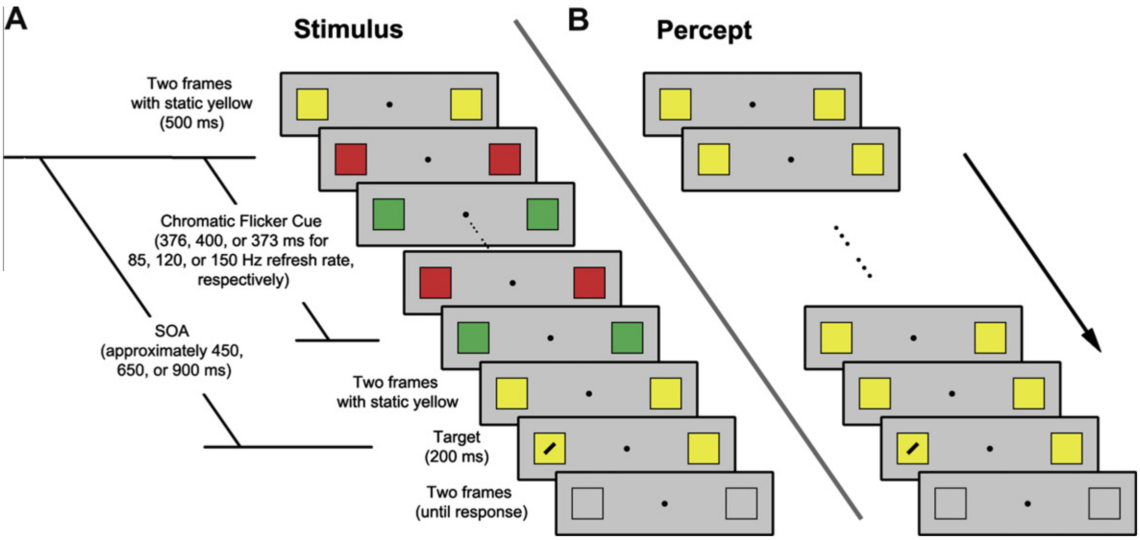

Fig. 1. Stimuli and procedure of Experiment 1a. (A) Sequence of events for a typical trial is shown. Each trial began with a fixation point and two black square frames that were filled with yellow color. After 500 ms, the chromatic flicker cue (filling both the two square frames with red and green colors alternately) was presented for 376, 400, or 373 ms in the 85, 120, or 150 Hz monitor refresh rate conditions, respectively, and then the yellow color was resumed inside both the two square frames. After a variable interval, the target was presented for 200 ms. Subsequently, only the two square frames were presented until the participant responded. The stimulus onset asynchrony (SOA) between the cue and the target was approximately 450, 650, and 900 ms in each refresh rate condition. For the invisible-cue trial, the chromatic flicker frequency was 42.5, 60, and 75 Hz in the three refresh rate conditions, respectively. For the visible-cue trial, the corresponding flicker frequency was 21.25, 20, and 18.75 Hz, respectively. For the no-cue trial (not shown), no chromatic flicker cue was presented and the yellow color remained inside both the two square frames during the cue period. (B) Subjective experience throughout an invisible-cue trial is shown. Chromatic flicker beyond the critical fusion frequency was perceived as one fused yellow color, which was perceptually identical to the physically static yellow color. Thus, participants could not perceive any luminance or color change and had the same subjective experience in invisible-cue trials as in no-cue trials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

two square frames any transient change had occurred during the entire trial, including color change, luminance change, or flickering percept. They were told to respond as accurately as possible, without speed pressure. Each participant completed 60 invisible-flicker trials and 60 visible-flicker trials.

In Experiment 1, the participants in all the six experimental groups performed at ceiling level for the respective visible-flicker comparison (data not shown). By contrast, they performed at chance level for the respective invisible-flicker comparison with a mean correct percentage of 51.59% [$t(21) = 1.55$, $p > .135$], 52.05% [$t(21) = 1.61$, $p > .121$], and 51.67% [$t(21) = 1.37$, $p > .186$] for the Experiment 1a group in the 85-Hz, 120-Hz, and 150-Hz monitor refresh rate conditions, respectively, and 52.08% [$t(19) = 1.43$, $p > .167$], 51.58% [$t(19) = 1.37$, $p > .186$], and 50.83% [$t(19) = 0.85$, $p > .404$] for the Experiment 1b group in the 85-Hz, 120-Hz, and 150-Hz monitor refresh rate conditions, respectively. The 2AFC results provided support that chromatic flickers beyond the critical fusion frequency were indeed fused and perceptually identical to the static control.

