Title	Multiple attentional sets while monitoring rapid serial visual presentations
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Citation	Quarterly journal of experimental psychology, 70(11), 2271-2289 https://doi.org/10.1080/17470218.2016.1231827
Issue Date	2016-10-11
Doc URL	http://hdl.handle.net/2115/67341
Rights	This is an Accepted Manuscript of an article published by Taylor & Francis in Quarterly journal of experimental psychology on 11/10/2016, available online: http://www.tandfonline.com/10.1080/17470218.2016.1231827
Type	article (author version)
File Information	QJE-STD-15-297.R2.pdf

Multiple Attentional Sets while Monitoring Rapid Serial Visual Presentations

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This study has been supported by Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (20530676; 26285168).

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Abstract

The present study examined the flexibility of attentional sets. Previous studies have shown that the visual system can be adaptively configured to control attention suitable for a behavioural goal. Seven experiments were conducted to test whether observers are able to establish multiple attentional sets to concurrently monitor two different spatial locations. Observers identified a target letter in red or cyan among nontarget letters of other heterogeneous colours presented as a rapid serial visual stream during a feature search. A distractor display consisted of items in the periphery such that one was either the same colour as the target of the current trial, the other potential target colour, or an irrelevant colour that could never be the target. They identified an odd-ball colour letter among homogenous colours during a singleton search. The results revealed that observers maintained multiple attentional sets for detecting two singletons or for targets involving two (or three) features. However, they were unable to maintain a mixture of sets. Moreover, exposure to a distractor containing feature that corresponded to a feature of the target in the current trial was advantageous for target identification. The presence or absence of this set-specific capture depended on top-down knowledge and did not occur automatically in the singleton-detection stream. These results demonstrate a limitation in the flexibility of attentional sets. Although two singleton detections were possible, multiple attentional templates for a more complex attentional set could not be maintained concurrently when monitoring multiple rapid serial visual presentations.

(244 words)

Keywords: visual attention; attentional set; cognitive control; attention and memory;

One of the primary functions of visual attention is to restrict visual processing to items relevant to behavioural goals, given that the cognitive system cannot perform detailed processing on multiple objects simultaneously. Traditional models of spatial attention have posited this view of single attentional focus (Posner, Snyder, & Davidson, 1980; for a review, Wright & Ward, 2008), and empirical studies have generally supported this claim (e.g., Eriksen & Yeh, 1985; Heinze, Luck, Muente, Goes, Mangun, & Hillyard, 1994; Woodman & Luck, 2003). Nevertheless, several studies have shown that spatial attention may be split under certain specific conditions (e.g., Kramer & Hahn, 1995; Awh & Pashler, 2000; McMains & Sommers, 2004; Kawahara & Yamada, 2006), demonstrating that attention can be allocated to multiple non-contiguous spatial locations. Researchers have used various approaches to examine the possibility of the spatial splitting of attention (Feng & Spence, 2013; Jans et al., 2010; Jefferies, Enns, & Di Lollo, 2014).

Feature-based attention, another type of attentional selection, is also a powerful mechanism for restricting visual processing to behaviourally relevant information (Scolari, Ester, & Serences, 2014). Studies have demonstrated that multiple target feature values, such as colours, can be monitored and selectively processed when distributed over a search display containing multiple items (e.g., Irons, Folk, & Remington, 2012) or when embedded in one or several rapid streams (e.g., Moore & Weissman 2010). Specifically, Irons et al. (2012; but see also Folk & Anderson, 2010) demonstrated that when participants searched for a target item (red or green) among one blue and two white nontarget items, reaction times were shorter at a validly cued location only when the cues matched potential target colours (i.e., red or green; Although features can be determined as dimensions, such as colour and orientation, or as values, such as red and green, we used the term feature to refer to values of a dimension otherwise specified in the present study.). Cues of irrelevant colour (blue) produced no such spatial cueing effect, suggesting that participants could monitor two target colours simultaneously. Similarly, Moore and Weissman (2010, Experiment 1; Roper & Vecera, 2012) instructed participants to search for a letter of one of the potential colours (green or orange) amid a rapid stream of heterogeneously coloured nontarget letters. A peripheral distractor preceded the target presented in the central stream. Identification accuracy of a target was lower when a target-coloured (green or orange) distractor appeared than when an irrelevantly coloured (purple) distractor appeared, suggesting that participants maintained attentional sets for two target colours. Using a slightly different procedure, Adamo, Pun, Pratt, and Ferber (2008; but see also Parrott et al., 2010) demonstrated that observers established two attentional sets to search for a blue item on the left and a green item on the right. Similarly, Adamo, Wozny, Pratt, and Ferber (2010) demonstrated that more complex, cross-dimensional attentional sets can be established (e.g., green on the right, triangle on the left). These studies on feature-based attention suggest that visual selective attention is flexible and thus capable of maintaining complex attentional sets.

However, the notion of divisible attentional sets involving multiple features and locations is not unanimously supported. Becker, Ravizza, and Peltier (2015; see also Anderson, 2014) demonstrated that observers cannot maintain separate attentional sets for two specific colours linked to two specific spatial regions. In their study, observers identified a red letter in one hemifield and a green letter in the opposite hemifield. Identification accuracy was impaired when a letter that matched the opposite side's target colour appeared in the same hemifield as the target in the current trial. The researchers interpreted these results as indicating that attentional sets are applied globally to the visual field, rather than being confined to specific spatial locations. The availability of multiple concurrent attentional sets is an open question that requires further examination.

We argue that the two aforementioned types of findings regarding the splitting of attentional sets may not be inherently contradictory and that both have failed to directly address the question of whether two attentional sets can be applied to specific locations. This failure is due to the following: First, relevant distractors that shared the same features as targets occurred in the same potential locations as the true targets in these studies; hence it is plausible that the distractors captured attention as a result of shared sets for location. Second, as claimed by Becker et al. (2015), the findings by Adamo and colleagues (Adamo et al., 2008, 2010) involved cueing, and therefore did not reflect the ability of the visual system to maintain multiple attentional sets confined to various specific locations. Therefore, it remains unclear whether two attentional sets for different colours at different spatial locations can be established. The present study aimed to address this question. To rigorously test whether attentional sets for specific colours may be restricted to specific locations, distractors should be presented at a location where the target never appears. We therefore presented targets and distractors in separate locations and informed observers at the beginning of the experiment that they would not occur in the same location.

In the present study, we approached the question of split of attention by introducing a novel aspect, rather than merely instructing observers to search for specific feature values (e.g., orange and green). Specifically, we evaluated the possible configuration of the visual system by focusing on general attentional control settings, which are assumed to involve at least two subtypes (Bacon & Egeth, 1994; Folk, Leber, & Egeth, 2002): the singleton-detection mode, in which observers are prepared to detect an oddball among homogenous nontargets, and the feature-search mode, in which observers are prepared to detect a specific stimulus feature (e.g., red). We introduced these two abstract attentional sets because several studies (e.g., Becker et al., 2015) have reported that participants failed to establish separate sets involving two specific colour features and locations; we reasoned that a more abstract and non-specific set, such as searching for an oddball, would impose less stringent demands on the system. We examined whether participants could apply these two different search modes concurrently within a single trial as well as separately at different spatial locations.

We pursued this question in several steps. In the first few experiments, we examined whether observers could split their search mode between two different feature values. To achieve this goal, we used the temporal search procedure of Leber & Egeth (2006) to lead participants to adopt one of the aforementioned search modes. For example, in some trials, targets were defined as a colour singleton appearing among homogeneous nontargets. This leads participants to search for an oddball-coloured item using the singleton-detection mode. In other trials, targets were defined by a designated feature value (e.g., a red item) among heterogeneously coloured items to induce a visual search using the feature-search mode. The key manipulation during this procedure was the task-relevance of the distractor colours. A distractor frame, consisting of a set of grey symbols and one uniquely coloured symbol in the periphery, was inserted briefly before onset of a target. The colour of this unique item could be the same (i.e., relevant) colour as the target of the trial or different (i.e., irrelevant). This procedure satisfies the aforementioned requirement to present targets and distractors at separate spatial locations. If observers adopted the singleton-detection mode, the mere presence of the distractor would impair identification of the target regardless of the compatibility of the target-distractor colour relative to the control condition in which no distractor was presented. This would occur because any uniquely coloured item in the distractor frame would capture attention at a peripheral location; thus, target identification would suffer from lack of attention to the central stream. If observers adopted a feature-search mode, the same capture would occur only when the distractor of a known target colour was presented. In contrast, the presence of a distractor of an irrelevant colour would not affect identification of the target. We presented two streams of rapid visual items, one above and the other below the central fixation point, so we could examine whether participants could apply two attentional sets to different streams.

In Experiment 1, we tested whether participants could apply singleton detection mode to two locations simultaneously while monitoring RSVP streams for two distinct color singletons. In Experiments 2-4, we examined whether participants could use two different feature-search modes concurrently to monitor for two different colours at different locations. Experiments 5-7 tested whether participants could apply a mixture of these two search modes: a singleton-search mode for the top and a feature-search mode for the bottom stream. Given that the visual system is flexible and highly programmable (Adamo et al., 2008, 2010; Irons et al., 2012; Moore & Weissman, 2010; Roper & Vecera, 2012), we predicted that participants would be able to adopt two different search modes concurrently to monitor different rapid visual streams. Alternatively, participants may not be able to maintain two different search modes (Becker et al., 2015); observers may fail to maintain separate attentional sets when engaging in a relatively demanding search task. Our results indicate that attentional sets can be split between different visual locations as long as the split involves a single search mode, but that splitting fails across search modes. We also observed several limitations and a set-specific advantage during the simultaneous splitting of attentional sets. We describe the details in the following experiments.

