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Hold the future, let the past go: Attention prefers the features of future targets

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ABSTRACT

Previous studies have shown that attention can be captured by task-irrelevant distractors under the guidance of attentional control settings. However, it is unknown whether people can establish an attentional control setting (ACS) for a sequence of distinct events. The present study tested that question by asking observers to expect a sequence of two colored targets in a specific order. The results show that irrelevant distractors that matched either the color of the first expected target or that of the second target captured attention. Thus observers are unable to temporarily suppress the color of the future target in their ACS. However, the temporal order of targets is still useful for guiding attention: Observers were able to abandon the color of the first target and maintain an ACS for the second one as long as there was a sufficient time interval between the two targets.

1. Introduction

Attentional selection makes people highly adaptive in a complicated environment and thus is critical for our survival. Attentional selection based on a unique feature of a target is one of the most important ways through which attention works. Studies have shown that people can selectively attend to objects that match a target-defining feature such as color and luminance (Du & Abrams, 2008, 2010; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Motter, 1994a; Motter, 1994b), orientation (Du & Abrams, 2012; Haenny, Maunsell, & Schiller, 1988; Haenny & Schiller, 1988; Maunsell, Sclar, Nealey, & DePriest, 1991), size (Becker, 2010), or motion direction (Maunsell & Treue, 2006; Serences & Boynton, 2007; Treue & Martinez-Trujillo, 1999), and sometimes even complicated figures (Chelazzi, Duncan, Miller & Desimone, 1998).

More interestingly, the effect of feature-based attention just described is able to override location-based selection. For example, Motter (1994a, 1994b) showed that prior knowledge of target color can enhance the neural response of many V4 cells which selectively respond to the target color and whose receptive-fields are spread across the whole visual field. Consistent with this line of physiological evidence, many behavioral studies revealed similar dominance of feature-based attention over location-based attention. For example, stimuli that match the color we are seeking can capture our attention even when they appear outside of the area of interest (Du & Abrams, 2008, 2010, 2012; Folk, Leber, & Egeth, 2002; Serences et al., 2005). This involuntary capture of attention is referred to as contingent capture because it is contingent upon the feature match between the target and the irrelevant distractors (Folk et al., 1992). As Folk and colleagues proposed, our attention is guided by our behavioral goals, with this type of guidance also known as an attentional control setting (ACS).

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Initially, Folk et al. (1994) found that when the target-defining feature was color, neither onset nor motion captured attention. When the target-defining feature was motion, both motion and onset but not color captured attention. Thus they proposed that ACSs could only be set to broad categories such as dynamic discontinuities (dynamic events such as the onset or movement) or static discontinuities (static features such as color or shape singletons). However, more and more converging evidence has shown that attentional control settings are highly flexible and can change according to specific task demands (Bacon & Egeth, 1994). For example, people can either precisely tune the ACS to a specific target color (Folk & Remington, 1998; Folk et al., 2002) or maintain multiple colors in their attentional control setting (Irons, Folk, & Remington, 2012). In addition to categorical information or specific feature values, recent studies showed that attentional control settings also maintain relational information of how the target differs from irrelevant distractors. Thus attention can be guided by the relationship between the target and distractors. For example, when the target (orange) is always redder than the yellow distractors, attention is captured by any distractor that is redder than yellow. As a result, both red and orange distractors capture attention (Becker, 2010; Becker, Folk, & Remington, 2010).

Only a few studies have ever examined whether our attentional control setting can integrate multiple features into one unified control setting. For example, one study showed that participants can simultaneously maintain separate attentional control settings at distinct spatial locations (Adamo, Pun, Pratt, & Ferber, 2008). It is tempting to conclude that people can integrate a unique color and a specific location into a conjunctive control set of attention (eg. red-left). However, a follow-up electrophysiological study showed that the selection of location occurred irrespective of attentional selection based on a color-match between cue and target. Thus the authors suggested that color-based and location-based selection of attention work in parallel and the attentional facilitation contingent upon a color-match occurred after spatial attention had been allocated to the cued location (Adamo, Pun, & Ferber, 2010).

To survive in the real world, observers might desire to change their attentional control settings often to adapt to a rapidly changing environment. Thus it is very important to know more about the temporal dynamics of changing ACSs. However, few studies have examined the temporal features of attentional control settings for multiple targets. Of interest in the present study is how observers represent the temporal order of multiple targets in ACSs. In order to test whether people can integrate a specific temporal order of targets with colors of multiple targets, we presented two colored targets in a RSVP stream at the center of the display, and some irrelevant distractors in the periphery. If observers can use the temporal order of multiple targets in attentional control settings perfectly, attention will only be captured by irrelevant distractors that match the current target. In addition, if observers can combine the temporal order with multiple target colors, it is unknown how long it takes observers to switch from one color to another in ACSs. We examined that question also.

2. Experiment 1

The present experiment was designed to examine how observers represent the temporal order of multiple targets in ACSs. A previous study showed that observers could make quick switches between multiple attentional control settings when the target color changed across trials (Lien, Ruthruff, & Johnston, 2010). But it is unknown whether observers can switch from one color to another in ACSs when they have to identify multiple targets in a single trial. In real life, people often have to deal with multiple events continuously rather than facing one event at a time. Thus it is important to test whether observers can combine the temporal order of multiple targets into their ACS when they have to monitor multiple targets in an RSVP stream of letters with multiple colors.

In the present study, observers were required to identify two specifically colored targets embedded in a RSVP stream of letters at the center of the display. If observers are perfectly efficient, a peripheral color singleton that matches the color of the first target (T1) should capture attention only when it appears before T1, and a peripheral color singleton that matches the color of the second target (T2) should capture attention only if it appears after T1 but before T2.

2.1. Methods

2.1.1. Participants

Twenty undergraduate students at Washington University participated in an hour-long experiment for course credit. All had normal or corrected-to-normal visual acuity. No participants had experience in similar experiments.