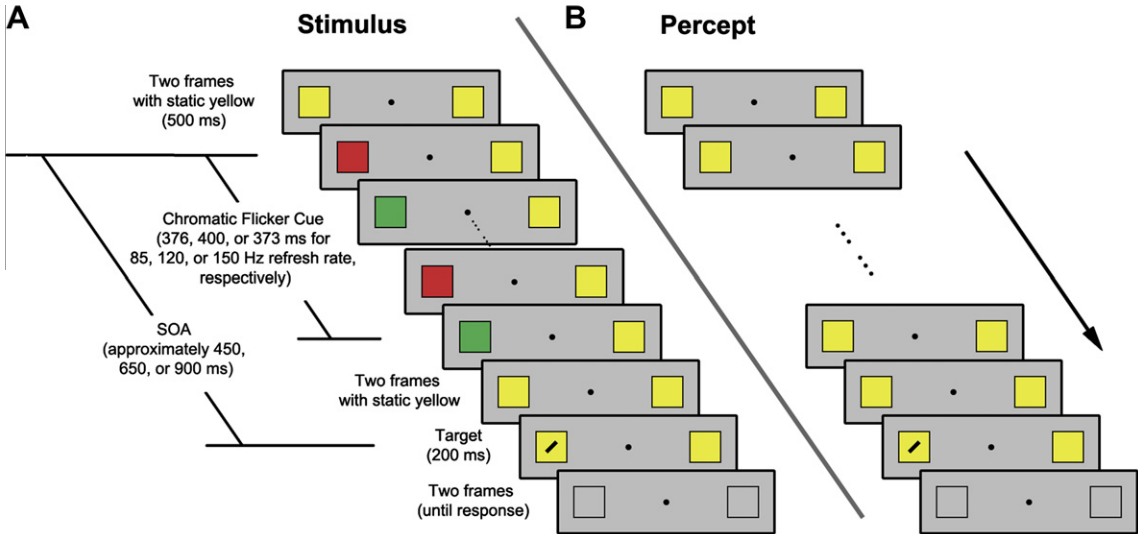

Fig. 2. Stimuli and procedure of Experiment 1b. (A) Sequence of events for a typical trial is shown. Each trial began with a fixation point and two black square frames that were filled with yellow color. After 500 ms, the chromatic flicker cue (filling one of the two square frames with red and green colors alternately) was presented for 376, 400, or 373 ms in the 85, 120, or 150 Hz monitor refresh rate conditions, respectively, and then the yellow color was resumed inside the cued square frame. After a variable interval, the target was presented for 200 ms. Subsequently, only the two square frames were presented until the participant responded. The SOA between the cue and the target was approximately 450, 650, and 900 ms in each refresh rate condition. For the invisible-cue trial, the chromatic flicker frequency was 42.5, 60, and 75 Hz in the three refresh rate conditions, respectively. For the visible-cue trial, the corresponding flicker frequency was 21.25, 20, and 18.75 Hz, respectively. This illustration shows a valid trial on which the target appeared at the cued location. (B) Subjective experience throughout an invisible-cue trial is shown. Chromatic flicker beyond the critical fusion frequency was perceived as one fused yellow color, which was perceptually identical to the physically static yellow color. Thus, participants could not perceive any luminance or color change. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Results and discussion

2.2.1. Experiment 1a: unconscious alerting

In this experiment, the attentional cue occurred at the two possible target positions simultaneously (see Fig. 1). With such design, the attentional cue informed the participants that a target was about to appear, but provided no information about where the target would appear (Fan et al., 2002; Fernandez-Duque & Posner, 1997). The alerting effect referred to the extent to which RTs to targets following the attentional cue were faster than those to targets without the cue.

