Contingent attentional capture across multiple feature dimensions in a temporal search task

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The present study examined whether attention can be flexibly controlled to monitor two different feature dimensions (shape and color) in a temporal search task. Specifically, we investigated the occurrence of contingent attentional capture (i.e., interference from task-relevant distractors) and resulting set reconfiguration (i.e., enhancement of single task-relevant set). If observers can restrict searches to a specific value for each relevant feature dimension independently, the capture and reconfiguration effect should only occur when the single relevant distractor in each dimension appears. Participants identified a target letter surrounded by a non-green square or a non-square green frame. The results revealed contingent attentional capture, as target identification accuracy was lower when the distractor contained a target-defining feature than when it contained a nontarget feature. Resulting set reconfiguration was also obtained in that accuracy was superior when the current target's feature (e.g., shape) corresponded to the defining feature of the present distractor (shape) than when the current target's feature did not match the distractor's feature (color). This enhancement was not due to perceptual priming. The present study demonstrated that the principles of contingent attentional capture and resulting set reconfiguration held even when multiple target feature dimensions were monitored.

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1. Introduction

When confronted with multiple objects, the human visual system must select relevant locations and objects and restrict processing for irrelevant others due to capacity limitations. During this selection process, visual attention plays a critical role in a cluttered visual environment in achieving our current behavioral goals (Desimone & Duncan, 1995; Lamy, Leber, & Egeth, 2012; Theeuwes, 2010). Researchers have reached a general consensus that allocation of attention is determined through an interplay between top-down and bottom-up guidance, although definitive conclusions are still subject to debate (Awh, Belopolsky, & Theeuwes, 2012; Carrasco, 2011). Bottom-up selection refers to automatic and compulsory attention to salient stimuli (Itti & Koch, 2000, 2001; Van der Stigchel et al., 2009). Top-down selection refers to flexibly programmable and adaptive guidance of attention toward an object with a particular property based on the observer’s prior knowledge (a template or “attentional control setting”; Bacon & Egeth, 1994; Egeth, Leonard, & Leber, 2010). For example, when we search for a friend at a crowded station, we may activate stored representations of her/him (e.g., size, hair color, and typically worn jacket) and use these as attentional control settings, biasing incoming visual information involving particular features (e.g., shape, color, size, and location) that match the settings.

The flexibility of attentional control settings has been demonstrated in the literature, indicating that observers can search for a target defined by various types of stimulus features, such as color (Nagy & Sanchez, 1990; Navalpakkam & Itti, 2006), intensity (Navalpakkam & Itti, 2006), motion (Dick, Ullman, & Sagi, 1987), shape (Treisman & Gormican, 1988), depth (He & Nakayama, 1992), and size (Hodson & Humphreys, 2001; Navalpakkam & Itti, 2006). Similarly, targets can also be defined by arbitrary combinations of these features (Shen, Reingold, & Pomplun, 2000). The flexibility of attentional control settings has also been demonstrated using spatial cueing tasks (Folk, Remington, & Johnston, 1992; Pratt & Hommel, 2003).

Notably, recent studies have shown that observers can keep track of two target features concurrently as potential attentional control settings. For example, Adamo, Pun, Pratt, and Ferber (2008) asked participants to respond only to targets of specific colors at specific locations (e.g., a green item on the right or a blue item on the left). A non-predictive cue appeared before the target such that the cue shared the same location and/or color as the target. The results revealed contingent attentional capture (Folk et al., 1992; Folk, Leber, & Egeth, 2002; Most & Astur, 2007), in which cues consistent with the attentional control settings for color and location decreased reaction times for responding to the target, suggesting that separate attentional control settings can be simultaneously maintained at two different spatial locations.
The finding that two different attentional control settings can be maintained is not limited to the case in which two targets belong to the same feature dimension (i.e., color; Adamo et al., 2008; Adamo, Pun, & Ferber, 2010; Folk & Anderson, 2010), but is also true when they belong to different feature dimensions (i.e., color and shape; Adamo, Wozny, Pratt & Ferber, 2010, color and orientation; Parrott, Levinthal, & Franconeri, 2010). Specifically, participants in the study by Adamo, Wozny, Pratt, and Ferber, 2010 responded to a target of one of two colors at one location (e.g., green on the right) and one of two shapes at another location (e.g., triangle on the left), while ignoring nontarget colors and shapes everywhere. The results revealed a contingent capture effect: cues consistent with the attentional control settings of color and space decreased reaction times for responding to the target relative to trials in which the target and distractor shared no common features. These results suggest that two attentional control settings representing different feature dimensions (color and shape) can be maintained concurrently. In short, the studies reviewed above consistently found that responses were facilitated by leading cues with multiple visual features that match current attentional control settings as indexed by decreased reaction times.