Experiment 1: Singleton-detection Mode

In this experiment, we examined whether participants could apply singleton detection mode to two spatially separated streams of rapid visual presentation sequences to search for a singleton target among nontargets of homogenous colour. This experiment did not examine whether observers could detect two potential target colours presented within a single letter stream, as this was previously determined by Roper and Vecera (2012), who increased the number of potential target colours to two, extending the findings of a prior study involving a single target colour (Folk, Leber, & Egeth, 2002). Roper and Vecera (2012) presented either a red or a green target among grey nontargets, or a critical distractor frame consisting of four pound signs, one of which was a colour singleton that appeared shortly before the onset of the target. The researchers found that the accuracy of target identification was impaired in trials in which a singleton distractor was presented relative to trials in which no such singleton was presented. This result suggests that observers can monitor one homogenous stream to detect a colour singleton. The present experiment differed in that we used two nontarget streams whose colours differed from each other. In other words, we examined whether two differently coloured homogenous streams could be independently monitored for a singleton.

Method

Participants. Sixteen undergraduates recruited from the subject pool at the National Institute of Advanced Industrial Science and Technology (Tsukuba, Japan) participated for pay in this and the following Experiments 2-5. All participants reported normal or corrected-to-normal visual acuity and normal colour vision.

Apparatus and Stimuli. In this and the following experiments, stimuli were displayed on a CRT monitor controlled by a computer using MATLAB software and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007) at a viewing distance of approximately 60 cm. The stimuli were adapted from those used in a typical temporal letter-search task with peripheral distractors (Folk et al., 2002; Leber & Egeth, 2006). The stimulus sequences consisted of letters selected randomly from the English alphabet, excluding I, O, Q, and Z, with the constraint that the letter selected was not one of the two immediately preceding items in both streams and that the two concurrently presented letters differed from each other. One stream was presented 1.2° above the centre of the screen and the other steam was presented 1.2° below the centre. The letters appeared in BorisBlackBloxx font and subtended a visual angle of approximately 1.0° in height and 0.8-1.2° in width (stroke = 0.2°). The target colour was chosen from among blue (RGB palette value: 0, 0, 255), orange (255, 102, 0), magenta (255, 153, 204), cyan (0, 204, 255), dark yellow (128, 128, 0), purple (128, 0, 128), and red (255, 0, 0). Two colours were chosen from the rest for the nontarget items in the two streams; one colour for the top stream and the other for the bottom. The distractor frame consisted of six pound signs (i.e., #) of the same height as the letters, flanking both streams and the central fixation point (2.0° to the right and left, see Figure 1). One of the pound signs in the middle row (right or left side, determined randomly on every trial) was either yellow (255, 255, 0), green (0, 255, 0), or the same colour as the target. The other pound signs in the distractor frame were grey (128, 128, 128). All stimuli were presented on a black background.

Procedure. Observers were instructed to maintain fixation at the centre of the screen and identify an oddball-coloured target that appeared unpredictably and with equal probability in either the top or bottom stream. Each trial started with a 500 ms fixation display of a dot (0.1° × 0.1°) in the centre of the screen once the observers pressed the space bar. Two rapid sequences of 20 letters appeared simultaneously above and below the fixation point following a 500-ms blank interval (Figure 1). Target colour was assigned randomly from seven possible colours (blue, orange, magenta, cyan, dark yellow, purple, and red were used for half of the observers; green was used instead of red for the other half). The colour of the target and that of nontarget items in the two streams differed from each other. The colours were randomly assigned during every trial. As a result, observers were forced to adopt the singleton-detection mode for each stream because they were not informed of the target colour for every trial. The target was chosen randomly from the letters, and the nontargets were chosen from the remaining letters without selecting the same letter in successive frames. The temporal position of the target varied randomly from item 12 to 15 of the stream. Each item was presented for 67 ms, followed by a 50 ms blank interval before the next item was presented, resulting in 117 ms of stimulus onset asynchrony. The onsets and offsets of the items in the two streams were synchronised. Following the study by Folk et al. (2002), a distractor frame, when present, preceded the target frame by two frames (233 ms). The side on which the oddball- coloured distractor (singleton) appeared was determined randomly from trial to trial.

The critical independent variable was the type of distractor. Under the same-colour condition, the distractor singleton was the same colour as the target of that trial. Under the different-colour condition, the colour of the distractor singleton (green, yellow, or grey) differed from the target. No distractor was presented under the distractor-absent condition, which served as a control. Observers were required to ignore the distractors and identify the target letter by pressing a corresponding key on the keyboard after all stimuli were presented. When an incorrect response was made, an alarm sounded through headphones. The same number of trials (120 trials) was assigned for each of the three conditions, and the trials were randomly ordered throughout the experimental session. Observers participated in 24 practice trials before the start of the experimental trials. To familiarise observers with the procedure, practice began at a very slow presentation rate, with the rate gradually increased to full speed for practice trial 12. The accuracy scores for the practice trials were excluded from analyses in this and the following experiments.

Results

Mean accuracy scores in the experimental trials are shown in Figure 2. A two-way ANOVA with target stream (top or bottom) and distractor type (same, different, or no-distractor) as within-subject variables revealed a significant main effect of target stream, $F(1, 15)=14.9$, $p = .002$, $\eta_p^2=0.50$, indicating that the accuracy of the top stream was higher than that of the bottom. The effect of distractor type was also significant, $F(2, 15) = 70.8$, $p < .001$, $\eta_p^2=0.83$. In this and following experiments, multiple comparisons, if necessary, were conducted by Bonferroni's method. The accuracy scores obtained under the same and different colour conditions were lower than those obtained under the control condition, $ts(15) >7.41$, $ps < .001$. The difference between the same and different conditions was not significant, $t(15) = 1.78$, $p = .09$. The interaction between these two factors was not significant, $F(2, 30) = 0.2$, $p = .82$, $\eta_p^2 = 0.01$.

Discussion

The results of Experiment 1 suggest that observers were able to detect two singletons in separate streams because identification of the target was impaired by any singleton distractor, suggesting attentional capture by the distractor regardless of its colour. Although subjects can monitor two streams successfully, the experimental design did not require them to detect two simultaneous targets. Moore and Weissman (2010, Experiment 2, “any colour condition”) reported a similar result. The present results represent an extension of the previous findings reported by Folk et al. (2002) and Roper and Vecera (2012), as those studies reported attentional capture due to the presence of a uniquely coloured item in a single stream of homogenous nontarget items, whereas the present study revealed attentional capture for two spatially separate nontarget streams involving different colours.

We consistently found superior accuracy for the top stream relative to the bottom stream in the first three experiments. Such superior performance for an upper position relative to a lower one has been previously reported (e.g., Awh and Pashler, 2000; Pomplun, Reingold, &Shen, 2001). However, when taken together with the absence of such an asymmetry in Experiments 5-8, where two different types of task were implemented as the top and bottom streams and the tasks and positions were counterbalanced, the effect of position does not appear to play a critical role in the present study. Thus, we provide no further discussion of the difference between the top and bottom streams and consider this issue to be outside of the scope of the present study.

Experiments 2-4: Feature-search Mode

In Experiment 2, we examined whether participants could apply two different feature-search modes concurrently to two different spatial locations. Although this possibility has not been tested with two streams of rapid serial visual presentation, recent studies using a relevant condition suggest that a complex attentional set for space-feature combinations is feasible. On the one hand, as shown by Adamo and colleagues (Adamo et al., 2008, 2010), there is evidence that observers are able to establish two attentional sets. On the other hand, Becker et al. (2015) demonstrated that attentional sets were applied globally to the visual field, rather than being confined to specific spatial locations.

Experiment 2 examined whether two potential target colours (red or cyan) can be concurrently monitored. Experiments 3 and 4 represent variations on the design of Experiment 2, presenting three target colours (red, cyan, or yellow) in two streams (Experiment 3) and two target colours (red or cyan) in a single letter stream (Experiment 4) to identify boundary conditions by examining the patterns of attentional capture and priming effects across these conditions.

We predicted that if observers were able to apply feature-search mode (i.e., identify any letter that appears in either red or cyan) to two locations simultaneously, then target identification accuracy should be impaired on trials in which a peripheral distractor of either of these colours preceded the target relative to trials in which the colour of the distractor was irrelevant (i.e., green). Moreover, we also predicted a facilitation effect for a distractor of the same colour as the target, as reported by Moore and Weissman (2010, Experiment 1). These researchers instructed participants to search for a target letter in one of two possible colours (e.g., red or cyan) among a single stream of nontargets of various colours. The results indicated a standard attentional capture effect, such that accuracy for target identification was lower when a distractor appeared in one of the two possible target colours than when it appeared in an irrelevant colour (e.g., purple). Importantly, the capture effect greatly decreased (i.e., accuracy was less impaired) when the colour of the distractor (i.e., red) was identical to that of the target in that trial (red) in comparison with trials in which the colour of the distractor was the second possible colour (cyan). The same pattern of results was obtained in the current study when observers were required to monitor two rapid letter sequences.