Not surprisingly, compared with the no cue condition, the visible chromatic flicker cues produced stable alerting effects at all SOAs (i.e., approximately 450, 650, and 900 ms for each experimental group) (for the 21.25-Hz cue: all $ts > 3.15$, $ps < .006$; the 20-Hz cue: all $ts > 3.06$, $ps < .007$; the 18.75-Hz cue: all $ts > 2.43$, $ps < .025$). Intriguingly, when the flicker cue was invisible, we obtained the same overall pattern of results for all the three experimental groups with respective invisible flicker frequency (see Fig. 3). An analysis of variance (ANOVA) with flicker frequency group (42.5, 60, and 75 Hz), SOA (450, 650, and 900 ms), and alerting (invisible cue and no cue) as factors on the RT data revealed a significant SOA $\times$ alerting interaction [$F(2, 126) = 3.15$, $p < .05$] but no significant SOA $\times$ alerting $\times$ group interaction [$F(4, 126) = 0.56$, $p > .686$]. For all invisible cues, the alerting effect was observed only at the short 450-ms SOA [for the 42.5-Hz cue: $t(21) = 2.63$, $p < .017$; the 60-Hz cue: $t(21) = 3.08$, $p < .007$; the 75-Hz cue: $t(21) = 2.67$, $p < .015$] but not at the other two longer SOAs (for the 42.5-Hz cue: $ts < 0.73$, $ps > .47$; the 60-Hz cue: $ts < 1.79$, $ps > .09$; the 75-Hz cue: $ts < 1.44$, $ps > .16$). Furthermore, the magnitude of the alerting effect induced by the invisible cue was comparable to that of the corresponding visible cue at the 450-ms SOA for each experimental group [for the invisible 42.5-Hz cue versus the visible 21.25-Hz cue: $t(21) = 1.26$, $p > .220$; the 60-Hz cue versus the 20-Hz cue: $t(21) = 0.68$, $p > .500$; the 75-Hz cue versus the 18.75-Hz cue: $t(21) = 0.09$, $p > .928$]. To our knowledge, these findings were the first to show that visual information that could not enter observers' consciousness, such as the fused chromatic flicker, could activate the alerting network, and the alerting effect of the invisible flicker remained unchanged as the flicker frequency increased.

Consistent with previous studies (Fernandez-Duque & Posner, 1997), the alerting effect of the visible flicker was observed at a wide range of SOA. In contrast, the alerting effect of the invisible flicker was observed only at the 450-ms SOA, suggesting that the unconscious alerting effect might be a transient process. We assumed that perhaps the invisible flicker activated the alerting network in a purely exogenous fashion whereas for the visible flicker, endogenous (intrinsic) alerting might be also involved, especially at the long SOAs, resulting in the different time course of the alerting effect of the invisible versus visible flicker.

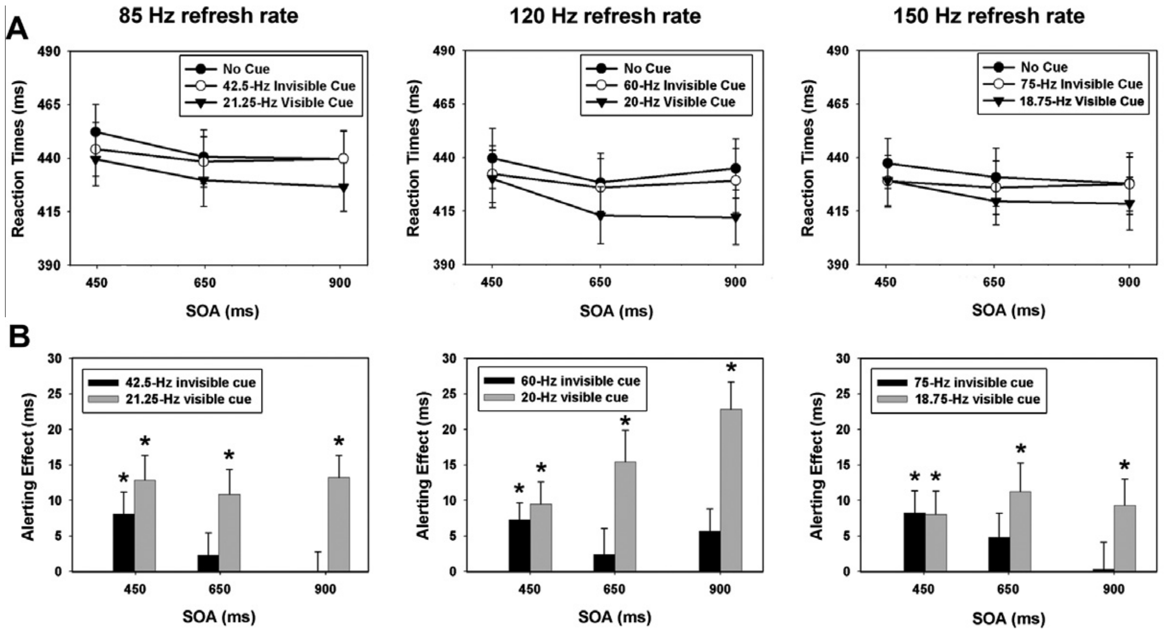

Fig. 3. Results of Experiment 1a. (A) Mean reaction times in the 85, 120, and 150 Hz refresh rate conditions, plotted as a function of SOA for no-cue, invisible-cue, and visible-cue trials. Error bars represent SEM. (B) The corresponding alerting effects as a function of SOA for invisible-cue and visible-cue trials. Error bars represent SEM. Asterisks indicate statistical significance from zero ($p < .05$).