Additional converging evidence for flexible attentional settings has been reported from a different paradigm using the attentional capture phenomenon in temporal search. This phenomenon refers to decrements in target identification accuracy resulting from the presentation of a task-relevant distractor that shares target-defining features; it is taken as an index of the establishment of top-down attentional control settings. For example, Folk et al. (2002) had participants search for a letter of a particular color (e.g., red) within a rapid stream of nontarget letters of heterogeneous colors. The results indicated that identification accuracy was lower when a red distractor in the periphery preceded the target than when distractors of other colors, or no distractors at all, preceded the target. This impairment is said to be triggered by the involuntary capture of attention by irrelevant peripheral distractors that match attentional control settings, resulting in errors of omission in the identification of central targets.

Furthermore, Moore and Weissman (2010, 2011) demonstrated that contingent attentional capture occurred when participants searched for either of two possible target letters (e.g., orange and green) within the color dimension, using a procedure similar to Folk et al.’s (2002) study. As predicted, Moore and Weissman (2010) found evidence of contingent attentional capture. Importantly, however, they also found evidence of resulting set reconfiguration (set-specific capture; Moore & Weissman, 2011, 2014) in which the effect of contingent attentional capture was greater when a distractor feature (e.g., orange) was inconsistent with the feature of the current target (green) than when a distractor feature (e.g., orange) was consistent with the feature of the current target (orange). The researchers interpreted this finding as evidence of the involuntary transfer of an attentional control setting into the focus of attention. Subsequent target identification is disturbed by the transfer when the color of the following target is different from the transferred color, and it is facilitated when the color of the target is the same (Moore & Weissman, 2010, 2011). The contingent capture effect has been replicated and has been shown to occur when both possible target features change on every trial (Roper & Vecera, 2012). These findings from multiple-target studies suggest that attention can be highly selective and that attentional control setting can maintain two different feature values.

The literature reviewed above is summarized in Table 1. Studies regarding the flexibility of attentional set differ with respect to paradigm (spatial cuing, visual search and temporal search) and target definitions (within versus across dimensions). One cell is obviously missing in this summary table; to address this gap, the present study examined whether attention could be guided by a control setting across two different feature dimensions (shape and color) in a temporal search task. Specifically, we examined whether contingent attentional capture and resulting set reconfiguration would occur (e.g., Moore & Weissman, 2010) when multiple target feature dimensions were to be monitored. If observers can restrict searches to a specific value for each relevant feature dimension independently, the capture and the reconfiguration effect should only occur when the single relevant feature in each dimension appears. We also predicted that a resulting set reconfiguration should occur if the principle that Moore and Weissman (2010) introduced applies to searches for targets across dimensions. In contrast, if observers cannot restrict searches to a specific value for each relevant feature dimension independently, then attention should be captured by all distractors regardless of their features.

### 2. Experiment 1

We examined whether contingent attentional capture and/or resulting set reconfiguration were specific to multiple-target searches based on one feature dimension (e.g., color; Moore & Weissman, 2010) or could be extended to searches based on multiple feature dimensions (e.g., color and shape). Participants searched for one of two possible target letters surrounded by a non-green square (of any color) or a non-square green frame (of any shape) in the center of three rapid streams of letters. A distractor preceded the target in the peripheral stream. Critically, we manipulated the distractors such that one type of distractor (critical) shared the same target-defining feature as the target in the current trial and the other type (control) had no features in common with the target in the current trial. Given that each target was presented as a letter surrounded by a square frame, a critical distractor could correspond to a letter surrounded by a square frame of any color or a letter surrounded by a green frame of any shape (see Fig. 1 for details). Under the control condition, a distractor with nontarget-defining features (e.g., a non-green triangle or a non-square blue frame) preceded the target. We reasoned that contingent attentional capture should occur if observers can restrict searches to a specific value for each relevant dimension. However, if no such attentional set bridging two feature dimensions is available, distractors should capture attention regardless of their features. Regarding resulting set reconfiguration, we predicted that the effect would be obtained, provided that the principle suggested by Moore and Weissman (2010) applies to the present case of a temporal search across dimensions. That is, entering the distractor’s feature into the focus of attention would facilitate identification of the following target if it shared the same feature as the distractor.