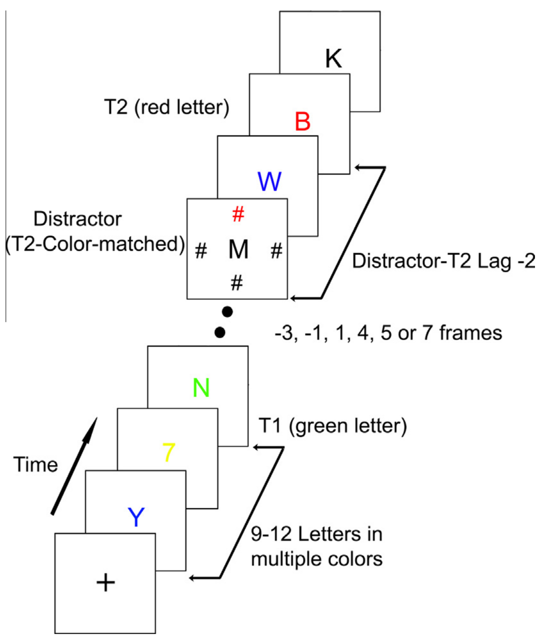

Fig. 1. A schematic representation of the procedure in Experiment 1. Each frame was presented for 40 ms, and followed by a blank interval of 40 ms.

2.1.2. Apparatus and procedure

All the stimuli were presented on a 19-in. monitor with a 100-Hz refresh rate in a dimly lit room at a distance of 60 cm. The sequence of events on a trial is illustrated in Fig. 1. Each trial began with a 500-ms presentation of a white fixation cross in the center of the screen, followed by the sequential presentation of 24 uppercase letters at the center. The background was black. The letters were selected randomly without replacement from the English alphabet, with the exception of "I." The letters were about 1.0° in width and 1.2° in height and presented in Courier New font. Each letter was presented for 40 ms, followed by a 40 ms blank interval, yielding a stimulus onset asynchrony of 80 ms. One half of the participants were required to report the sole red letter in the sequence as the first target (T1), then the sole green letter as the second target (T2); the other half searched for the sole green letter as T1 and the red letter as T2. Across trials, the first target letter (in either red or green) appeared in the 9th through 12th frames of the letter sequence. The second target letter (in either green or red) always appeared in the 8th frame after T1 in order to avoid the suppression of contingent capture by attentional selection of T1 (Du, Yang, Yin, Zhang, & Abrams, 2013; Folk, Ester, & Troemel, 2009). The colors of the remaining letters were randomly chosen from three colors (gray, blue, or yellow). Blue and yellow were picked as non-target colors so that red and green could not be treated as one broad category (Becker, 2010). The participants reported the two target letters by pressing the corresponding keys after each trial. In the stream of letters, one of the letters randomly chosen from the 7th to 20th frames, was surrounded by four hash signs (#) whose inner edges appeared 4.5° above, below, to the right of, and to the left of the center of the letter. For one third of the trials, all of the hash signs were gray; on the other trials, one of the hash signs was either red or green (equally likely) and the other three were gray. The frame containing the colored distractor could appear 2 frames before T1 (T1-distractor lag of −2), simultaneously (T1-distractor lag of 0), or 2, 5, 6 or 8 frames after T1 (T1-distractor lag of 2, 5, 6, 8). And since T2 always appeared 8 frames after T1, the frame containing the colored distractor could appear 10, 8, 6, 3, 2 frames before or simultaneously with T2, resulting in T2-distractor lag of −10, −8, −6, −3, −2 and 0.

2.1.3. Design

Each trial was in one of three distractor conditions: (1) The four hash signs could be all gray (*Gray*); (2) one hash sign could match the first target in color and thus be complementary to the color of the second target (*T1-color-matched*); or (3) one hash sign was in the same color as T2 and the complementary color to T1 (*T2-color-matched*). Each block contained 20 replications of each combination of three distractor conditions and six distractor–target lags, for a total of 360 trials. The participants first performed one block of 16 trials for practice. They then completed the test trials. After every 60 trials, they received a brief break.

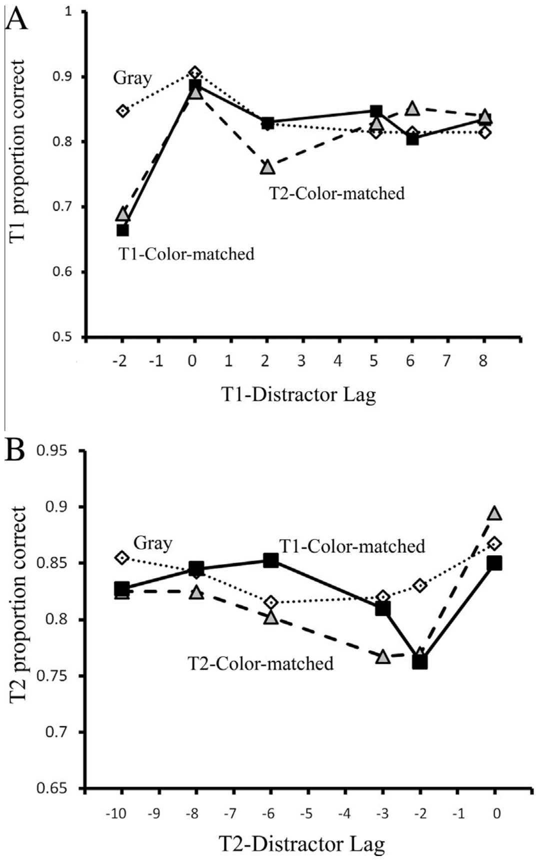

Fig. 2. The results of Experiment 1. (A) Accuracy of first target (T1) identification as a function of T1-distractor lag and distractor condition. (B) Accuracy of second target (T2) identification as a function of T2-distractor lag and distractor condition.

2.2. Results

Mean accuracy for T1 identification is plotted as a function of T1-distractor lag and distractor condition in Fig. 2A. T1 accuracy was analyzed using a repeated measures ANOVA. Results showed a marginally significant main effect of distractor condition, $F_{(2,38)} = 3.124$, $p = 0.055$, $\eta_p^2 = 0.141$; and there was a main effect of T1-distractor lag, $F_{(5,95)} = 15.22$, $p < 0.001$, $\eta_p^2 = 0.445$, with lower T1 accuracy at the T1-distractor lag −2. Interestingly, there was a significant interaction involving the distractor condition and lag, $F_{(10,190)} = 5.208$, $p < 0.001$, $\eta_p^2 = 0.215$, with lowest accuracy when either a *T1-color-matched* (*unmatched to T2*) or a *T2-color-matched* (*unmatched to T1*) distractor appeared at T1-distractor lag −2. Consistent with many previous studies, contingent capture mostly occurred at two lags before the target (Du & Abrams, 2008; Folk et al., 2002). A further pairwise comparison (Bonferroni correction) of T1 accuracy at T1-distractor lag −2 was performed. The results confirmed that both the *T1-color-matched* and *T2-color-matched* distractors produced larger capture than gray distractors, $p = 0.001$ and $p = 0.002$, respectively. But *T1-color-matched* distractors did not differ from *T2-color-matched* distractors ($p = 1$). These results indicate that participants could not precisely tune their attention to the T1 color when searching for T1. Instead both the color of the present task (T1) and the color of future task (T2) were maintained in their ACS. Surprisingly, the T2-colored distracters cause marginally larger impairment on T1 performance than gray distracters at T1-distractor lag 2, $p = 0.052$. But T2-colored distracters only caused numerically larger capture than T1-colored distracters at that lag, $p = 0.113$. And T1-colored distracters caused almost the same capture effect as gray distracters, $p = 1$. It is unknown why a T2-colored distracter captured attention when it appeared 2 frames after T1.