2.2.2. Experiment 1b: unconscious orienting

In this experiment, the attentional cue occurred at one of the two possible target positions randomly (see Fig. 2), so that it had equal chance of being valid or invalid and did not predict the target position. Typically, the exogenous orienting of spatial attention should exhibit a biphasic pattern of initial facilitation followed by inhibition of return (IOR) (Klein, 2000; Posner & Cohen, 1984). That is, if this spatially uninformative cue is able to attract attention involuntarily, RTs for valid trials are faster than RTs for invalid trials at short SOAs, and slower for valid than invalid trials at longer SOAs.

Not surprisingly, the visible chromatic flicker cues produced a stable facilitation effect at the short 450-ms SOA [for the 21.25-Hz cue: $t(19) = 8.65$, $p < .001$; the 20-Hz cue: $t(19) = 6.86$, $p < .001$; the 18.75-Hz cue: $t(19) = 7.40$, $p < .001$]. When the flicker cue was invisible, however, the pattern of results differed across the three experimental groups with respective invisible flicker frequency (see Fig. 4). An ANOVA with flicker frequency group (42.5, 60, and 75 Hz), SOA (450, 650, and 900 ms), and cue validity (valid and invalid) as factors on the RT data revealed a significant SOA × validity interaction [$F(2, 114) = 4.30$, $p < .020$] but a marginally significant SOA × validity × group interaction [$F(4, 114) = 2.11$, $p = .091$]. For the 42.5-Hz cue, a significant interaction between SOA (450, 650, and 900 ms) and validity (valid and invalid) was found [$F(2, 38) = 7.35$, $p < .007$]. There was a significant facilitation effect at the short 450-ms SOA [$t(19) = 2.30$, $p < .034$], a marginally significant IOR effect at the middle 650-ms SOA [$t(19) = 1.93$, $p = .069$], and a significant IOR effect at the long 900-ms SOA [$t(19) = 2.44$, $p < .026$]. For the 60-Hz cue, a significant interaction between SOA and validity was also found [$F(2, 38) = 3.79$, $p < .043$]. There was a significant facilitation effect at the 450-ms SOA [$t(19) = 2.49$, $p < .023$] but no IOR at the 650-ms and 900-ms SOAs (all $ps > .200$). For the 75-Hz cue, no significant interaction was found [$F(2, 38) = 0.25$, $p > .722$]. There was neither facilitation at the 450-ms SOA [$t(19) = 0.19$, $p > .850$] nor IOR at the 650-ms and 900-ms SOAs (all $ps > .233$). Because the early facilitation and late IOR effects were observed at the 450-ms and 900-ms SOAs respectively, the RT data for the two SOAs were further entered into an ANOVA with flicker frequency group, SOA, and cue validity as factors. Both the SOA × validity and SOA × validity × group interactions were significant [$F(1, 57) = 9.31$, $p < .004$, and $F(2, 57) = 5.24$, $p < .009$, respectively]. These findings further confirmed that invisible information could activate the orienting network in an exogenous fashion, although the orienting effect of the fused chromatic flicker attenuated as a function of the increasing flicker frequency. Furthermore, the magnitude of the facilitation effect induced by the invisible cue was significantly smaller than that of the corresponding visible cue [for the invisible 42.5-Hz cue versus the visible 21.25-Hz cue: $t(19) = 4.48$, $p < .001$; the 60-Hz cue versus the 20-Hz cue: $t(19) = 3.56$, $p < .003$]. This observation might be due to the following reasons. First, consistent with previous findings (Ivanoff & Klein, 2003), the magnitude of the facilitation effect was impaired when visual awareness was absent. Second, the cue duration was so long for the visible cue that the visible cue might evoke endogenous attentional orienting (see Footnote 3), resulting in an enhanced facilitation effect of the visible cue.