### Table 1

Summary of the literature regarding within- and cross-dimensional effects with spatial cuing, visual search, or temporal search task and dependent measures.

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2.1. Method

2.1.1. Participants

Thirty undergraduate students (ranging between 18 and 22 years, \( M = 19.4 \) years old; 16 female) from the participant pool at Chukyo University participated for pay or in exchange for course credit. All participants had normal or corrected-to-normal visual acuity and normal color vision.

2.1.2. Apparatus

Stimuli were presented on a 24-inch LCD monitor (100 Hz of refresh rate, 1920 × 1028 pixels) controlled by a PC/AT-compatible computer operating with Linux, Matlab, and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Viewing distance was approximately 60 cm. Responses were collected via a keyboard connected to the computer. Stimuli were displayed on a black background.

2.1.3. Procedure and design

We adopted a procedure similar to that described above involving three rapid streams of letters (Moore & Weissman, 2010; see Fig. 1). Stimuli were drawn from among 21 English upper-case alphabet letters (excluding I, O, Q, W, and Z) using Courier New font: they subtended 1.72° in height and up to 1.53° in width. Regardless of the stream, the nontarget letters were gray. The letters in the central stream were surrounded by one of the four different shapes (square, circle, triangle, or diamond) synchronized with the onset and offset of each letter. The color of the shape frame was determined randomly for every display with the constraint that any given letter never appeared in the same frame more than once, and successive letters in the same stream differing. Each letter (and its surrounding shape, if any) was presented for 130 ms, followed by 30 ms of blank screen, yielding a stimulus onset asynchrony (SOA) of 160 ms. The number of nontargets preceding the target was determined randomly on each trial and varied between 11 and 15.

The experiment involved a 4 × 4 factorial design, with two within-subject factors: SOA at four levels (160, 320, 480, and 640 ms) and type of distractor at the following four levels (Fig. 1): (1) the target alone condition, under which a distractor was not presented; (2) the nontarget-defining feature distractor condition (hereafter, nontarget feature condition), under which a distractor frame without a target-defining feature (e.g., a turquoise-colored diamond) was presented; (3) the same-target-defining feature condition (same-target feature condition), under which a distractor with the same target-defining feature as the target in the current trial was presented, so that, for example, if a target was surrounded by a square, the distractor was also surrounded by a square; and (4) the different-target-defining feature condition (different-target feature condition), under which a distractor with a different target-defining feature than the target in the current trial was presented, so that, for example, if a target was surrounded by a square, the distractor was surrounded by a green frame, and vice versa. Under the nontarget feature, same-target feature, and different-target feature conditions, the distractor was presented one to four frames prior to the target frame.

**Fig. 1.** Example of each distractor type (target alone, nontarget feature, same-target feature, or different-target feature) used in Experiment 1. Participants searched for a target letter surrounded by either a non-square green frame (of any shape) or a non-green square (of any color) in the central letter stream. A distractor without a target-defining feature (nontarget feature) or with a target-defining distractor that either matched the current target's feature (same-target feature) or mismatched the current target's feature (different-target feature) preceded the target in the peripheral stream. Under the nontarget feature, same-target feature, and different-target feature conditions, the distractor was presented one to four frames prior to the target frame.
to four frames prior to the target, resulting in four levels of distractor-target lags (SOAs).

In total, the experimental session consisted of 240 trials: 48 target alone, 48 nontarget feature (12 trials per SOA), 72 same-target feature (18 per SOA), and 72 different-target feature (18 per SOA) trials, preceded by 45 practice trials. To familiarize participants with the procedure, the displays were presented slowly for the first 10 practice trials. The display presentation gradually accelerated over the next 20 trials and operated at full speed for the remaining 15 trials.