Unlike an attentional blink paradigm in which T2 accuracy is only analyzed when T1 is correct, we examined T2 accuracy irrespective of T1 accuracy for the following reasons. First, it may be conceptually inappropriate to exclude T1-incorrect trials from T2 analysis. When participants were maintaining the T1 color (and presumably also the T2 color) in their attentional control settings, they were very likely to be distracted by either T1-color-matched or T2-color-matched distractors, resulting in errors on T1. Thus, in theory, participants could have maintained the same attentional control settings in the T1-incorrect trials as in the T1-correct trials, although they were unable to suppress peripheral distractors in the T1-incorrect trials. Thus T1-incorrect trials should be included in the analysis for T2. Second, T1 accuracy here is impaired when either a T1-colored or T2-colored distractor preceded T1 in the present experiment. If we only consider T2 performance when T1 was correct, the total trial number will be uneven for the different distractor conditions, making comparisons between different distractor conditions difficult. Finally, a recent study systematically examined the effect of T1 processing on subsequent contingent capture (Du et al., 2013). The present study is not interested in the effect of T1 processing on contingent capture. Thus the analysis of T2 should not be limited to the T1-correct trials.

Mean accuracy for T2 identification is plotted as a function of T2-distractor lag and distractor condition in Fig. 2B. There was no main effect of distractor condition, $F_{(2,38)} = 2.492$, $p = .096$, $\eta_p^2 = 0.116$. The main effect of T2-distractor lag was significant, $F_{(5,95)} = 7.355$, $p < 0.001$, $\eta_p^2 = 0.279$, with lowest T2 accuracy at the lag -2. In addition, the interaction between lag and distractor condition was marginally significant. $F_{(10,190)} = 1.842$, $p = 0.056$, $\eta_p^2 = 0.088$, with lowest accuracy when either a *T2-color-matched* or a *T1-color-matched* distractor appeared at T2-distractor lag -2. A further pairwise comparison (Bonferroni correction) of T2 accuracy at T2-distractor lag -2 confirmed that both the *T2-color-matched* and *T1-color-matched* distractors produced larger capture than gray distractors, $p = 0.036$ and $p = 0.012$, respectively. But the T1-color-matched distractors did not differ from the T2-color-matched distractors, $p = 0.742$.

2.3. Discussion

When observers were searching for T1, irrelevant distractors that matched either the T1 color or the T2 color captured attention. This indicates that observers cannot suppress the color of a future target in their attentional control setting. In addition, both *T2-color-matched* and *T1-color-matched* distractors captured attention when observers were searching for T2. This suggests that observers cannot use the temporal order of the targets to constrain the attentional control setting.

3. Experiment 2

The impairment of T1 accuracy in Experiment 1 clearly showed that attention was captured not only by distractors that matched the current target (T1) color but also by distractors whose color matched the future target (T2). This seems to indicate that observers cannot suppress the color of an upcoming target in the attentional control setting. More surprisingly, observers did not even abandon the attentional control setting for the past target (T1) when they were searching for T2. Though it is attempting to conclude that observers cannot integrate the temporal order of targets with the colors of multiple targets, it is possible that they actually maintained both colors in their ACS because the task did not force them to precisely tune to a color at a specific moment. Since maintaining both colors in the ACS is not going to interfere with the current task, it may be ecologically a better strategy to maintain both colors rather than to switch from one color to another.

The present experiment was designed to force participants to only select one color at any particular moment by presenting both red and green letters at the center simultaneously. This design forced observers to precisely tune attention to the target color and suppress the color of the future target.

3.1. Methods

3.1.1. Participants

Thirty-four undergraduate students at Washington University participated in an hour-long experiment for course credit. All had normal or corrected-to-normal visual acuity. No participants had experience in similar experiments.

3.1.2. Apparatus, procedure and design

All the stimuli, procedure and design were similar as those of Experiment 1 with several exceptions. First, two streams of letters were presented either 0.8° to the left or 0.8° to the right of the center of the screen, resulting in 1.6° of separation between the two streams. Second, each frame of letters was presented for 50 ms, followed by a 40 ms blank interval, yielding a stimulus onset asynchrony of 90 ms.

Third, to force participants to only select one color at a particular moment, in the target frames both a red and a green letter appeared in the central streams simultaneously. In each trial, there were two such frames in the sequence. The first pair of red and green letters was presented in the 9th through 12th frames of the letter sequence. One of these letters served as T1. The second pair of red and green letters always appeared in the 8th frames after the first pair (one of these was T2). One half of the participants were required to report the red letter in the first red-green pair of letters as T1, then the green letter in the second red-green pair as T2. The other half searched for the green letter in the first red-green pair as T1 and the red letter in the second red-green pair as T2.

Finally, there were four distractor–target lags. The frame containing the colored distractor could appear 2 frames before T1 (T1-distractor lag of −2), simultaneously (T1-distractor lag of 0), 6 or 8 frames after T1 (T1-distractor lag of 6, 8). And since T2 always appeared 8 frames after T1, the frame containing the colored distractor could appear 10, 8, 2 frames before or simultaneously with T2, resulting in T2-distractor lag of −10, −8, −2 and 0.

The experiment contained 20 replications of each combination of three distractor conditions and four disractor–target lags, for a total of 240 trials.

3.2. Results

Mean accuracy for T1 identification is plotted as a function of T1-distractor lag and distractor condition in Fig. 3A. Results showed a significant main effect of distractor condition, $F_{(2,66)} = 11.656$, $p < 0.001$, $\eta_p^2 = 0.261$; and a main effect of T1-distractor lag, $F_{(3,99)} = 28.86$, $p < 0.001$, $\eta_p^2 = 0.467$, with lower T1 accuracy at the T1-distractor lag −2. And there was a significant interaction involving the distractor condition and lag, $F_{(6,198)} = 6.675$, $p < 0.001$, $\eta_p^2 = 0.168$, with lowest accuracy when either a *T1-color-matched* or a *T2-color-matched* distractor appeared at T1-distractor lag −2. A further pairwise comparison (Bonferroni correction) of T1 accuracy at T1-distractor lag −2 confirmed that both the *T1-color-matched* and *T2-color-matched* distractors caused larger impairment than gray distractors, both *ps* < 0.001. But *T1-color-matched* distractors did not differ from *T2-color-matched* distractors ($p = 0.212$). This pattern indicates that participants could not precisely tune their attention to the T1 color when searching for T1. Instead both the color of the present task (T1) and the color of the future task (T2) were maintained in their ACS.