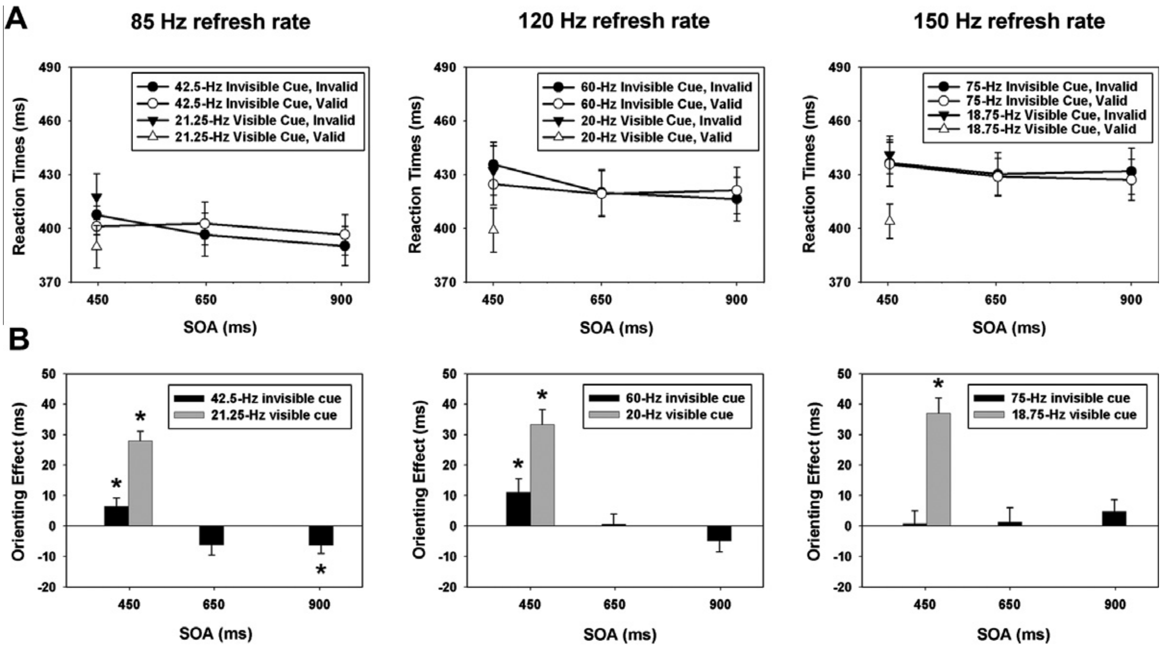

Fig. 4. Results of Experiment 1b. (A) Mean reaction times in the 85, 120, and 150 Hz refresh rate conditions, plotted as a function of SOA for valid and invalid trials of both invisible and visible cue types. Error bars represent SEM. (B) The corresponding orienting effects as a function of SOA for invisible-cue and visible-cue trials. Error bars represent SEM. Asterisks indicate statistical significance from zero ($p < .05$).

3. Experiment 2

In Experiment 1, we found not only the unconscious alerting and orienting effects, but also their distinct dependences on flicker frequency. However, one may argue that these unconscious attentional effects we observed in Experiment 1 could have been due to the offset of the flickering cue, rather than high-frequency chromatic flicker per se. This explanation seems possible for the following reasons. First, it is well known that the visual system is sensitive to events that exhibit transient change, such as abrupt onset and offset, and offset has been established to have the ability to attract visual attention reflexively (Hopfinger & Mangun, 1998; Pratt & McAuliffe, 2001). Second, in Experiment 1b, the facilitation and IOR effects were observed at the 450-ms and 900-ms SOA between cue onset and target onset, respectively. Although these SOAs we used were relatively longer, the corresponding intervals between the offset of the flickering cue and the onset of the target (e.g., 71 and 529 ms in the 85-Hz refresh rate condition) were more consistent with cue-target onset asynchronies typically used in studies investigating the facilitation and IOR effects of exogenous attentional orienting (Klein, 2000; Posner & Cohen, 1984).

Hence, we conducted Experiment 2 to determine whether high-frequency chromatic flicker per se or the offset of the flickering cue contributed to unconscious alerting and orienting effects observed in Experiment 1. This experiment was the same as the 85-Hz refresh rate, 447-ms SOA condition of Experiment 1, except that the duration of the flickering cue was variable: 94 ms or 376 ms. A crucial aspect of the design of Experiment 2 was that the interval between cue offset and target onset was identical in the two cue duration conditions, i.e., 71 ms. If unconscious alerting and orienting effects in Experiment 1 were indeed due to the offset of the flickering cue, these unconscious attentional effects would be expected under both the two cue duration conditions in Experiment 2.

3.1. Methods

3.1.1. Participants

A total of 24 students (17 females, 7 males; age range = 19–25 years) participated in this study (12 in Experiment 2a and 12 in Experiment 2b). All had normal or corrected-to-normal vision and provided informed consent. This study was approved by the ethics committee in Department of Psychology and Behavioral Sciences, Zhejiang University.

3.1.2. Perceptual equiluminance between red and green colors

Before the experimental session, each participant matched the red and green colors for perceptual luminance by using the same luminance matching test as that used in Experiment 1 (see Section 2.1.2).