Method

Participants. Forty-three undergraduates participated for pay (n =17, 10, and 16 for Experiments 2, 3, and 4, respectively). None had participated in any of the previous experiments. All reported normal or corrected-to-normal visual acuity and normal colour vision. In this and following experiments, the same subjects as previous experiments did not participate repeatedly.

Stimuli and procedure. The stimuli and procedure in Experiment 2 were identical to those used in Experiment 1 except for the following changes. The colours of the nontarget items in the two letter streams were chosen so as to force observers to use the feature-search mode; they were blue, orange, magenta, yellow, dark yellow, purple, or grey. The observers were informed that the target colours were red and cyan, and they identified the target letter in one of these two possible colours. The target appeared at equal frequencies in either the top or bottom stream. The distractor was red, cyan, or green. Red and green were exchanged for half of the observers. Even-number participants used red as a potential target and odd-number participants used it as a distractor.

There were four distractor types; (1) same colour: the distractor was the same colour as the target of that trial (e.g., red target with red distractor); (2) second colour: the distractor was the other possible colour (e.g., red target with cyan distractor); (3) different colour: the distractor colour was different and irrelevant to the task (e.g., green); and (4) no-distractor: distractor was absent. These four conditions occurred equally often (90 trials each), resulting in a total of 360 trials. The trials were presented in random order.

In Experiment 3, observers searched for three potential target colours (red, cyan, or yellow). The distractor colour of yellow used in Experiment 2 was replaced with brown (RGB: 153, 51, 0). There were four distractor types: (1) same colour: the distractor was the same colour as the target of that trial (e.g., red target with red distractor, in case red was chosen as a target colour from two possible target colours); (2) second colour: the distractor was in one of the remaining possible target colours (e.g., red target with cyan or yellow distractor, randomly chosen); (3) different colour: the distractor colour was different and irrelevant to the task (i.e., green); and (4) no-distractor: distractor was absent. Other aspects of the procedure were the same as described for Experiment 2.

In Experiment 4, stimuli and procedures were the same as in Experiment 2, except that only one rapid stream of nontarget letters was presented in the center of the screen. The observers identified a red or cyan letter among variously coloured nontarget letters. The spatial arrangement of the distractor frame was identical to that of Experiment 2.

Results

<u>Experiment 2 (two target colours with two streams).</u> Mean accuracy scores are shown in Figure 3. A two-way ANOVA with target stream (top or bottom) and distractor type (same colour, second colour, different colour, or no-distractor) as within-subject variables revealed a significant main effect of target stream, $F(1, 16) = 11.6$, $p = .004$, $\eta_p^2 = 0.42$, indicating that accuracy for the top stream was higher than that for the bottom. The effect of distractor type was also significant, $F(3, 48) = 23.2$, $p < .001$, $\eta_p^2 = 0.59$. Multiple comparisons indicated that accuracy under the second colour condition was lowest among the four conditions, ts(16) > 5.05, ps < .001. Accuracies under the same-colour and different-colour conditions were lower than that under the no-distractor condition, $t(16) = 2.83$, $p = .012$, and $t(16) = 3.35$, $p = .004$, respectively. No difference was found between the accuracies under the same-colour and different colour conditions, $t(16) = 1.32$, $p =.210$. The interaction between the target stream and distractor type was not significant, $F(3, 48) = 0.1$, $p = .97$, $\eta_p^2 = 0.01$.

<u>Experiment 3 (three target colours with two streams).</u> Mean accuracy scores for the test session are shown in Figure 4. A two-way ANOVA with target stream (top or bottom) and distractor type (same colour, second colour, different colour, or no distractor) as within-subject variables revealed a marginally significant main effect of target stream, $F(1, 9) = 4.42$, $p = .06$, $\eta_p^2 = 0.33$, indicating that accuracy for the top stream tended to be higher than that for the bottom. The effect of distractor type was significant, $F(3, 27) = 9.30$, $p < .001$, $\eta_p^2 = 0.51$. Multiple comparisons indicated that accuracy under the second-colour condition was lowest among the four conditions, ts(9) > 2.35, $p < .05$. No

other combinations of conditions differed from each other. The interaction between target stream and distractor type was not significant, $F(3, 27) = 0.33$, $p = .80$, $\eta_p^2 = 0.04$.

Experiment 4 (two target colours in a single stream). Mean accuracy scores for the test session are shown in Figure 5. A one-way ANOVA with distractor type (same colour, second colour, different colour, or no distractor) as within-subject variables revealed that the main effect of distractor type was significant, $F(3, 45) = 13.12$, $p < .001$, $\eta_p^2 = 0.47$. Multiple comparisons indicated that accuracy under the same-colour condition was lower than that under the different-colour and no-distractor conditions, ts(15) > 3.73, ps < .006. Similarly, accuracy under the second-colour condition was lower than those under the different-colour and no-distractor conditions, ts(15) > 4.07, ps < .005. No other condition combinations differed from each other.

Discussion

Two major findings were obtained from Experiments 2-4. First, the observers were able to maintain at least one of the two target colours when engaging in feature-search mode. This was evidenced by the occurrence of attentional capture, with identification accuracy being lowest under the second-colour condition in Experiments 2 and 4 (tying for lowest,) and under the second-colour condition in Experiment 3, where the distractor colour was the same as the colour that was to-be-memorised but not presented. If these to-be-memorised colours were not maintained in the attentional set, no impairment relative to the different-colour condition should have occurred. This result is consistent with those of Moore and Weissman (2010, Experiment 1) and Roper and Vecera (2012) with regard to being able to the ability to maintain more than one concurrent attentional set , although these researchers used a single critical stream.

Second, a facilitation effect was observed when the colours of the distractor and the target were identical (i.e., same-colour condition) in Experiments 2 and 3. This effect was comparable to the one observed by Moore and Weissman (2010, Experiment 1), who argued that facilitation occurs because processing a target-coloured distractor causes the corresponding attentional set (i.e., involving the search for a red letter) to enter the focus of attention or gain special status in working memory (Olivers, Peters, Houtkamp, & Roelfsema, 2011) until the item has been successfully identified. Such entry of the critical colour into the focus of attention facilitates identification of a subsequent target that shares the same colour. Experiment 2 revealed that this facilitation effect occurred even though observers monitored two streams concurrently without distractor streams containing rapidly presented items. The same result occurred when observers needed to monitor three colours (Experiment 3). However, no such effect was found when only one stream of letters was monitored (Experiment 4), suggesting that heavy spatial load, such as that imposed by the need to monitor multiple locations or by greater uncertainty to search for a target from multiple potential locations was required for the facilitation effect to occur; such heavy loads were involved in Experiments 2 and 3 and in previous studies (Moore & Weissman, 2010, 2011) but not in Experiment 4.

Experiment 5: Feature-search and singleton-detection modes

Our results indicated that the observers were able to maintain the attentional sets needed to detect two concurrent singletons (Experiment 1) and to conduct two concurrent feature searches (Experiment 2). In the latter case, a facilitation effect also occurred if the colour of the distractor was the same as the target of the current trial only when observers were monitoring two streams. In Experiment 5, we examined whether observers could monitor two streams of stimuli with a mixture of singleton-detection and feature-search modes. That is, we asked observers to apply the singleton-detection mode to the top stream and the feature-search mode to the bottom stream.

Experiment 5 consisted of a 2 (search mode: singleton detection or feature search) × 3 (distractor type: same colour, different colour, or no distractor) factorial design. If participants are able to split and assign two attentional sets separately for different locations, the accuracies of the same and different colour conditions in the top stream should be equivalent, whereas accuracy of the same colour condition should be lower than that of the different colour condition in the bottom stream. An interaction between search mode and distractor type should be obtained if such a split is possible.

Method

Participants. Sixteen undergraduates participated for pay. None had participated in any of the previous experiments. All reported normal or corrected-to-normal visual acuity and normal colour vision.

Stimuli and procedure. The stimuli and procedure were identical to those used in Experiment 1, except for the following differences. The targets in the top stream were defined as colour singletons, whereas those in the bottom stream were defined as letters of a specific colour (i.e., red).

We asked observers to search for a colour singleton in the top stream. The potential colours of the target and nontargets in the top stream were chosen from blue, orange, magenta, cyan, dark yellow, and purple. One of the remaining colours , which was chosen randomly for every trial (i.e., the rest of the above six -1 (chosen for a target colour) colours), served as the homogenous nontarget colour for the top stream. The potential distractor colours (i.e., an oddly coloured #) for the top stream target were red, green, yellow, grey, or the same colour as the target for that trial. Three distractor types were created using these colours: (1) same colour distractor: one of the pound signs in the middle row was the same colour as the target of the top stream in that trial, (2) different coloured distractor: one of the pound signs in the middle row differed from the target colour for that trial in the top stream, (3) no-distractor: no pound signs were presented. This condition served as a control. We asked observers to search for a red item in the bottom stream, and the colour of the potential distractor was red or green. The principle of the distractor-colour assignment was identical to the top stream; thus, these three (same colour, different colour and no-distractor) distractor conditions occurred equally often (60 trials each) but separately for the singleton- and feature-search modes, resulting in 360 trials, preceded by 24 practice trials. The experimental trials were presented in random order.