Mean accuracy for T2 identification is plotted as a function of T2-distractor lag and distractor condition in Fig. 3B. There was no main effect of distractor condition, $F_{(2,66)} < 1$, $p = .736$, $\eta_p^2 = 0.009$. The main effect of T2-distractor lag was significant, $F_{(3,99)} = 6.103$, $p = 0.001$, $\eta_p^2 = 0.156$, with lowest T2 accuracy at the T2-distractor lag −2. Moreover, the interaction between lag and distractor condition was significant. $F_{(6,198)} = 2.\ 346$, $p = 0.033$, $\eta_p^2 = 0.066$, with the largest accuracy reduction occurring when either a *T2-color-matched* or a *T1-color-matched* distractor appeared at T2-distractor lag −2. A further pairwise comparison (Bonferroni correction) of T2 accuracy at T2-distractor lag −2 confirmed that both the *T2-color-matched* and *T1-color-matched* distractors produced a greater impairment of T2 performance than gray distractors, $p = 0.040$ and $p = 0.032$, respectively. But the *T2-color-matched* distracters and the *T1-color-matched* distracters produced almost equivalent amounts of capture, $p = 1$. This indicates that both the color of the present task (T2) and the color of the past task (T1) were maintained in the ACS.

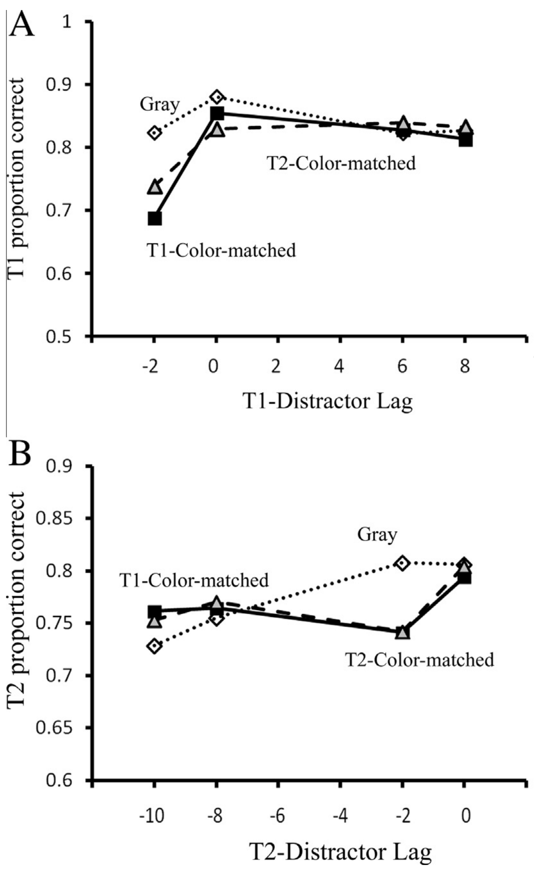

Fig. 3. The results of Experiment 2. (A) Accuracy of first target (T1) identification as a function of T1-distractor lag and distractor condition. (B) Accuracy of second target (T2) identification as a function of T2-distractor lag and distractor condition.

3.3. Discussion

Even when observers were forced to narrow their attentional control setting to a particular color at a particular moment, irrelevant distractors that match either the T1 color or T2 color captured attention. This indicates that observers maintained the color of the future target, the present target and the past target in their attentional control setting at all times.

4. Experiment 3

Experiment 2 replicated Experiment 1 by showing that both a *T2-color-matched* distractor and a *T1-color-matched* distractor captured attention when observers had to search for one color at a time. This indicates that observers can neither suppress the color of the future target nor ignore the color of the past target in their attentional control setting. However, since either red or green distractors in the periphery were presented as a color singleton, the capture effect in Experiments 1 and 2 might be due to stimulus-driven saliency of a color singleton. The present experiment was designed to examine this possibility by presenting another irrelevant color singleton in the periphery (blue singleton) as a distractor. If the capture reported in

Experiments 1 and 2 was due to the color singleton, we should find a similar capture in the blue singleton condition here.

In addition, a previous study indicated that observers could switch from one color to another in attentional control settings across trials (Lien et al., 2010). That result conflicts with the present findings which suggest that observers cannot abandon the color of a past target in their attentional control setting. The discrepancy might be due to the difference in the time interval between the two targets across studies. Thus, the present experiment was designed to examine whether observers can suppress the ACS for the past target when the interval between the two targets becomes longer.

4.1. Method

4.1.1. Participants

Twenty-eight undergraduate students participated in an hour-long experiment for cash compensation. All had normal or corrected-to-normal visual acuity. No participants had experience in similar experiments.

4.1.2. Apparatus, procedure and design

A single stream of letters was presented at the center of the display. The stimuli and procedure were identical to those of Experiment 1 with several exceptions. First, stimuli were presented on a 17-in. monitor with an 85-Hz refresh rate. Each letter was presented for 35 ms, followed by a 59 ms blank interval, yielding an SOA of 94 ms. Second, T2 could appear either 6 frames or 10 frames after T1, with equal probability. If it takes time to abandon the color of the past target in the ACS, we might observe a reduced capture effect when T2 appears 10 frames after T1 compared to 6 frames after. Third, when T2 appeared 6 frames after T1 (half of the trials), the frame containing the colored distractor could appear 2 frames before T1 (T1-distractor lag of −2), simultaneously (T1-distractor lag of 0), or 4 or 6 frames after T1 (T1-distractor lag of 4, 6), resulting in T2-distractor lags of −8, −6, −2 and 0. And when T2 appeared 10 frames after T1 (for the other half of the trials), the frame containing the colored distractor could appear 2 frames before T1 (T1-distractor lag of −2), simultaneously (T1-distractor lag of 0), or 8 or 10 frames after T1, resulting in T2-distractor lags of −12, −10, −2 and 0. Finally, Each trial was in one of four distractor conditions: (1) The four hash signs could be all gray (*Gray*); (2) one hash sign was blue and the other three were gray (*Blue singleton*); (3) one hash sign could match the first target in color and be complementary to the color of the second target (*T1-color-matched*); or (4) one hash sign was in the same color as T2 and the complementary color to T1 (*T2-color-matched*).