2.2. Results

We excluded three participants whose mean accuracy (below 55%) did not fall within 1 SD of the mean for the target alone condition. In the remaining 27 participants, the total mean accuracy under the target alone condition was 74.9%. Fig. 2 displays the mean accuracy of target identification as a function of distractor condition and SOA. The mean accuracy for the target alone condition represents the means from both the square and green target conditions, as these did not significantly differ from each other [square target (75.2%) vs. green target (74.7%); t(26) = 1.56, p = .88, r = .29]. We collapsed the results with the square target and those with the green target into one score because the pattern of the results was similar.

First, to examine whether contingent attentional capture occurred, we compared the identification accuracies for the nontarget feature and same-target feature conditions. We conducted an analysis of variance (ANOVA) to test the interaction of distractor type (nontarget feature condition and same-target feature condition) and SOA (160, 320, 480, and 640 ms). The main effect of SOA was significant [F(3, 78) = 10.21, p < .001, \(\eta^2_{p} = .27\)], indicating that accuracy was higher with longer SOAs than with the shortest SOA. The main effect of distractor type was significant [F(2, 52) = 6.48, p < .01, \(\eta^2_{p} = .20\)], indicating that accuracy under the different-target feature condition was lower than that under the same-target feature condition. The interaction between distractor type and SOA was not significant [F(3, 78) = 0.96, p = .42, \(\eta^2_{p} = .04\)].

Third, we conducted an overall ANOVA with all the factors to examine how the interaction of distractor type (nontarget feature, same-target feature, and different-target feature conditions) and SOA (160, 320, 480, and 640 ms). The main effect of SOA was significant [F(3, 78) = 9.83, p < .001, \(\eta^2_{p} = .27\)], indicating that accuracy was higher with longer SOAs than with the shortest SOA. The main effect of distractor type was significant [F(2, 52) = 6.48, p < .01, \(\eta^2_{p} = .20\)], indicating that accuracy under the different-target feature condition was lower than other conditions [t(52) > 2.21, ps < .03, rs > .29]. Furthermore, the interaction between distractor type and SOA was significant [F(6, 156) = 2.64, p = .02, \(\eta^2_{p} = .09\)]. An analysis of simple-main effects at the SOA of 160 ms [F(2, 208) = 9.40, p < .001, \(\eta^2_{p} = .08\)] revealed that accuracies under the same-target feature condition (65.6%) and the different-target feature condition (59.1%) were lower than that under the nontarget feature condition (73.5%) at the shortest SOA [t(208) > 2.35, ps < .02, rs > .31]. This also indicates that the contingent attentional capture and resulting set reconfiguration occurred.

Finally, to examine whether attentional capture occurred only when the target-relevant feature appeared, we compared the accuracy under the target alone condition with those under all the other conditions at the shortest SOA by a single factor ANOVA with four levels (same-target feature, different-target feature, nontarget feature, and target alone conditions). The ANOVA revealed a significant main effect of distractor type [F(3, 78) = 10.21, p < .001, \(\eta^2_{p} = .28\)]. Importantly, the mean accuracies under the same-target feature and different-target feature conditions were lower than that under the target alone condition [t(78) > 2.85, ps < .01, rs > .31]. However, the accuracy did not differ from the target alone condition and nontarget feature condition [t(78) = 0.45, p = .65, r = .05]. These results indicated that attentional capture occurred only when the target-relevant distractors (such as a non-square green frame or a non-green square) appeared.

2.3. Discussion

The effects of contingent attentional capture and resulting set reconfiguration were observed in Experiment 1 even when multiple attentional control settings across different feature dimensions (color and shape) were monitored. Contingent attentional capture was evident in that identification accuracy at the SOA of 160 ms was significantly lower for the same-feature condition than for the nontarget feature condition. This difference implies impairment at the shortest lag, reflecting the involuntary shift of attention toward a peripheral distractor that shares a target-defining feature with the target. Importantly, resulting set reconfiguration was observed: identification accuracy was significantly higher for the same-feature condition than for the different-feature condition. This result is consistent with that of Moore and Weissman (2010), suggesting that an attentional control setting that matches a target-defining feature can enter the focus of attention while processing a distractor with that target-defining feature, subsequently improving identification of the target. However, this enhancement could be a result of perceptual priming due to mere repetition of the same features between target and distractor. In Experiment 2, we distinguished between two possible explanations of this result, namely, that enhancement was due to perceptual priming and that two attentional control settings were maintained.