Results and Discussion

Mean accuracy scores are shown in Figure 6. A two-way ANOVA with search mode (singleton detection or feature search) and distractor type (same colour, different colour, or no-distractor) as within-subject variables revealed a significant main effect of distractor type, $F(2, 30) = 9.32$, $p < .001$, $\eta_p^2 = 0.38$. Multiple comparisons indicated that accuracy under the different colour condition was lowest among the three conditions, *t*s(15) > 2.90, *p*s < .022. The difference between the no- and same-colour distractor conditions was not significant, $t(15) = 1.51$, $p < .15$. Neither the main effect of search mode nor the interaction between search mode and distractor type was significant, $F(1, 15) = 1.53$, $p = .23$, $\eta_p^2 = 0.09$ and $F(2, 30) = 0.2$, $p = .84$, $\eta_p^2 = 0.01$, respectively.

The present results indicate that the observers were unable to establish two different search modes concurrently because no interaction was detected between search mode and distractor type. Interestingly, the result pattern was neither singleton detection nor feature search. Instead, a new pattern of interference from the distractors emerged. Specifically, identification accuracy was impaired when a different-colour distractor appeared relative to when no such distractor was presented, reflecting ordinary attentional capture. However, the pattern of results for singleton-search mode (top stream) did not indicate attentional capture when a same-colour distractor appeared, as accuracy under this condition *improved* relative to that under the different colour distractor condition. The ordinary result pattern for feature-search mode (bottom stream) should have had the lowest accuracy under the same-colour condition and equivalently higher accuracy under the different-colour and no-distractor conditions. However, accuracy under the same-colour condition *improved* relative to that under the different colour distractor condition. In addition, accuracy under the different-colour condition was lower than that under the no-distractor condition. Therefore, these results indicate that the observers were unable to apply the singleton-detection and the feature-search modes concurrently in the same visual display.

Importantly, a facilitation effect was observed for both search modes. This pattern was similar to the facilitation effect observed under the same-colour distractor condition tested in Experiment 2, and the “same-target-coloured” condition in the study of Moore and Weissman (2010, Experiment 1) in which accuracy under the same colour condition was higher than that under the different-colour condition. However, the facilitation effect pattern deviates from that of Moore and Weissman (2010, Experiment 1) in which the accuracy under the same-colour condition was significantly lower than that under the control condition. In contrast, accuracy under the same-colour condition in the present study was nominally, although non-significantly, higher than that under the no-distractor (control) condition. The present results demonstrate that the observers were unable to split search modes concurrently for two different spatial locations. Notably, a facilitation effect was detected. Accuracy under the same-colour condition was higher than that under the different-colour condition in both search modes.

However, this facilitation effect may be due to an artefact of the present task configuration. Specifically, the only possible distractor colours in the feature-search trial were red and green, whereas the singleton-detection trials included 10 possible distractor colours. This means that red and green distractors disproportionately preceded the appearance of targets in the feature-search stream (a and b in Table 1). In fact, this bias explains why observers may have adopted a search set for green and red targets in particular, thereby resulting in higher accuracy under the same-colour distractor condition relative to under the different-colour distractor condition in the feature-search stream (Footnote 1). Experiment 6 was designed to address this issue.

Experiment 6

Experiment 6 was conducted to examine the aforementioned possibility regarding Experiment 5: that the observers in Experiment 5 may have used the bias in distractor frequency as a cue to expect a red item as the feature-search target. This distractor-target contingency may have contributed to improved accuracy under the same-colour condition of feature-search trials. To discourage this strategy, we changed the composition and reduced the number of trials in Experiment 6, as shown in Table 1. This was done with the aim of reducing the opportunities for observers to discern the operation of any contingencies involving the distractor colour and upcoming target. We also reduced the proportion of same-colour distractor trials under the feature-search mode (d in Table 1) relative to the proportion of the different-colour trials, which involved neither red nor green distractors (e in Table 1), while maintaining the equivalence of the total numbers of feature-search and singleton-detection trials (144 each). If the results of Experiment 5 relied on a contingency bias involving distractor and target items, and if feature-search and singleton-detection modes were concurrently available, the present manipulation should result in the typical patterns observed for the feature-search mode (i.e., impaired accuracy only under the same-colour distractor condition in the feature-search stream) and the singleton-search mode (i.e., similarly decreased accuracy under the same- and different-colour distractor conditions in the singleton-detection stream).

We implemented two additional changes (footnote 2). First, we included red distractor trials under the singleton-detection mode (f in Table 1). These trials served to discourage the red-cue strategy described above and to explore the impact of the target's colour (i.e., red) on the singleton-detection trials and compare it with its effect on the trials in which non-red items were presented as different-colour distractors (g in Table 1). If the establishment of an attentional set for red items with the goal of detecting the feature-search target were spatially imprecise and leaked into the singleton-detection stream, the presence of a red (f in Table 1) distractor would impair accuracy in the singleton-detection stream. Second, we counterbalanced the assignments of the search modes (feature or singleton) and the locations of the streams (top or bottom) across observers to avoid additional potential confounds that may have contributed to the results in Experiment 5.

We examined whether observers could split search modes concurrently for two different spatial locations. If such a split were possible, typical singleton-detection and feature-search patterns would be obtained for the pertinent streams. Otherwise, no such typical search patterns would be observed, with the possible emergence of novel patterns.

Method

Participants. Thirty-two undergraduates from Hokkaido University participated for pay in Experiment 6 and subsequent Experiment 7. All reported normal or corrected-to-normal visual acuity and normal colour vision.

Apparatus, stimuli and procedure. An LCD monitor was used in the present study because the CRT monitor that was used in the previous experiments was no longer available. The stimuli and procedure were similar to those used in Experiment 3, with the exception that the experimental software was rewritten by using a new version of the Psychophysics Toolbox library (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007).

The search modes (singleton-detection or feature-search) and locations of the streams (top or bottom) were randomly assigned across observers at the beginning of the experiment. That is, half the observers searched for a singleton in the top stream and for a red (or green) feature in the bottom stream, whereas the other half searched in the opposite manner.

Potential target colours for the singleton-detection search stream were chosen from among blue, orange, magenta, dark yellow, purple, yellow, brown, white, grey, and green (with green replaced by red for green-target observers). One of the remaining colours, randomly chosen for every trial, served as a homogenous nontarget colour for the singleton-detection stream. Potential distractor colours for the singleton-detection stream were chosen from among the remaining colours, with the constraint that the target colour in the feature-search stream was included as a distractor colour in the singleton-detection stream in 24 trials (f in Table 1). Under the same-colour distractor condition, the singleton target and the distractor appeared in the same colour. Under the different-colour distractor conditions, these appeared in different colours.

With regard to the feature-search stream, the target colour, red or green, was randomly assigned across observers. The distractor colour under the different-colour condition of the feature-search trial was randomly chosen for every trial from among the potential colours listed above, with the constraint that this distractor colour differed from the nontarget colour of the singleton-detection stream of that trial. This was done to discourage observers from using the distractor colour as a cue for the upcoming target, as was possible in Experiment 5, where the same- and different-distractor colours uniquely predicted the target stream. No such strategy was available in the present study, because equal numbers of red and non-red distractor trials were assigned in each of the two search modes. Under the same-colour distractor condition, the distractor colour was red (green for half the observers). Under the different-colour distractor conditions, the distractor colour was chosen from among remaining possible colours.

We instructed observers to search for a colour singleton in one of the two streams and a red (green for the other half of the observers) colour target in the other stream. Details pertaining to the number of experimental trials are summarised in Table 1. The experimental trials were preceded by 24 practice trials, beginning at a very slow presentation rate, with the rate gradually increased to full speed by the end of the practice trials.

Results

A three-way ANOVA with, search mode (singleton detection or feature search), distractor type (same colour, different colour, or no distractor) and the assignment of search mode to stream (top-singleton group or bottom-singleton group) as between-subject variables revealed no effect of assignment, $F(1, 30) = 1.14$, $p = .71$, $\eta_p^2 = 0.004$. Therefore, we collapsed the data across assignment for all further analyses.

Mean accuracy scores are shown in Figure 7. A two-way ANOVA with search mode (singleton detection or feature search) and distractor type (same colour, different colour, or no distractor) as within-subject variables revealed a significant main effect of search mode, $F(1, 31) = 48.99$, $p < .001$, $\eta_p^2 = 0.61$, indicating that accuracy for the feature-search mode was higher than that for the singleton-detection mode. This contrasts with the results of Experiment 5 and was probably due to the inclusion of four additional possible colours, increasing the task difficulty of the current experiment. The main effect of distractor type and the interaction between these two factors were also significant, $F(2, 62) = 10.57$, $p < .001$, $\eta_p^2 = 0.25$, and $F(2, 62) = 17.76$, $p < .001$, $\eta_p^2 = 0.36$, respectively. Multiple comparisons pertaining to the simple main effect of distractor type in the singleton-detection mode ($F(2, 62) = 7.31$, $p = .0014$, $\eta_p^2 = 0.19$) indicated that accuracy was lower under the different-colour condition than under the same-colour condition, $t(31) = 4.10$, $p < .001$. This pattern of results is consistent with the results of Experiment 5, in which improved accuracy was also obtained under the same-colour distractor condition for the singleton-detection mode. We discuss the potential reasons for this interaction in the Discussion section. In contrast, multiple comparisons pertaining to the simple main effect of distractor type for the feature-search mode ($F(2, 62) = 16.96$, $p < .001$, $\eta_p^2 = 0.35$) indicated that, among the three distractor conditions, accuracy was highest under the no-distractor condition, ts(31) > 4.82, ps < .001, with no significant difference between the same- and different-colour distractor conditions, $t(31) = 1.24$, $p = .22$. This result is inconsistent with Experiment 5, in which improved accuracy for the feature-search mode was obtained even under the same-colour distractor condition relative to under the different-colour condition. The present results suggested a failure of the feature-search mode; instead , the resulting search pattern is characteristic of singleton detection.