Each block contained 16 replications of each combination of four distractor conditions and six T1-distractor lags, for a total of 384 trials. The participants first performed one block of 16 trials for practice. They then completed the test trials. After every 64 trials, they received a brief break.

4.2. Results

Since the present experiment was not a full factorial design, the mean accuracy for T1 identification under T1–T2 lags of 6 and 10 were separately analyzed, and are plotted as a function of T1-distractor lag and distractor condition in Fig. 4A and B. The ANOVA on T1 accuracy under T1–T2 lag 6 showed that there was a main effect of distractor condition, $F_{(3,81)} = 3.945$, $p = 0.011$, $\eta_p^2 = 0.127$; and a main effect of T1-distractor lag, $F_{(3,81)} = 14.847$, $p < 0.001$, $\eta_p^2 = 0.355$, with lowest T1 accuracy at the T1-distractor lag −2. And there was a significant interaction involving the distractor condition and lag, $F_{(9,243)} = 4.231$, $p < 0.001$, $\eta_p^2 = 0.135$, with lowest accuracy when either a *T1-color-matched* or a *T2-color-matched* distractor appeared at T1-distractor lag −2. This was confirmed by a further analysis of T1 accuracy (Bonferroni correction) at the T1-distractor lag −2, a *T1-color-matched* or a *T2-color-matched* distractor caused larger impairment than either Gray or Blue-singleton distractors, all *ps* < 0.05. But *T1-color-matched* distractors did not differ from *T2-color-matched* distractors ($p = 1$).

Consistent with T1–T2 lag 6, the ANOVA on T1 accuracy under T1–T2 lag 10 showed that there was a main effect of distractor condition, $F_{(3,81)} = 7.105$, $p < 0.001$, $\eta_p^2 = 0.208$; and a main effect of T1-distractor lag, $F_{(3,81)} = 29.1$, $p < 0.001$, $\eta_p^2 = 0.519$, with lowest T1 accuracy at the T1-distractor lag −2. And again there was a significant interaction involving the distractor condition and lag, $F_{(9,243)} = 7.346$, $p < 0.001$, $\eta_p^2 = 0.214$, with lowest accuracy when either a *T1-color-matched* or a *T2-color-matched* distractor appeared at T1-distractor lag −2. A further analysis of T1 accuracy (Bonferroni correction) at the T1-distractor lag −2 confirmed that a *T1-color-matched* or a *T2-color-matched* distractor caused larger impairment than either Gray or Blue-singleton distractors, all *ps* < 0.01. But *T1-color-matched* distractors did not differ from *T2-color-matched* distractors, $p = 0.222$.

The results just reported replicated findings from the two previous experiments and indicate that participants could not ignore the T2 color when they were searching for T1. Instead both the color of the present task (T1) and the color of the future task (T2) were maintained in the ACS.

Mean accuracy for T2 identification under T1–T2 lag 6 and lag 10 are separately plotted as a function of T2-distractor lag and distractor condition in Fig. 4C and D. The ANOVA on T2 accuracy under T1–T2 lag 6 showed a main effect of distractor condition, $F_{(3,81)} = 9.517$, $p < 0.001$, $\eta_p^2 = 0.261$; and a main effect of T2-distractor lag, $F_{(3,81)} = 6.634$, $p < 0.001$, $\eta_p^2 = 0.197$, with lowest T2 accuracy at the lag −2. In addition, the interaction between lag and distractor condition was significant. $F_{(9,243)} = 1.923$, $p = 0.049$, $\eta_p^2 = 0.066$, with the largest accuracy reduction when either a *T2-color-matched* or a *T1-color-matched* distractor appeared at T2-distractor lag −2. A post-hoc test of T2 accuracy (Bonferroni correction) at T2-distractor lag −2 revealed that T2 accuracy was significantly lower when distractors matched either the *T2 color* or *T1 color* relative to when distractors were blue or gray (all *ps < 0.008*). But *T1-color-matched* distractors did not differ from *T2-color-matched* distractors at T2-distractor