3. Experiment 2

We examined whether the resulting set reconfiguration we obtained in Experiment 1 was due to the maintenance of two attentional...
control settings or mere perceptual priming. The same procedure as in Experiment 1 was adopted, except that participants did not need to maintain any target features. Participants searched for a target surrounded by a frame (of any color and shape) that appeared only once in the central stream. If the resulting set reconfiguration in the previous experiment reflects perceptual priming, target identification scores should be higher for trials in which the distractor matches the target’s feature than for those in which the target and distractor features are mismatched. However, if the resulting set reconfiguration truly reflects a process of entering the pertinent attentional control setting into the focus of attention (Moore & Weissman, 2010, 2011), target identifications should not differ regardless of the match or mismatch between the target and distractor features because participants are not required to maintain any particular attentional control settings in Experiment 2.

3.1. Method

3.1.1. Participants

Twenty-eight undergraduate students (ranging between 18 and 22 years old, \(M = 19.75\) years; 19 female), newly recruited from the participant pool at Chukyo University and Hokkaido University, participated for pay or in exchange for course credit. All participants had normal or corrected-to-normal visual acuity and normal color vision.

3.1.2. Apparatus, procedure, and design

In Experiment 2, the apparatus and stimuli were the same as those used in Experiment 1. Unlike in Experiment 1, however, we doubled rapid stream frames (total 40 frames). Furthermore, participants were not required to search for a target surrounded by a frame characterized by either of two possible critical features. Rather, on every trial, they were required to identify the target surrounded by a frame of any color and shape that occurred uniquely during the central letter stream (see Fig. 3). To avoid ceiling effects, we used the same procedure as Moore and Weissman (2010); thus, the SOA of each frame was reduced to 80 ms (duration = 50 ms). To equate the duration of distractor presentation with that of Experiment 1, peripheral distractors were presented for two frames (i.e., 160 ms). Consequently, the distractor was presented for 0–160, 160–320, 320–480, or 480–640 ms prior to the onset of a target.

In total, the experimental session consisted of 192 trials: 48 target alone, 72 same-target feature (18 per SOA), and 72 different-target feature (18 per SOA) trials, preceded by 40 practice trials. To familiarize participants with the procedure, the display was initially presented slowly for the first 10 practice trials. The display presentation then gradually accelerated over the next 15 trials and operated at full speed for the remaining 15 trials.

3.2. Results and discussion

We excluded four participants whose mean accuracy (below 40%) did not fall within 1 SD of the mean for the target alone condition. In the remaining 24 participants, the total mean accuracy under the target alone condition was 58.6%. Fig. 4 shows the mean accuracy of target identifications as a function of each distractor condition and SOA. Consistent with Experiment 1, mean accuracy scores from the square and green target, trials under the target alone condition were collapsed into one score because the separate scores were not significantly different from each other [square target (58.6%) vs. green target (58.7%); \(t(23) = 0.02, p = .98, r = .01\)]. The SOA functions were virtually identical across the two distractor conditions. This informal inspection was supported by an ANOVA examining the interaction between distractor type (same-target feature condition and different-target feature condition) and SOA (160, 320, 480, and 640 ms). The results revealed a main effect of SOA [\(F(3, 69) = 5.96, p < .01, \eta^2_p = .21\)], indicating that accuracy was lower with an SOA of 160 ms than with longer SOAs [\(t(69) < 2.91, p < .01\)]. More importantly, neither the main effect of distractor type [\(F(1, 23) = 0.04, \eta^2_p = .000\)] nor the interaction between distractor type and SOA [\(F(3, 69) = 1.04, p = .39, \eta^2_p = .04\)] was significant. These results suggest that the effect of distractor type on accuracy is not modulated by the duration of distractor presentation.
conditions (i.e., the same-target feature or the different-target feature) as a function of SOA in Experiment 2.