To investigate possible “leakage” from an attentional set in the feature-search stream to the singleton-detection stream, we examined the effect of the red (green for half of the observers) distractor on singleton detection. The inset of Figure 7 shows the accuracy scores for the red and non-red singleton distractors. Accuracy for singleton-detection was lower when the distractor colour was the same colour as the target of the feature-search mode (i.e., red; M = 22.4%; f in Table 1; the hatched bar in the inset) than when the distractor appeared in a different colour (i.e., non-red; M = 32.4%; g in Table 1; the dotted grey bar in the inset). A t-test revealed this difference to be statistically significant, $t(31) = 4.53$, $p < .001$, $r = .63$. Importantly, no difference in accuracy was found between the same-colour condition (the white bar from the singleton data) and the different-colour condition excluding red trials (the dotted grey bar in the inset), $t(31) = 0.75$, $p = .46$, $r = .13$.

Discussion

Three major findings emerged from Experiment 6. First, the results for the singleton-detection mode did not indicate an ordinary attentional capture when a same-colour distractor appeared. Instead, accuracy under this condition improved relative to that under the different-colour distractor condition. This pattern was consistent with the results of Experiment 5. Second, no such improvement was obtained for the feature-search mode. Rather, accuracy rates under the same- and different-colour distractor conditions were equivalent to each other, and both were lower than that under the no-distractor condition, demonstrating a typical pattern of attentional capture using singleton detection. It is important to note that attentional capture occurred regardless of the colour of distractor when observers engaged in a feature-search mode. In this regard, the results were inconsistent with those of Experiment 5. These two major findings suggest that it is impossible to concurrently split attentional sets related to feature search and singleton detection between two spatial locations. Finally, the observed leakage from the feature-search set to the singleton-detection mode, as indicated by the severe impairment of singleton-detection accuracy when the distractor appeared in the same colour as the feature-search target relative to when it appeared in a different colour, implies that the aforementioned failure of attentional set splitting is accompanied by a contamination between sets across two spatial locations.

The present experiment revealed a novel pattern of attentional capture. When observers were required to split attentional sets related to singleton-detection and feature-search modes, a hybrid pattern of capture emerged. The present results do not indicate that observers ignored the instruction to apply the feature-search mode for one stream and the singleton-detection mode for the other. If observers had abandoned any attempt to maintain separate sets and were instead inclined to adopt the feature-search mode for both streams, then accuracy for the feature-search stream should have been impaired only by the same-colour distractor, with higher accuracy under the different-colour distractor condition relative to under the same-colour distractor condition. In reality, accuracies rates did not differ between the same- and different-colour conditions for the feature-search stream, demonstrating a pattern that is typical of singleton detection even for the *feature-search* stream. Similarly, if observers had adopted the singleton-detection mode for both streams, we would not be able to explain the “leakage” effect (Figure 7, inset) indicated attentional capture in cases of a match between the feature-target colour and a singleton-stream distractor. Therefore, the present results suggest that observers complied with the instructions but failed to maintain distinct sets for each of two separate locations. Importantly, no difference in accuracy rates for singleton detection was found between the same-colour condition and the different-colour condition excluding red trials. This means that the seemingly superior accuracy under the same-colour condition than under the different-colour condition was driven by the presence of red distractors under the different-colour condition. A similar pattern in Experiment 5 (c in Table 1) may also have been induced by the occurrence of red distractors in Experiment 5; however, we were unable to assess this possibility because the experimental program we used did not output colour values.

Aside from these major findings, we also found that accuracy for the feature-search mode was higher than that for the singleton-detection mode in the present experiment, whereas the opposite was true in Experiment 5. This difference was probably due to the inclusion of four additional possible colours, which increased the difficulty of the task.

Experiment 7

Thus far, the experiments in the current study have consistently demonstrated that it is impossible to concurrently maintain separate attentional sets for singleton-detection and feature-search modes at two different locations. Nonetheless, several minor inconsistencies arose between the results of Experiments 5 and 6. The present experiment was conducted to identify the sources of these inconsistencies.

Specifically, Experiment 5 showed an apparent increase in identification accuracy due to exposure to a same-colour distractor prior to the target (Moore & Weissman, 2010, 2011, 2014; Roper & Vecera, 2012). However, no such advantage appeared in either stream in Experiment 6. It should be noted that this apparent same-colour advantage disappeared in the singleton stream when red distractor trials were excluded (as in the inset of Figure 7). We argue that the same-colour advantage occurred for different reasons in each stream. With respect to the feature-search stream, observers in Experiment 5 saw red and green distractors occurring with disproportionate frequency; thus, they may have adopted a particular attentional set for these items, resulting in higher accuracy rates under the same-colour distractor condition relative to under the different-colour condition. Experiment 6 was designed to discourage such a bias for specific colours. Thus, the presence or absence of the set-specific capture effect in the feature-search steam should be attributable to the array of possible distractor colours and their frequencies, and any resulting bias for a specific feature value (i.e., red in the current study). With regarding to the singleton-detection stream, the advantage of the same-colour condition obtained in Experiment 5 was not due to exposure to the same-colour distractor but due to the apparent decrease in the scores under the different-colour condition, as indicated by the analysis of Experiment 6 (see the inset of Figure 7). That is, the red distractors under the different-colour condition reduced the overall accuracy under this condition, yielding an apparent advantage of the same-colour condition over the different-colour condition.

Based on these conjectures, we made the following two predictions for

Experiment 7, which was a replication of Experiments 5 and 6 with a few modifications. First, when using the same composition of trials as in Experiment 5, we should observe an advantage associated with the exposure to a same-colour distractor shortly before the appearance of target in the feature-search stream. Specifically, we presented red distractors in one-third of the feature-search trials, which should have restored a search set biased in favour of red targets, resulting in set-specific capture for the feature-search mode (Moore & Weissman, 2010, 2011, 2014; Roper & Vecera, 2012). Second, this apparent advantage for the same-colour distractor condition in the singleton-detection trials should be eliminated if we removed red distractors from the different colour-distractor conditions (i.e., no red items in trials h of Table 1). Accordingly, we predicted no difference in the accuracy rates between the same- and different-colour distractor conditions in singleton-detection trials.

Method

Thirty-two undergraduates participated for pay. None had participated in any of the previous experiments. All reported normal or corrected-to-normal visual acuity and normal colour vision. The apparatus, stimuli and procedure were identical to those of Experiment 6, except for the following two changes. First, the composition of trials was the same as that of Experiment 5, but with 48 (rather than 60) trials under each of the six conditions (Table 1). Second, no red distractors were included in the different colour singleton-detection trials (h in Table 1). The search modes (singleton-detection or feature-search) and locations of the streams (top or bottom) were counterbalanced across observers. As in Experiment 6, 24 practice trials preceded the experimental trials.

Results

Mean accuracy scores are shown in Figure 8. A two-way ANOVA with search mode (singleton detection or feature search) and distractor type (same colour, different colour, or no-distractor) as within-subject variables revealed a significant main effect of search mode, $F(1, 31) = 25.72$, $p < .001$, $\eta_p^2 = 0.45$, indicating that accuracy was higher for the feature-search mode than it was for the singleton-detection mode. This main effect is consistent with the outcome of Experiment 6. The main effect of distractor type and the interaction between these two factors were also significant, $F(2, 62) = 14.26$, $p < .001$, $\eta_p^2 = 0.32$, and $F(2, 62) = 7.25$, $p = .0015$, $\eta_p^2 = 0.19$, respectively. There was a significant simple main effect for the feature-search mode, $F(2, 62) = 15.29$, $p < .001$, $\eta_p^2 = 0.33$ but not for the singleton-detection mode, $F(2, 62) = 0.96$, $p = .39$, $\eta_p^2 = .03$. Multiple comparisons pertaining to the significant simple main effect observed for the feature-search trials indicated that accuracy was lowest under the different-colour condition and highest under the no-distractor condition, ts(31) > 3.16, $p < .007$. Importantly, accuracy was higher under the same-colour condition than under the different colour condition, ts(31) > 2.28, ps < .03, indicating an advantage of the same-colour distractor condition over the different-colour distractor condition with respect to the accuracy of feature target identification.