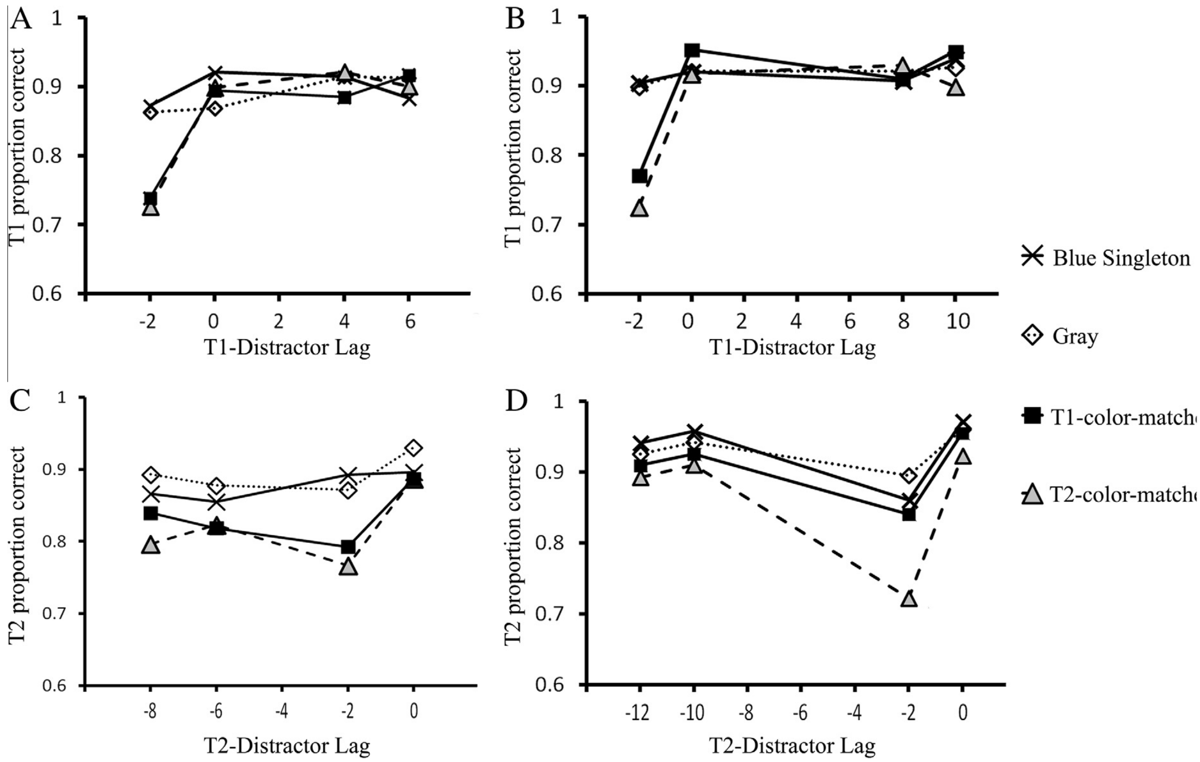

Fig. 4. The results of Experiment 3. (A) Accuracy of first target (T1) identification as a function of T1-distractor lag and distractor condition when T1–T2 lag was 6. (B) Accuracy of first target (T1) identification as a function of T1-distractor lag and distractor condition when T1–T2 lag was 10. (C) Accuracy of second target (T2) identification as a function of T2-distractor lag and distractor condition when T1–T2 lag was 6. (D) Accuracy of second target (T2) identification as a function of T2-distractor lag and distractor condition when T1–T2 lag was 10.

lag −2 ($p = 1$). This shows a large contingent capture effect by both a *T2-color-matched* and a *T1-color-matched* distractor, indicating that observers maintained colors for both the current target (T2) and the past target (T1) in their ACSs at least till 380 ms after T1 (T1-distractor lag of 4). In addition, the blue and gray distracters were not different from each other at T2-distractor lag −2 ($p = 1$). Thus a salient blue singleton failed in capturing attention.

We found a slightly different pattern of T2 accuracy under T1–T2 lag 10 relative to that of lag 6. There was a main effect of distractor condition, $F_{(3,81)} = 9.821$, $p < 0.001$, $\eta_p^2 = 0.267$; and a main effect of T2-distractor lag, $F_{(3,81)} = 19.339$, $p < 0.001$, $\eta_p^2 = 0.417$, with lowest T2 accuracy at the T2-distractor lag −2. Again, the interaction between lag and distractor condition was significant. $F_{(9,243)} = 2.488$, $p = 0.01$, $\eta_p^2 = 0.084$. But a post hoc test (Bonferroni correction) on T2 accuracy at T2-distractor lag −2 revealed that only a *T2-color-matched* distractor caused an accuracy reduction at the T2-distractor lag −2 compared to blue or gray distractors ($p = 0.023$; $p = 0.002$ respectively). A *T1-color-matched* distractor did not affect T2 performance more than blue or gray distractors ($p = 1$; $p = 0.667$ respectively), but the difference between T1-color-matched and T2-color-matched distractors was only marginally significant ($p = 0.085$). The overall pattern suggests that only a *T2-color-matched* distractor produces a large contingent capture effect when observers have sufficient time to switch from T1 to T2. Thus observers were able to abandon the color of the past target (T1) in their ACS about 750 ms after T1. In addition, the blue distracters did not cause larger impairment than the gray distracters at T2-distractor lag −2 ($p = 1$). Thus a salient blue singleton was unable to capture attention in this case.

4.3. Discussion

When there was sufficient time between T1 and T2, observers were able to abandon the color of the past target (T1) in their attentional control setting. In the current experiment, observers maintained the color of the past target (T1) in their ACS for at least 380 ms after T1 (T1-distractor lag of 4), but eventually abandoned it within 750 ms after T1 (T1-distractor lag of 8).

5. Experiment 4

Experiment 3 replicated a part of Experiments 1 and 2 by showing that both T1-color-matched distractors and T2-color-matched distractors capture attention when observers were searching for T1. This indicates that observers cannot suppress the color of the future target in the ACS. But Experiment 3 also showed an important new finding that whether an irrelevant distractor that matched the color of the past target (T1) captures attention depends on the T1-T2 interval. When T2 appeared 6 frames after T1 (the distractor appeared 4 frames after T1 resulting in a 380 ms T1-distractor interval), both T1-color-matched distractors and T2-color-matched distractors captured attention. But when T2 appeared 10 frames after T1 (the distractor appeared 8 frames after T1 resulting in a 750 ms T1-distractor interval), only a *T2-color-matched* distractor produced a large contingent capture effect. This pattern indicates that it take observers more than 380 ms (but less than 750 ms) to suppress the color of the past target (T1) in their ACS.

The present experiment was designed to narrow down the temporal window of the switch in ACS. To do that T2 was presented either 6, 8 or 10 frames after T1. To simplify the design, distractors always appeared 2 frames before T2.

5.1. Methods

5.1.1. Participants

Twenty-six undergraduate students participated in a half hour experiment for cash compensation. All had normal or corrected-to-normal visual acuity. No participants had experience in similar experiments.

5.1.2. Apparatus, procedure and design

The stimuli and procedure were similar as those of Experiment 3 with several exceptions. First, T2 could appear either 6, 8 or 10 frames after T1 with equal probability. Second, for one fourth of the trials (96 trials), the frame containing the colored distractor appeared 2 frames before T1 (T1-distractor lag of −2), which were evenly distributed over three T1–T2 lags. For the other three fourths of trials (288 trials), the colored distractor always appeared 2 frames before T2 (T2-distractor lag of −2), which were also evenly distributed over the three T1–T2 lags (T1–T2 lag of 6, 8 or 10), thus resulting in T1-distractor lag of 4, 6 or 8. This was designed to test whether observers can suppress the color of T1 in the ACS before a T1-distractor lag of 8 (750 ms). Finally, only three distractor conditions (*Blue singleton, T1-color-matched,* and *T2-color-matched*) were used in the present experiment to simplify the design. There were 384 trials altogether. The participants first performed one block of 16 trials for practice. After every 64 trials, they received a brief break.

5.2. Results

The three earlier experiments in the present study and many previous studies have observed the strongest interference when distractors appeared 2 frames before targets. Thus we only analyzed T1 accuracy at T1-distractor lag −2 to examine whether colors of both T1 and T2 were active in ACS right before T1 appeared. And only T2 accuracy at T2-distractor lag −2 was reported here for the same reason.