3.1.3. Both Experiments 2a and 2b

The methods of Experiment 2 were the same as those in Experiment 1 (see Section 2.1.3) with the following two modifications. First, the monitor refresh rate was fixed at 85 Hz. Thus, the flicker frequency of the invisible and visible chromatic flicker cues was 42.5 Hz and 21.25 Hz, respectively. Second, the cue duration of the flickering cue was either 94 ms (8 refresh frames) or 376 ms (32 refresh frames) while the interval between the offset of the flickering cue and the onset of the target was fixed at 71 ms (6 refresh frames). Thus, the corresponding SOAs between cue onset and target onset were 165 ms and 447 ms, respectively (see Table 1). Note that the stimuli and procedure in the 376-ms cue duration condition were identical to those in the 85-Hz refresh rate, 447-ms SOA condition of Experiment 1. In addition, in Experiments 2a and 2b, approximately 4.1% and 4.7% of the trials were removed respectively, and the analyses of error rates revealed no significant effect.

3.1.4. Experiment 2a: unconscious alerting

The 12 students took part in this experiment. Each participant performed a total of 240 trials that were equally distributed to each combination of cue type (invisible cue, visible cue, and no cue) and cue duration (94 and 376 ms). Other aspects were the same as those in Experiment 1a (see Section 2.1.4).

3.1.5. Experiment 2b: unconscious orienting

The 12 students took part in this experiment. Each participant performed a total of 320 trials that were equally distributed to each combination of cue type (invisible cue and visible cue), cue duration (94 and 376 ms), and cue validity (valid and invalid). Other aspects were the same as those in Experiment 1b (see Section 2.1.5).

3.1.6. Perceptual equivalency between fused flicker and static control stimuli

Each participant underwent a 2AFC experiment under the 85-Hz monitor refresh rate condition to determine whether the fused chromatic flicker was perceptually indistinguishable from the luminance-matched static yellow color in a criterion-free way. This 2AFC experiment was the same as that in the 85-Hz monitor refresh rate condition of Experiment 1 (see Section 2.1.6) with the following two exceptions. First, the chromatic flicker cue, regardless of whether invisible or visible, was equally likely to be presented for 94 ms or 376 ms. Second, each participant completed 120 invisible-flicker trials and 60 visible-flicker trials.

For the visible-flicker comparison, the participants in Experiments 2a and 2b performed at ceiling level (data not shown). Of main interest was the invisible-flicker comparison. When the cue duration was 94 ms, the participants performed at a level which was close to but significantly higher than chance level. The mean correct percentage was 55.83% [$t(11) = 3.72$, $p < .004$] and 56.25% [$t(11) = 5.07$, $p < .001$] in Experiments 2a and 2b, respectively. When the cue duration was 376 ms, however, the participants performed at chance level with a mean correct percentage of 52.64% [$t(11) = 1.62$, $p > .134$] and 52.22% [$t(11) = 1.12$, $p > .285$] in Experiments 2a and 2b, respectively. The 2AFC results showed that the chromatic flicker beyond the critical fusion frequency was faintly visible under the 94-ms cue duration condition, but was indeed fused and perceptually identical to the static control under the 376-ms cue duration condition. We assume that when the cue duration was 94 ms (eight refresh frames, four red-green alternations), the high-frequency chromatic flicker might not be fully fused with such a short duration, resulting in the faint visibility. When the cue duration was long enough (e.g., 376 ms), the high-frequency chromatic flicker could be fully fused and became invisible.

3.2. Results

3.2.1. Experiment 2a: unconscious alerting

For the visible chromatic flicker cue, there was a marginally significant alerting effect with the 94-ms cue duration [$t(11) = 2.07$, $p = .063$] and a significant alerting effect with the 376-ms cue duration [$t(11) = 3.91$, $p < .003$]. Of main interest was the alerting effect induced by the invisible chromatic flicker cue (see Fig. 5). Therefore, an ANOVA was conducted on the RT data with cue duration (94 and 376 ms) and alerting cue (invisible cue and no cue) as factors. There was a significant interaction between the two variables [$F(1, 11) = 5.13$, $p < .046$]. When the cue duration was 94 ms, RTs for the two alerting cue conditions did not differ from one another significantly [$t(11) = -0.32$, $p > .751$], suggesting that no alerting effect was observed. When the cue duration was 376 ms, however, RTs on invisible-cue trials were significantly faster than those on no-cue trials [$t(11) = 2.49$, $p < .031$], indicating a reliable form of alerting effect.