\[ p = .95, \eta^2_p = .001 \] nor the interaction between distractor type and SOA \([F(3, 69) = 1.73, p = .16, \eta^2_p = .07]\) was significant. Furthermore, we examined whether attentional capture occurred by comparing the accuracies under the target alone condition (58.6%) with under the target-defined distractor conditions at the shortest SOA (mean accuracy under the same- and different-target feature conditions at the SOA of 160 ms; 52.0%). The result indicated that the accuracy under same-target feature and different-target feature conditions at the SOA of 160 ms was lower than that under the target condition \([t(23) = 2.30, p = .03, r = .43]\). These results therefore suggest that the enhancement effect obtained in Experiment 1 was not due to perceptual priming but reflects a specific effect involving the maintenance of multiple target features across two different feature dimensions.

4. General discussion

In the present study, we examined whether contingent attentional capture and/or resulting set reconfiguration occur exclusively for multiple-target searches based on one feature dimension (e.g., color; Moore & Weissman, 2010) or whether these effects also occur in multiple-target searches based on multiple feature dimensions (e.g., color and shape). Experiment 1 revealed the latter to be the case. Namely, contingent attentional capture occurred: the accuracy of target identification was significantly lower when a distractor shared the current target’s feature than when it shared no features in common with the current target. Moreover, resulting set reconfiguration was also obtained: target identification accuracy was higher when the distractor shared the same feature as the target (i.e., the same-target feature condition) than when it carried the other critical target feature (i.e., the different-target feature condition). In Experiment 2, we excluded the possibility that the resulting set reconfiguration was due to perceptual priming by demonstrating that mere repetition of the same feature without a particular attentional control setting did not improve identification. This suggests that resulting set reconfiguration is a unique effect that occurs only when multiple attentional control settings are involved.

The present findings are consistent with those obtained by Moore and Weissman (2010), which suggested that a preceding distractor containing features identical to the current target-defining feature entered into the focus of attention, and the contents of the focus of attention were subsequently used for target identification. As a result, subsequent target identification was impaired under the target-defining feature conditions (i.e., the same-target feature or the different-target feature conditions) compared with trials in which the distractor was irrelevant (i.e., nontarget feature condition). This insight was originally introduced by Oberauer (2002), who proposed that the focus of attention can be directed to only one item among multiple representations in working memory.

It should be noted that the magnitude of the contingent attentional capture effect was smaller than it was for those obtained in previous studies (Moore & Weissman, 2010, 2011); moreover, and the duration of the capture was shorter, with the contingent attentional capture effect observed only at the shortest SOA of 160 ms. This relatively small effect may be attributed to the fact that the present effect consisted of attentional capture involving a color distractor and a shape distractor, whereas the effect in Moore and Weissman’s (2010) study consisted of capture from two color distractors. Because attentional capture produced by shape distractors is, in general, relatively weak compared with that produced by color distractors (e.g., Adamo, Wozny, Pratt & Ferber, 2010), it is reasonable to expect that the mixture of shape and color capture effects should be weaker than a capture effect originated purely from color distractors. This difference in the impact of color versus shape distractors may be related to the relative speed of processing of color and shape distractors. For example, Quinlan and Humphreys (1987) demonstrated that the processing speed of color was shorter than shape. Because the present study was not designed to compare the relative magnitudes of attentional capture effects, a rigorous examination of these awaits future research.

In summary, the present study revealed contingent attentional capture and resulting set reconfiguration. The present results indicate that the principle underlying attentional capture and resulting set reconfiguration held even when observers were monitoring two features across different feature dimensions. The present results extend the previous view of attentional capture in demonstrating that visual attention is automatically directed to target relevant features, regardless of whether these belong to one dimension or are distributed across multiple feature dimensions in a temporal search task. Moreover, we demonstrated the robustness of the resulting set reconfiguration across the dimensions of color and shape. Therefore, the present findings serve to fill in the missing cell of Table 1. As shown in that table, the findings thus far, with the inclusion of the present study, provide a coherent picture indicating that visual attention can be flexibly deployed within and across feature dimensions by means of attentional control setting across a variety of tasks and dependent measures.

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References


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