Mean accuracy for T1 identification is plotted as a function of T1–T2 lag and distractor condition in Fig. 5A. The ANOVA on T1 accuracy showed that there was a main effect of distractor condition, $F_{(2,50)} = 5.496$, $p = 0.007$, $\eta_p^2 = 0.180$, with lowest T1 accuracy when a *T1-color-matched* or *T2-color-matched* distractor appeared 2 frames before T1, but no main effect of T1–T2 lag, $F_{(2,50)} = 1.252$, $p = 0.295$, $\eta_p^2 = 0.048$ and no significant interaction

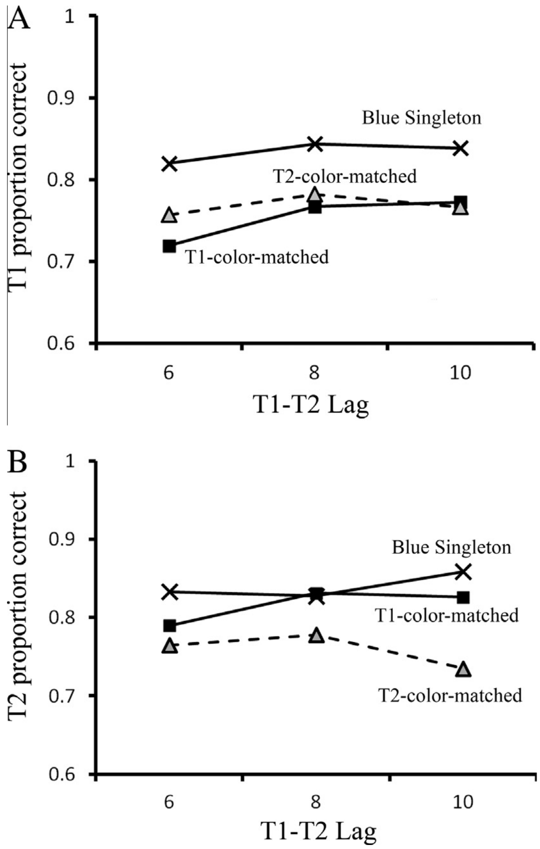

Fig. 5. The results of Experiment 4. (A) Accuracy of first target (T1) identification as a function of T1–T2 lag and distractor condition. (B) Accuracy of second target (T2) identification as a function of T1–T2 lag and distractor condition.

involving the distractor condition and T1–T2 lag, $F_{(4,100)} = 0.186$, $p = 0.945$, $\eta_p^2 = 0.007$. The pairwise comparisons with Bonferroni correction revealed that T1 accuracy was lower when distractors matched either *T2-color* or *T1-color* relative to when distractors were blue, all *ps* < 0.05. But *T1-color-matched* distractors caused almost equivalent impairment of T1 as *T2-color-matched* distracters, $p = 0.438$. These results indicate that both the *T1-color-matched* and the *T2-color-matched* distractors captured attention when they appeared at the T1-distractor lag of −2 irrespective of T1–T2 lag.

Mean accuracy for T2 identification is also plotted as a function of T1–T2 lag and distractor condition in Fig. 5B. The ANOVA on T2 accuracy showed a main effect of distractor condition, $F_{(2,50)} = 13.419$, $p < 0.001$, $\eta_p^2 = 0.349$, with lowest T2 accuracy when a T2-color-matched distractor appeared before T2; but no main effect of T1–T2 lag, $F_{(2,50)} = 0.634$, $p = 0.535$, $\eta_p^2 = 0.025$. But the interaction between T1–T2 lag and distractor condition was significant. $F_{(4,100)} = 2.559$, $p = 0.043$, $\eta_p^2 = 0.093$, with the largest accuracy reduction when a *T2-color-matched* distractor appeared at T1–T2 lag 10.

A further ANOVA of T2 accuracy at the T1–T2 lag of 6 found a main effect of distractor condition, $F_{(2,50)} = 5.326$, $p = 0.008$, $\eta_p^2 = 0.176$. The pairwise comparisons with

Bonferroni correction revealed that T2 accuracy was lower when distractors matched either *T2-color* or *T1-color* relative to when distractors were blue ($p = 0.012$, $p = 0.095$ respectively). In addition, the T2 accuracy of the *T2-color-matched* distractor condition was not different from that of the *T1-color-matched* distractor condition at the T1–T2 lag of 6, $p = 0.847$. These results show a contingent capture effect by a T2-color-matched distractor and a numerically smaller capture effect (only marginally significant) by a T1-color-matched distractor at the T1–T2 lag of 6 (T1-distractor lag of 4 which is about 380 ms after T1).

Another ANOVA of T2 accuracy at the T1–T2 lag of 8 found a main effect of distractor condition, $F_{(2,50)} = 4.567$, $p = 0.015$, $\eta_p^2 = 0.154$. The pairwise comparisons with Bonferroni correction revealed that T2 accuracy was significantly lower when distractors matched *T2-color* relative to when distractors were blue or *T1-color* ($p = 0.088$, $p = 0.027$ respectively). But T1-color-matched distractors did not differ from blue distractors at the T1–T2 lag of 8, $p = 1.00$. This shows a contingent capture effect by only a *T2-color-matched* distractor at the T1–T2 lag of 8 (T1-distractor lag of 6 which is about 570 ms after T1).

The ANOVA of T2 accuracy at the T1–T2 lag of 10 found a main effect of distractor condition, $F_{(2,50)} = 10.824$, $p < 0.001$, $\eta_p^2 = 0.302$. The pairwise comparisons with Bonferroni correction revealed that T2 accuracy was significantly lower when distractors matched *T2-color* relative to when distractors were blue or *T1-color* ($p = 0.001$, $p = 0.017$ respectively). But T1-color-matched distractors did not differ from blue distractors at the T1–T2 lag of 10, $p = 0.37$. This shows a large contingent capture effect by only a *T2-color-matched* distractor at the T1–T2 lag of 10 (T1-distractor lag of 8 which is about 750 ms after T1).

5.3. Discussion

Consistent with all three previous experiments, when observers were searching for T1, both the *T1-color-matched* distractor and the *T2-color-matched* distractor captured attention irrespective of the T1–T2 lag. Even when the T1–T2 interval was 940 ms, observers still could not ignore the color of the future target in the attentional control setting.

Nevertheless, observers were able to abandon the color of the past target (T1) in their ACS when the interval between T1 and T2 became longer. This process of dropping the color of the past target (T1) was gradual and took at least 380 ms after T1 (T1-distractor lag of 4). By the time of T1-distractor lag of 6 (about 570 ms after T1), observers seemed no longer under the influence of the color of the past target.