3.2.2. Experiment 2b: unconscious orienting

For the visible chromatic flicker cue, there were significant facilitation effects with both the 94-ms and 376-ms cue durations [$t(11) = 5.75$, $p < .001$, and $t(11) = 6.32$, $p < .001$, respectively]. Of main interest was the orienting effect induced by the invisible chromatic flicker cue (see Fig. 6). Therefore, an ANOVA was conducted on the RT data with cue duration (94 and 376 ms) and cue validity (valid and invalid) as factors. There was a significant interaction between the two variables [$F(1, 11) = 8.75$, $p < .014$]. When the cue duration was 94 ms, RTs for the two cue validity conditions did not differ from one another significantly [$t(11) = -0.44$, $p > .668$], suggesting that no any orienting effect was observed. When the cue duration was 376 ms, however, RTs on valid trials were significantly faster than those on invalid trials [$t(11) = 2.78$, $p < .019$], indicating a reliable form of facilitation effect.

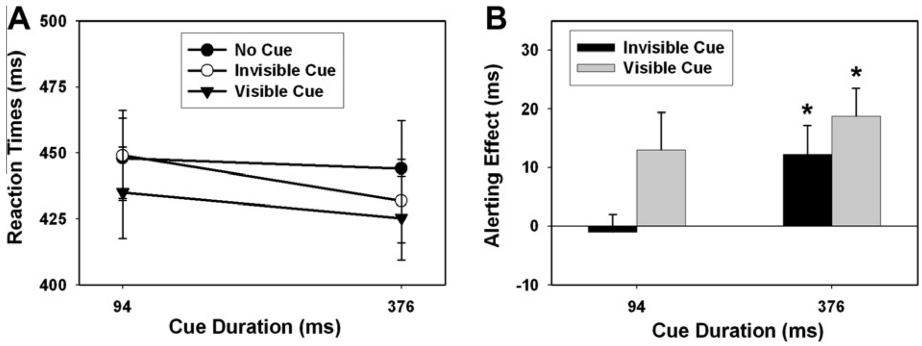

Fig. 5. Results of Experiment 2a. (A) Mean reaction times plotted as a function of cue duration for no-cue, invisible-cue, and visible-cue trials. Error bars represent SEM. (B) The corresponding alerting effects as a function of cue duration for invisible-cue and visible-cue trials. Error bars represent SEM. Asterisks indicate statistical significance from zero ($p < .05$).

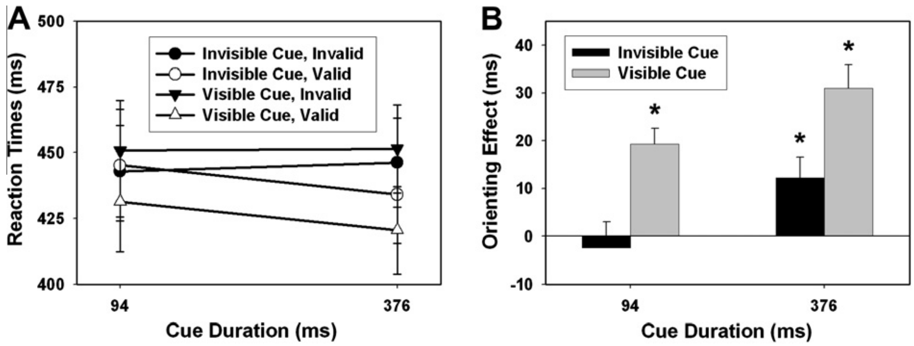

Fig. 6. Results of Experiment 2b. (A) Mean reaction times plotted as a function of cue duration for valid and invalid trials of both invisible and visible cue types. Error bars represent SEM. (B) The corresponding orienting effects as a function of cue duration for invisible-cue and visible-cue trials. Error bars represent SEM. Asterisks indicate statistical significance from zero ($p < .05$).

3.3. Discussion

In Experiment 2, both the alerting and orienting effects induced by the invisible chromatic flicker cue were observed in the 376-ms cue duration condition, replicating the results of the 85-Hz refresh rate, 447-ms SOA condition in Experiment 1. However, these unconscious attentional effects were not observed in the 94-ms cue duration condition. Given that the interval between cue offset and target onset was kept identical between the two cue duration conditions, it seems reasonable to infer that the offset of the invisible chromatic flicker cue alone is not sufficient to produce unconscious alerting and orienting effects. Thus, the unconscious attentional effects we observed in Experiment 1 were not due to cue offset, but rather might be due to high-frequency chromatic flicker per se.