Discussion

The present results are consistent with our two predictions. First, an advantage for the same-colour distractor condition was obtained in the feature-search stream. That is, accuracy was higher under the same-colour condition than under the different-colour condition, although attentional capture occurred, as indicated by the fact that the no-distractor condition yielded higher accuracy rates than the other conditions. Although no same-colour advantage was found in Experiment 6, in which the trial composition was designed to discourage an attentional set targeting red items, the restoration of such a set in the present experiment resulted in set-specific capture. Therefore, these results suggest that the involvement of a strong feature-search set is required for the set-specific capture obtained under the present circumstances. Second, set-specific capture in the singleton-detection trials did not occur when the red distractors in the different colour-distractor conditions were omitted. This result is consistent with our prediction and supports our interpretation that the set-specific-capture-like results in Experiment 5 arose from an artefact attributable to the appearance of red distractors under the different-colour condition in the singleton-detection trials.

In summary, the present results point to a coherent interpretation of the results of Experiments 5-7. Specifically, it appears to be impossible to concurrently maintain split attentional sets for singleton-detection and feature-search modes at two different locations. When participants were instructed to search concurrently for a singleton and a feature target, the resulting pattern of attentional capture did not represent either a typical singleton-detection or feature-search pattern. Under these circumstances, the feature-search mode failed, and different- colour distractors that are usually ignored captured attention. It is notable that same-colour distractors sometimes had an advantage over different-colour distractors (Moore & Weissman, 2010; Roper & Vecera,

2012) when it was reasonable for observers to develop a bias in favour of a specific feature value (e.g., red) that occurred frequently (Experiments 5 and 7). No such same-colour distractor advantage occurred for the singleton-detection trials.

General Discussion

The primary purpose of the present study was to examine attentional set flexibility. Previous studies using various experimental paradigms have examined whether observers are able to monitor multiple features and locations or their combinations (Adamo Pun, et al., 2008; Adamo, Wozny, et al., 2010; Irons, Folk, & Remington, 2012; Moore & Weissman, 2010, 2011; Parrott, Levinthal, & Franconeri, 2010; Roper & Vecera, 2012). In general, these findings suggest that visual selection can be flexibly configured to suit behavioural purpose. However, Becker et al. (2015) argued that attentional sets based on two features cannot be concurrently established and liked to particular spatial locations. Nevertheless, it has been unclear whether more general and conceptual attentional sets, i.e., singleton-detection and feature-search modes (Bacon & Egeth, 1994; Folk et al., 2002), can coexist. It is reasonable to assume that two such attentional sets would be concurrently viable because the singleton-detection mode is said to be a primitive or “default” attentional set (Kawahara, 2010; Pashler & Harris, 2001; Trick, Enns, Mills, & Vavrik, 2004). Hence, such a mode might remain available even under a high task load requiring the splitting of sets. Therefore, the present study examined whether observers could apply these two search modes to different spatial locations.

The results of Experiment 1 indicate that observers were able to monitor two separate letter streams to detect a colour singleton even when the nontarget colours of the two streams differed from each other. This finding extends those obtained by previous studies (Moore & Weissman, 2010; Roper & Vecera, 2012), in which observers were able to search for two potential target colours among a single nontarget letter stream; the present results demonstrate that the visual system is capable of monitoring two letter streams, differing in colour, to detect a unique but unknown colour singleton. Experiment 2 revealed that the configuring attentional set is more flexible. Observers were able to monitor two streams of differently coloured letters using two feature-search modes to find a target letter of one of two (or three in Experiment 3) potential target colours. These observations are based on findings that identification accuracy was lower when the distractor colour of a trial was one of the potential colours (but not the current target colour) than when the distractor colour was a task-irrelevant nontarget colour. If the potential target colours were not maintained as an attentional set, no such impairment should have been observed. The results of our first four experiments extend the previous notions of attentional sets (Ito & Kawahara, 2016; Moore & Weissman, 2010; Roper & Vecera, 2012), showing that the singleton-detection mode can be concurrently applied to wide spatial regions and that multiple-feature search sets (involving up to three colours) can be maintained over multiple locations.

However, the flexibility of the singleton-detection mode was severely limited when combined with the feature-search mode, resulting in the disappearance of a typical singleton-search pattern in Experiment 5. Instead, accuracy was higher under the same-colour condition than under the different-colour condition in Experiments 5 and 6.

This effect was not due to the same-colour advantage observed by Moore and Weissman (2010; Roper & Vecera, 2012) but due to the “leaking” of a set targeting red items from the feature-search mode to the singleton-detection mode. This argument is supported by the elimination of the same-colour advantage for red distractors in the singleton-detection stream in Experiment 7.

Most importantly, the results of Experiment 5 reveal that observers found it impossible to maintain a feature-search mode in one stream and a singleton-detection mode in the other stream. When such a splitting of attentional sets was required, the feature-search mode failed, as did the singleton-detection mode (Experiments 5-7). Instead, accuracy was higher under the same-colour distractor condition than it was under the different-colour distractor condition in the feature-search stream in Experiment 5. Further examination of the same-colour advantage was necessary because of the concern that this advantage could be due to the fact that observers might have searched specifically for red items, which appeared disproportionately frequently. Consistent with this reasoning, the same-colour advantage disappeared when this frequency bias was removed in Experiment 6, and it was restored when the bias was re-introduced in Experiment 7.

The present results address two issues of theoretical importance. First, they provide strong support for a view involving the roles of spatial precision and flexibility in the splitting of attentional sets. As described in the Introduction, a number of researchers have argued that the visual system can be configured in such a way as to maintain attentional sets for two different features at two separate spatial locations. For example, Adamo et al. (2008) asked observers to search for a green item on the right or a blue item on the left. The target was preceded by a non-predictive cue that shared the same location and/or colour as the target. Reaction times for target discrimination were shorter when the colour and location of the target were consistent with the cue. The researchers suggested that separate attentional sets can be concurrently maintained at two spatial locations. However, other studies have provided evidence against the configuration of such localised attentional sets for multiple features. For example, Becker et al. (2015) implemented a task that was conceptually similar task to the one used by Adamo et al. (2008), with the exception that the target was spatially accompanied by nontarget items. The accuracy of target identification was impaired by the appearance of a distractor item whose colour was the same as the potential target in the other hemifield. Becker et al. argued that when splitting is required, attentional sets are applied globally rather than restricted to a specific hemifield. We argue that Adamo et al.'s and Becker et al.'s tasks may not be optimal for examining the spatial precision of attentional splitting because of the possibility that distractors would appear at potential target locations. It is reasonable that attention would be captured by distractors appearing at locations that observers monitor for targets. In this sense, the present study represents the first rigorous examination of spatial precision in the maintenance of attentional sets when splitting is required.

Second, the present findings of set-specific capture (Experiments 5 and 7) highlight an aspect of attentional focus that is assumed to be involved during search involving multiple features (e.g., red and green). Specifically, Moore and Weissman

(2010, 2011, 2014) argued that set-specific capture is triggered by a distractor of the same colour (e.g., red) as the target. The distractor results in the corresponding attentional set (e.g., targeting red items, rather than targeting oddballs) to enter a limited-capacity focus of attention in working memory (Jonides et al., 2008; Oberauer, 2002). They suggest that the set is briefly maintained, resulting in poor identification of a differently coloured (i.e., green) item because one of the valid attentional sets (i.e., targeting green items) cannot enter the focus of attention. Hence, processing is easier when the colour of the subsequent target matches that of the set in focus. Our results suggest that the entry of an attentional set into the focus of attention is not entirely automatic but is modulated by top-down control. If entry were automatic, then target identification should have been facilitated by a same-colour distractor preceding the target in the singleton-detection stream. Given that the apparent benefit of exposure to the same-colour distractor was demonstrated to be spurious by the lower accuracy obtained under the different-colour condition, reflecting a feature bias in favour of red items (see the inset analysis of Experiment 6, Figure7), we have no clear evidence of a benefit arising from same-colour distractors. The elimination of the same-colour distractors advantage upon a reduction in the bias favouring red targets (Experiment 5) is also consistent with the idea that the entry of an attentional set into the focus of attention is modulated by top-down knowledge. This aspect of attentional focus has not been explicitly addressed in previous studies (Moore and Weissman, 2010, 2011, 2014) and is illuminated by the results of the present study.

Obviously, the present results do not indicate an overriding of one of the search modes by the other. If observers had relied exclusively on the feature-search mode, accuracy would have been unimpaired under the different-colour distractor condition relative to under the control condition for both streams. If the singleton-detection mode was used exclusively, accuracy under the same-colour condition would have been lowest for both streams. However, neither of these patterns was observed. Of course these results do not exclude the possibility that the singleton-detection mode was used with partial facilitation (e.g., Moore and Weissman, 2010). It is also possible that observers may have switched between strategies on a trial-by-trial basis. In that case, however, we would expect a consistent pattern of singleton detection for one stream and a consistent pattern of feature search for the other stream, although overall accuracy would have been low for both search types because observers would miss the target when it appeared in the unattended stream. This prediction is inconsistent with the present results.