6. General discussion

The present study examined temporal features of attentional control. Experiment 1 showed that irrelevant distractors that match the color of either the first or second expected target (T1 and T2, respectively) captured attention when observers were searching for T1. This shows that observers cannot suppress the color of a future target in their attentional control settings. Experiment 2 confirmed and extended that finding by showing that both *T1-color-matched* and *T2-color-matched* distractors interrupted central target identification even when observers were forced to narrow their attention to one target color at a time. Experiments 3 and 4 further demonstrated that, when observers were searching for T1, both *T1-color-matched* and *T2-color-matched* distractors captured attention irrespective of the T1-T2 interval. Taken together, these results show that the color of a future expected target cannot be retained in a way that does not affect performance. This occurred even under conditions in which an attentional set for the second target color was detrimental to first-target performance. Instead, it appears that the expected color of the second target must be incorporated into the observer's attentional control settings from the outset of the trial.

One reason that observers keep both colors in their ACS could be in order to avoid switch costs associated with changing their attentional set (Juola, Botella, & Palacios, 2004; Visser, Bischof, & Di Lollo, 1999). Nevertheless, it is surprising that observers maintained both colors when doing so was detrimental in Experiment 2. Further study is needed to examine whether this reflects an intrinsic limitation of attentional control settings or perhaps some strategic choice of the observers.

In addition, when observers were searching for the second target, they were unable to ignore irrelevant distractors that matched either the T1 color or the T2 color when theT1-distractor interval was 380 ms in Experiments 3 and 4, and was up to 480 ms in Experiment 1(the corresponding T1–T2 interval was 570 ms in Experiments 3 and 4 and 640 ms in Experiment 1). These results suggest that observers maintained both the color of the present target (T2) and that of the past target (T1) in their attentional control settings at least for about 480 ms. However, when the T1-distractor interval was 750 ms in Experiment 3 or 570 ms in Experiment 4 (the T1–T2 interval was 940 ms in Experiment 3 or 750 ms in Experiment 4), observers were able to suppress the color of the past target in their attentional control settings. Similar results were reported by Lien et al. (2010), who showed that attentional control settings could be switched from one target color to another across trials (the interval was about 3 s between two subsequent targets). As we have shown here, subjects can easily suppress information about the first target in much less time than 3 s—although more could be learned about the minimum time needed to do so. Admittedly, the elapsed time between T1 and T2 in present study is confounded by the intervening events between T1 and T2. Thus the gradual degradation of T1-color in the ACS after T1 has appeared could be due to the multiple intervening events between T1 and T2 rather than elapsed time per se. These factors could be examined more closely in a future study.

The inability of observers to exclude the color of the second target from their attentional control settings at the beginning of a trial, as noted earlier, suggests that the attentional control settings may not be very flexible. Neverthless, the ability of subjects to suppress the T1 color shortly after it has been presented while still maintaining an attentional set for the color of the second target suggests that there might be considerable flexibility in the construction and maintenance of the attentional control settings. More work will be needed to learn about the capabilities and limitations of the ACS.

It is also worth noting that T2-color-matched distractors caused numerically smaller impairment of T2 performance at T1–T2 lag 6 than at T1–T2 lag 10 in Experiment 3. Experiment 4 also shows a smaller contingent capture effect at short T1–T2 lags relative to long T1–T2 lags. This is probably due to the enhanced suppression of contingent capture by T1 processing as T1–T2 lags decrease. A recent study found that processing the earlier target (T1) has a suppressive effect upon the subsequent contingent capture and its suppression increases as the T1–T2 lag decreases (Du et al., 2013). However, Du et al. (2013) also found that the contingent capture effect does not vary across T1–T2 lags when identification of T1 is not required. Thus Du et al. (2013) proposed that object processing can interfere with the spatial orienting of contingent capture, resulting in stronger suppression of contingent capture at short T1–T2 lags relative to long lags. Alternatively, it is also possible that the setting for the second target is more effective once the setting for the first target is released. This definitely needs further examination in future.

Previous studies found that a repeated target across trials leads to faster detection in pop-out search than targets that keep changing across trials—an intertrial priming effect (Becker, 2008; Leonard & Egeth, 2008; Maljkovic & Nakayama, 1994). Since the sequence of two target colors was the same across trials in the present study, the intertrial priming effect might explain why both T1-colored and T2-colored distracters could capture attention irrespective of the color of the current target in Experiments 1 and 2. However, the intertrial priming effect cannot completely account for the present findings for two reasons. First, the intertrial priming effect cannot accommodate the data of Experiments 3 and 4: If repeated target colors prime both T1-colored and T2-colored distracters across trials, observers should be captured by both T1-colored and T2-colored distracters at all times. This prediction is in sharp contrast to the finding that observers abandoned the T1-color (the past target color) in their attentional control settings when the T1-distractor interval was 750 ms in Experiment 3 or 570 ms in Experiment 4. Second, the intertrial priming effect has been repeatedly found in pop-out search tasks. However it is still unknown whether the intertrial priming effect operates in a spatial blink task with heterogeneously colored distractors like that used here. In fact, a previous study showed that participants could successfully inhibit the previous target color in the attentional control setting across trials (Lien et al., 2010). In addition, Folk and Remington (2008) showed that top-down attentional control settings are subject to intertrial priming, but only when primed parameters of the control settings are left unspecified by the nature of the task.

Some recent studies examined the hierarchical structure of attentional control settings by combining multiple features in defining targets (Adamo et al., 2008, 2010; Kiss, Grubert, & Eimer, 2013; Parrott, Levinthal, & Franconeri, 2010). The behavioral results from these studies showed that an irrelevant cue that was fully congruent with the target captured attention, whereas cues that were partially congruent with targets were unable to capture attention. These results seem to indicate that observers integrated multiple target-defining features into a unified attentional control setting. As a result, only objects that fully match targets can capture attention. However, Adamo et al. (2010) showed that a peripheral cue could cause an N2pc response whether it matched the target color or not. Thus observers are using spatial information and color-match separately in guiding attention. In addition, a recent ERP study showed that even cues that were partially matching targets produced N2pc responses, though smaller than N2pc responses to the cue that fully matched the targets (Kiss et al., 2013). These studies indicate that attentional control setting might involve a very complex hierarchical structure. Attention can be initially captured by a partial feature match (e.g. location, color or size) between cue and targets and then rapidly disengaged from cues that share some but not all features of the target (Kiss et al., 2013). The present study is the first to extend the structure of attentional control setting into the temporal domain by showing that attentional control setting cannot perfectly combine the temporal order of targets with their corresponding colors within a short temporal window. This indicates that temporal information is represented and utilized in a fundamentally different way in the attentional control setting than other visual features including location and color.

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