In line with our pilot experiments (see Footnote 2), Experiment 2 revealed that both the alerting and orienting effects could be induced by the invisible chromatic flicker cue, provided that the cue duration was long enough. Likewise, a recent study also showed that for the 50-Hz invisible flicker, the orienting effect was not evident at short flicker durations of 100–200 ms, but became evident at longer durations of 300–400 ms (Bauer et al., 2009). In the present study, we suspect that the invisible chromatic flicker cue needs a long duration to be an effective attentional cue for the following two reasons. First, for the subliminal stimulus, its signal strength may be relatively weaker, and longer durations may be required such that the potential of the cue may be accumulated to a particular level to generate observable attentional effects. Second, because of the coarse temporal resolution of the parvocellular pathway, the chromatic cue should be presented for a longer duration to be processed as an effective cue by the visual system (Lu, 2006).

4. General discussion

In everyday situations, attention and awareness co-occur very often. Despite such a tight relationship between attention and awareness, recent studies have shown that they are two distinct brain processes and can be disentangled from each other (Kanai, Tsuchiya, & Verstraten, 2006; Koch & Tsuchiya, 2007; Lamme, 2003). In the present study, both the two experiments together demonstrate that chromatic flicker beyond the critical fusion frequency, which cannot be consciously perceived, is effective in producing both the alerting and orienting effects. These findings provide further evidence for the dissociation between attention and awareness. According to the ecological perspective, it makes sense that both the two attentional networks may exert their functions even before conscious perception occurs. Such an automatic and rapid mechanism may supposedly facilitate the organism to deal with environmental events for survival.

Furthermore, the present findings also suggest that as the flicker frequency increases, the orienting effect of the invisible flicker attenuates whereas the alerting effect appears to be unaffected. Regarding the temporal processing capacity of the visual system, neurophysiological studies have demonstrated a systematic decline in temporal frequency sensitivity across the visual hierarchy. The primary visual cortex (V1) is sensitive to a much lower range of temporal frequencies than the lateral geniculate nucleus (Hawken et al., 1996). Likewise, the temporal processing capacity of the human visual cortex is progressively declined as visual information is transferred from early visual cortex to high cortex (McKeeff et al., 2007). Presumably, the greater frequency-dependent characteristic of the orienting versus alerting effect of the invisible flicker suggests that the neural mechanisms underlying the two unconscious attentional functions are likely to be different. Perhaps the unconscious alerting effect is associated with activity in earlier visual areas than the unconscious orienting effect.

When high-frequency flicker information is processed and transmitted along the visual pathway, despite its failure to reach visual awareness, it has been demonstrated to elicit cortical responses (Carmel, Lavie, & Rees, 2006; Falconbridge, Ware, & MacLeod, 2010; Gur & Snodderly, 1997; Jiang, Zhou, & He, 2007; Shady et al., 2004; Vul & MacLeod, 2006; Williams, Mechler, Gordon, Shapley, & Hawken, 2004). For instance, a psychophysical study has shown that the 30-Hz chromatic flicker induced flicker adaptation in human observers, suggesting that this invisible flicker could pass through the neural site for flicker adaptation (Shady et al., 2004). In another study, it is reported that even the 50-Hz color alternation could still induce the orientation contingent color aftereffect, which presumably arose from cortical mechanisms (Vul and MacLeod, 2006). A more direct evidence supporting cortical responses induced by high-frequency flicker comes from a neurophysiological study, which has shown that the 30-Hz chromatic flicker could stimulate color-opponent cells in monkey V1 (Gur and Snodderly, 1997). Furthermore, Jiang et al. (2007) had assessed the extent of cortical activation induced by the imperceptible high-frequency chromatic flicker in human vision. In their study, the 30-Hz chromatic flicker evoked greater cortical activation than its matched static control did in many visual cortical areas, including from V1 to hV4 but with the exception of VO (the area just anterior to hV4). In terms of these previous studies, we cannot yet determine the exact visual areas activated by the three high-frequency chromatic flickers used in the present study. However, according to the systematic decline in temporal frequency sensitivity across the visual hierarchy (Hawken et al., 1996; McKeeff et al., 2007), we infer that these neural activation, compared with those of the 30-Hz chromatic flicker (Jiang et al., 2007), might take place at earlier stages of the visual pathway. Thus, in our study, when the invisible cue was presented, the transition from the static yellow to high-frequency chromatic flicker might evoke changes in the level of neural activation in early visual areas, at least before VO (Jiang et al., 2007). Therefore, we suppose that merely neural activation changes in early visual areas, despite the failure to lead to conscious perception, might be sufficient to activate both the alerting and orienting networks.

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