To conclude, the present results highlight the flexibility, as well as the limitations, of the attentional sets used to monitor for the appearance of targets presented among multiple, sequential nontarget items. Previous studies have primarily focused on whether two feature-based attentional sets can be concurrently established, whereas the present study was unique in addressing whether two different attentional control settings can be concurrently maintained. In other words, the central issue addressed by previous studies was the assignment of multiple features to multiple locations using the feature-search mode. The present study extended the domain of investigation beyond the scope of the feature-search mode by testing for the possibility of combining search modes, as well as examining the limits of multiple feature-search strategies. The visual system was found to be flexible enough to maintain attentional sets when observers detected two singletons at different locations. However, the results indicate that the observers were unable to apply the singleton-detection and the feature-search modes concurrently in the same visual display. The system was not capable of maintaining a mixture of singleton-detection and feature-search modes at different locations, as shown by the disruption of a clear pattern in the singleton-detection stream. We found set-specific capture (Ito & Kawahara, 2016; Moore & Weissman, 2010, 2011, 2014; Roper & Vecera, 2012) occurring in both singleton-detection and feature-search streams. The finding that the presence or absence of set-specific capture in the feature-search stream depends on the trial composition of distractor colours suggests that the entry of an attentional set into the focus of attention is not entirely automatic but is modulated by top-down control.

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Footnotes

1. We thank Katherine Moore for pointing out this possibility.

2. We thank Katherine Moore for these suggestions.

Table 1 Types of distractors and number of trials in Experiments 5-7.

	No distractor	Same colour	Different colour	
Experiment 5				
Feature search	60	Red 60[a]	Green 60[b]	
Singleton detection	60	60	60[c]	
Experiment 6				
Feature search	48	Red 24[d]	Non-red 72[e]	
Singleton detection	48	Non-red 48	Red 24[f]	Non-red 24[g]
Experiment 7				
Feature search	48	48	48	
Singleton detection	48	48	Non-red 48[h]	

See text for details about superscripts a-h.

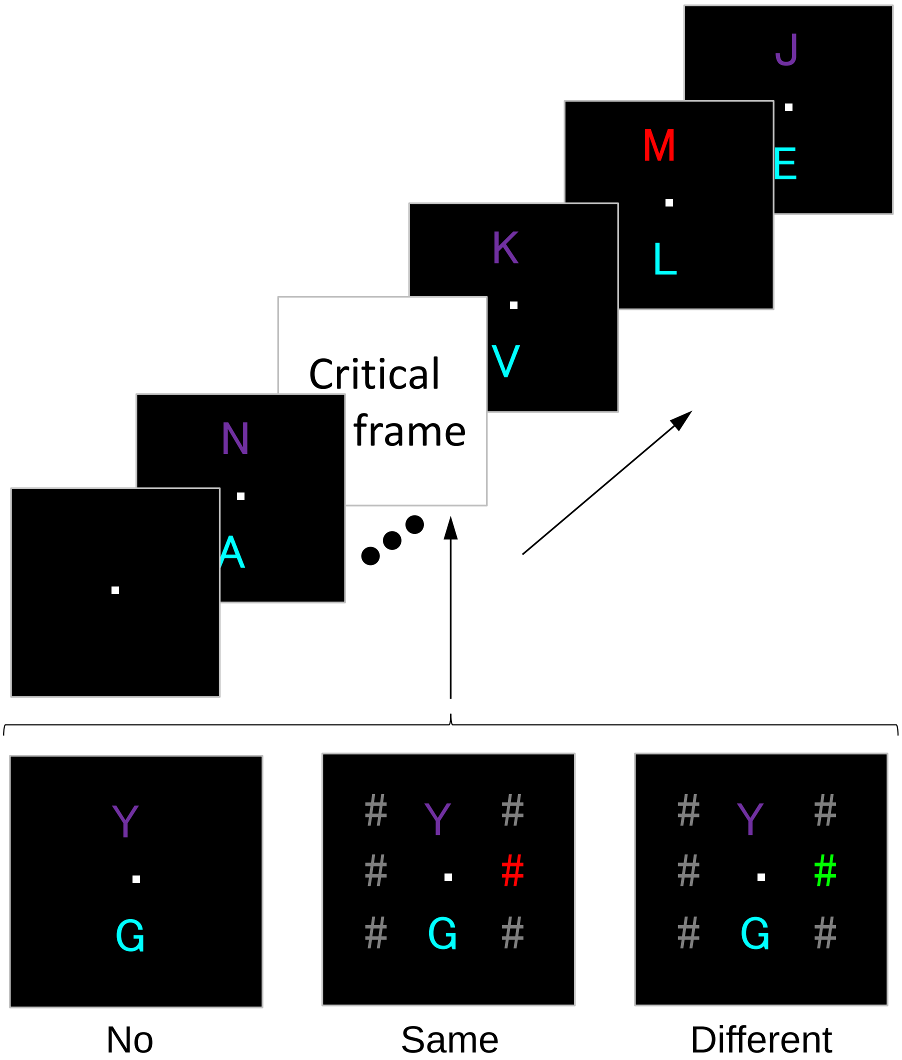

Figure 1. A schematic diagram of the stimulus sequence in Experiment 1. Participants were required to identify a color singleton (target) embedded in a rapid sequence of nontarget letters in homogenous colors. The SOA of the letter stream was 100ms and a distractor frame (if any) appeared 200ms before the target. A distractor # could appear either in the middle row of the left or right column of the distractor frame.

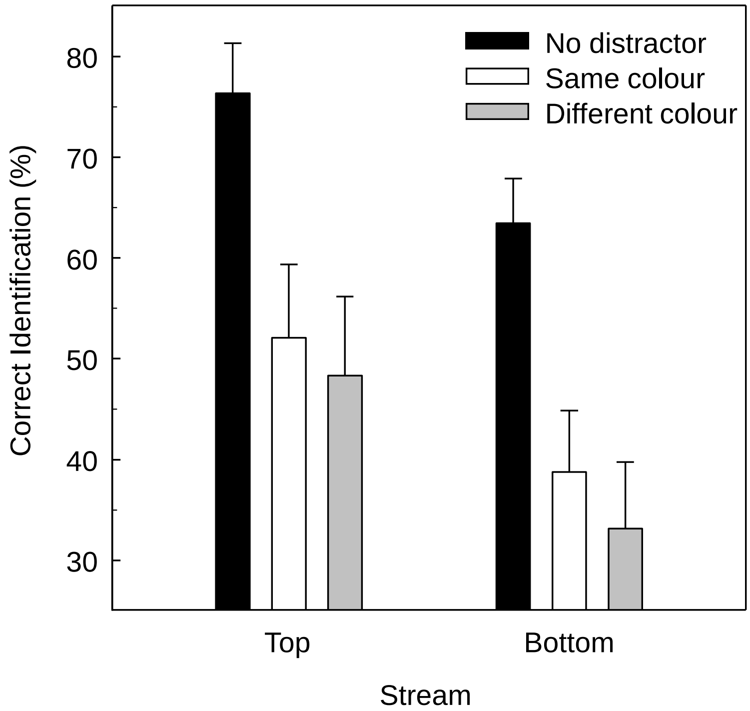

Figure 2. Mean percentages of correct responses as a function of distractor conditions in Experiment 1. Error bars indicate 95% confidence intervals.

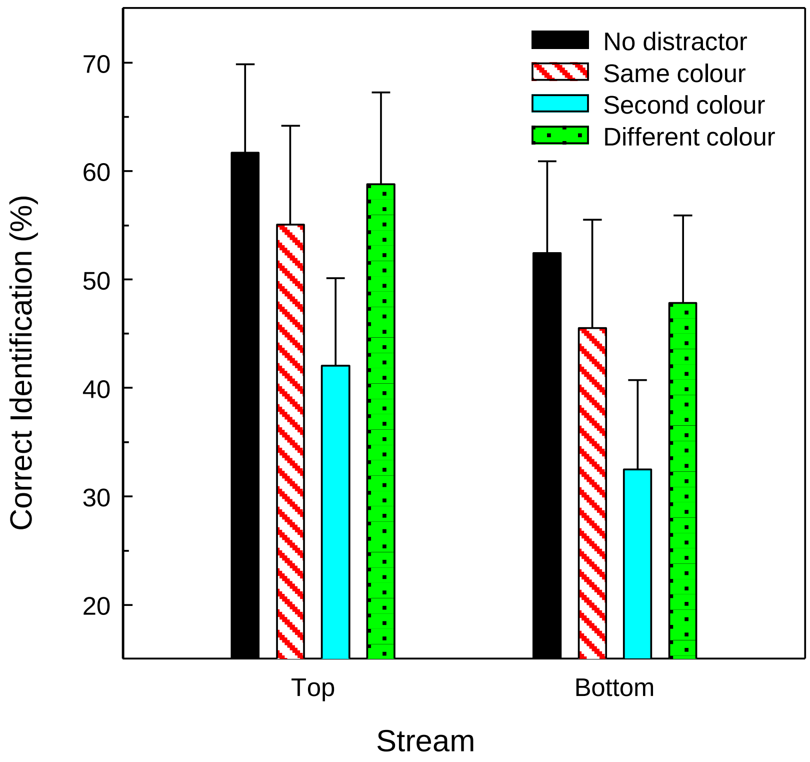

Figure 3. Mean percentages of correct responses as a function of distractor conditions in Experiment 2. Error bars indicate 95% confidence intervals.

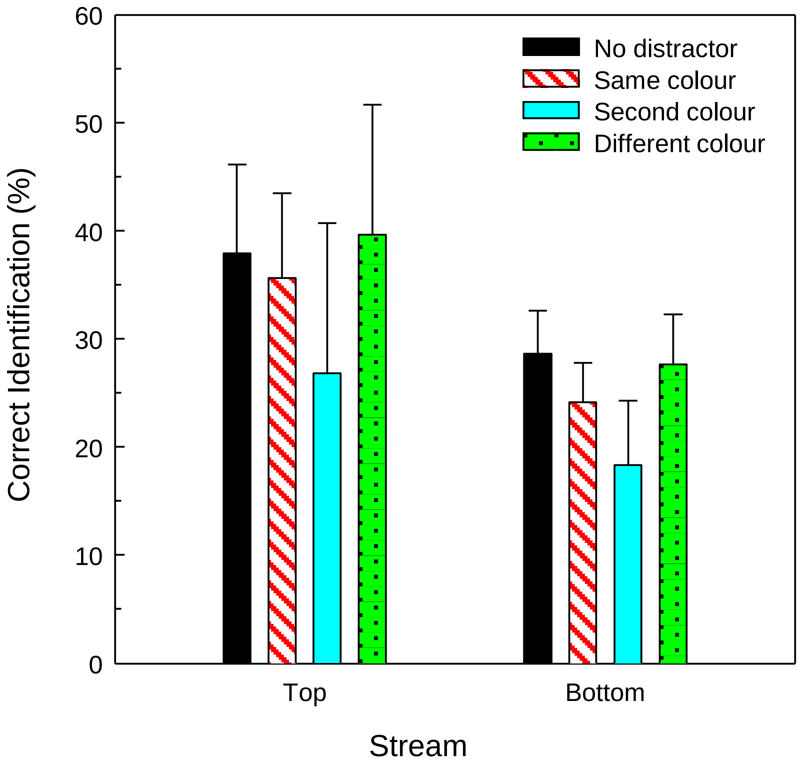

Figure 4. Mean percentages of correct responses as a function of distractor conditions in Experiment 3. Error bars indicate 95% confidence intervals.

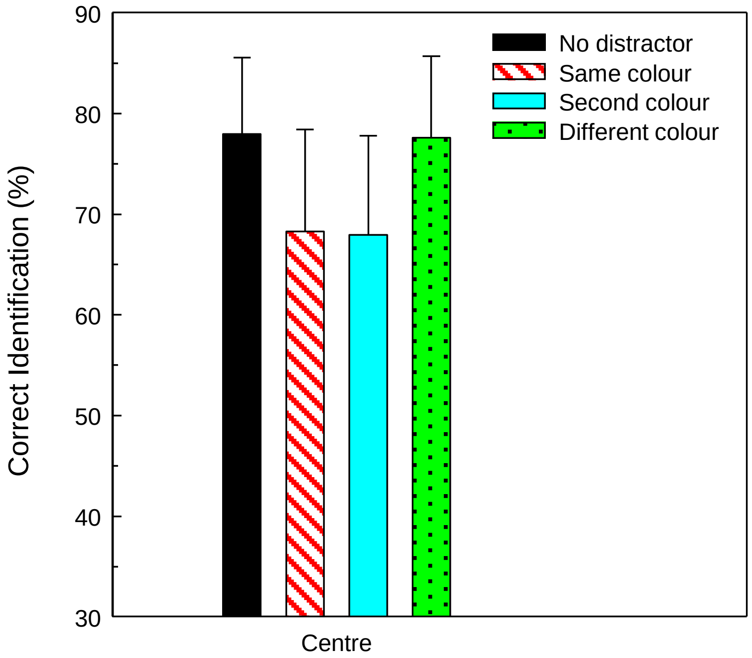

Figure 5. Mean percentages of correct responses as a function of distractor conditions in Experiment 4. Error bars indicate 95% confidence intervals.

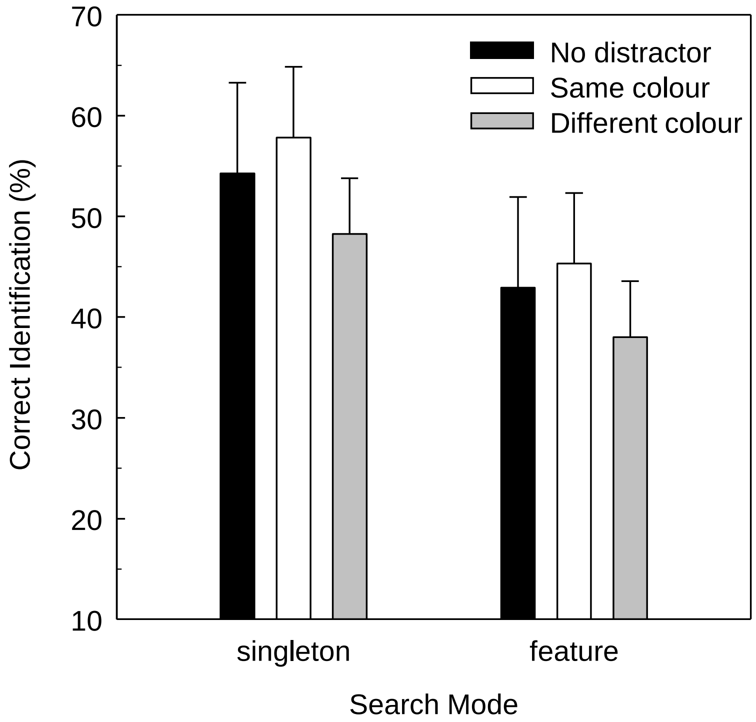

Figure 6. Mean percentages of correct responses as a function of distractor conditions in Experiment 5. Error bars indicate 95% confidence intervals.

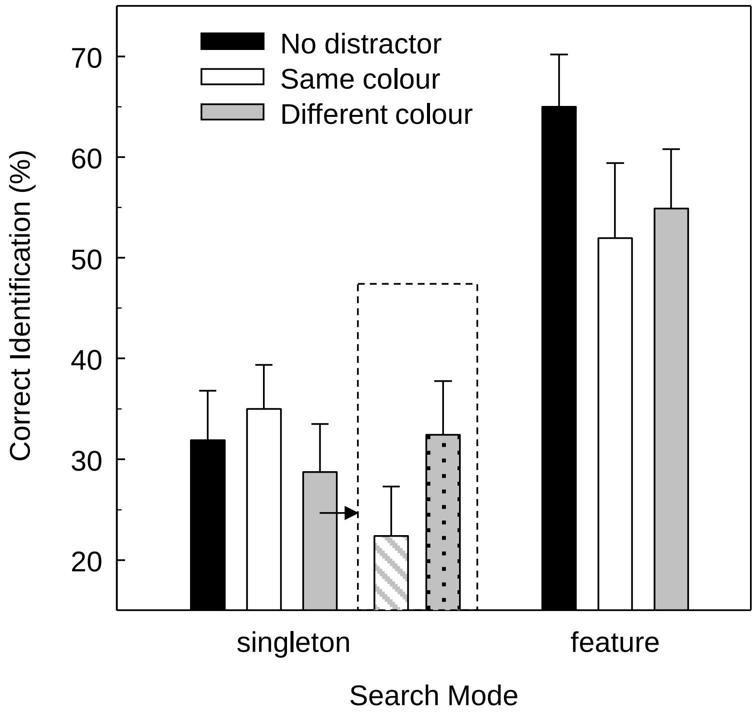

Figure 7. Mean percentages of correct responses as a function of distractor conditions in Experiment 6. Error bars indicate 95% confidence intervals. The inset within the dotted area represents the breakdown of the different colour condition into when the distractor was red (the hatched bar) or non-red colours (the dotted gray bar).

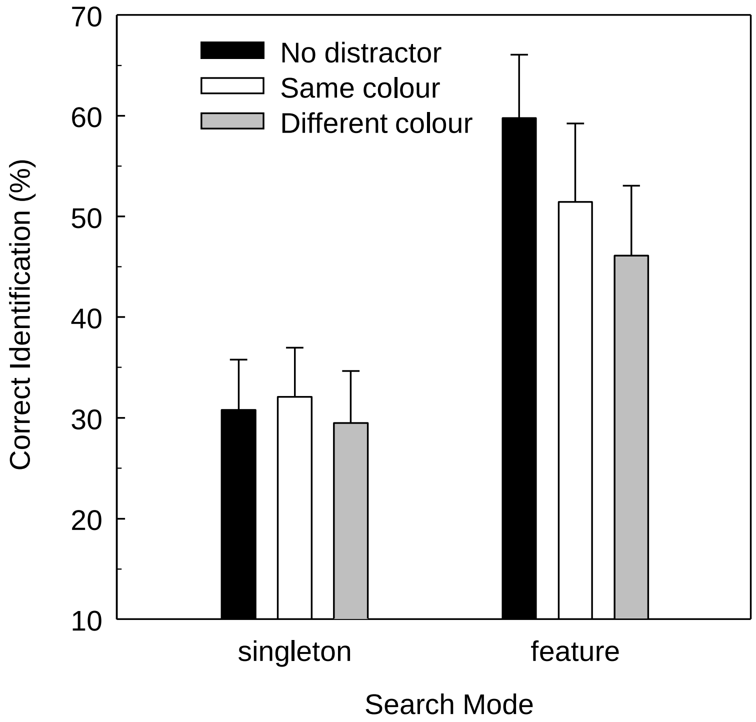

Figure 8. Mean percentages of correct responses as a function of distractor conditions in Experiment 7. Error bars indicate 95% confidence intervals.