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Contingent Capture Is Weakened in Search for Multiple Features From Different Dimensions

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Can observers maintain more than 1 attentional set and search for 2 features in parallel? Previous studies that relied on attentional capture by irrelevant distractors to answer this question focused on features from the same dimension and specifically, on color. They showed that 2 separate color templates can guide attention selectively and simultaneously. Here, the authors investigated attentional guidance by 2 features from different dimensions. In three spatial-cueing experiments, they compared contingent capture during single-set versus dual-set search. The results showed that attention was guided less efficiently by 2 features than by just 1. This impairment varied considerably across target-feature dimensions (color, size, shape and orientation). Confronted with previous studies, our findings suggest avenues for future research to determine whether impaired attentional guidance by multiple templates occurs only in cross-dimensional disjunctive search or also in within-dimension search. The present findings also showed that although performance improved when the target feature repeated on successive trials, a relevant-feature cue did not capture attention to a larger extent when its feature matched that of the previous target. These findings suggest that selection history cannot account for contingent capture and affects processes subsequent to target selection.

Public Significance Statement

Can we search for 2 things at once? Recent studies suggest that we can search for 2 different colors simultaneously, based on the finding that only objects matching these colors grab our attention. However, it remains possible that instead of maintaining 2 goals in parallel, observers in these studies alternated from 1 goal to the other. Here, the authors addressed this issue when observers searched for a target matching 1 of 2 features defined on different dimensions (color or shape, color or size, size or orientation). They found that although observers could search for 2 properties at a time, their search was less efficient and less selective than when they searched for only 1 object property. These findings thus reveal a structural limitation of our attentional system.

Keywords: selective attention, top-down control, attentional capture, spatial cueing, intertrial priming

Searching the environment is an essential part of our daily activities. Efficient search requires that observers construct a mental representation or search template of the relevant information and actively maintain it in working memory to guide their attention to candidate targets (e.g., Moore & Weissman, 2014; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). In most visual search experiments observers are required to search for a single target, while ignoring irrelevant distractors. However, real-world visual search often involves looking for more than one target at a time (e.g., searching for a tomato and a cucumber at the grocery store). Can simultaneous search for more than one feature be carried out efficiently?

On the one hand, given that the estimated capacity of visual working memory is three to four items (Cowan, 2001; Luck, 2008), it is reasonable to predict that observers can maintain more than one search template at a time. Accordingly, several studies have shown that simultaneous search for more than one feature is possible (e.g., Adamo, Pun, Pratt, & Ferber, 2008; Irons, Folk, & Remington, 2012) and incurs no cost (Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2016; Moore & Weissman, 2010). On the other hand, it has been suggested that not all visual working memory representations enjoy the same status and that only a single representation can be held fully active at any moment (McElree, 2001; Oberauer, 2002) and guide attention (Olivers et al., 2011). In line with this view, a different group of studies has shown that search performance is impaired when observers search for a target defined by two possible features relative to just one (e.g., Dombrowe, Donk, & Olivers, 2011; Houtkamp & Roelfsema, 2009; Menneer, Barrett, Phillips, Donnelly, & Cave, 2007;

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Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; Stroud, Menneer, Cave, & Donnelly, 2012; see Olivers et al., 2011 for review).

The various studies that investigated attentional guidance by multiple search templates differ on the primary measure they used to probe the efficacy of attentional guidance. Some compared overall performance and eye movements to distractors during search for two possible features versus search for just one feature, whereas others focused on the pattern of attentional capture by irrelevant cues during dual-set search.

Overall Performance and Eye Movements During Dual-Set Search

Poorer performance (lower accuracy, higher reaction times [RTs] or more frequent eye movements to distractors) in single- relative to dual-set search is taken to indicate that only a single feature at a time can efficiently guide attention. For instance, Houtkamp and Roelfsema (2009) had observers search for a target defined by one of two features in a rapid stream of colored objects, with either a single target or none appearing on each trial. Target detection accuracy rates were lower than in control single-search conditions. The data best fitted a model assuming one search template, suggesting that no more than one target template can actively guide search. In a similar vein, Menneer et al. (2007) used a staircase procedure to adjust the exposure time required to detect the target at a fixed level of accuracy in a spatial search task. They showed that search for one of two possible targets required longer exposure times than search for only one of the targets. They concluded that search can be guided by only one target template at a time.

However, these findings are not necessarily incompatible with the notion that two target templates can guide attention in parallel. At this point it may be helpful to distinguish between two separate stages in which templates stored in working memory play a role during search: (a) an early preselection stage, during which search templates guide attention toward the location of a potential target and which is the focus of the present study, and (b) a later postselection stage, during which the selected item is matched to the search templates. As acknowledged by Houtkamp and Roelfsema (2009), in their experiments the items were presented one by one, so that the first selection step was unnecessary. Likewise, the longer exposure times required to detect the target during dual- relative to single-set search in Menneer et al.'s (2007) study may index an impairment in attentional guidance, in postselective processes or in both.

However, evidence from eye-movement studies (e.g., Menneer et al., 2012; Stroud et al., 2012) provides more direct support for the notion that attentional guidance is impaired during dual-set search. For instance, Stroud et al. (2012) showed that simultaneous search for two colors produces a dual-target cost that manifests in more fixations on distractors dissimilar to both possible targets. The authors interpreted this pattern of results as indicating that two separate colors can guide search simultaneously, but less efficiently so than just one. However, also relying on eye movements during visual search, Beck et al. (2012) demonstrated that, depending on the instructions, observers are able to search for two targets either simultaneously and at no cost or successively with switching costs. They speculated that previous findings suggesting that attention cannot be guided by more than one search template at a time might have resulted from failures to induce observers to use two templates simultaneously.

Attentional Capture During Dual-Set Search

The studies reviewed above showed that searching for two possible targets simultaneously (henceforth, dual-set search) incurs a cost—yet most of the findings (but not all) were compatible with the notion that this cost emerged at postselection stages. Studies that relied on the pattern of attentional capture during dual-set search can provide a more specific test of the effects of dual-set search on attentional guidance. These studies converged on the conclusion that attention can be guided in parallel by two templates.

The rationale of these studies (pioneered by Adamo et al., 2008)[1] capitalizes on the finding that attentional capture is contingent on attentional control settings (Folk, Remington, & Johnston, 1992). In a typical contingent-capture experiment, observers search for a known target among distractors, following a cue display in which one item (the cue) has a unique feature that either matches the search template (relevant-feature cue) or does not (irrelevant-feature cue), and the location of which is uncorrelated with the target location. Attentional capture by the cue is indexed as shorter RTs when the target appears at the same versus at a different location relative to the cue. Contingent capture refers to the finding that relevant-feature cues capture attention, whereas irrelevant-feature cues can be successfully ignored. Accordingly, to demonstrate that two search templates can guide attention simultaneously, one must show that cues matching one of the two possible target features capture attention, whereas cues not matching either target feature do not.

Using this rationale, Irons et al. (2012) had observers search for a target that could appear in one of two colors inside one of four placeholders. A spatially nonpredictive cue preceded the target display. When the target appeared among gray distractors and was therefore a color singleton (Exp.1, see also Folk & Anderson, 2010; Harris, Becker, & Remington, 2015), both relevant- and irrelevant-color cues captured attention. This finding is consistent with the idea that observers adopted a search template for color singletons in general (i.e., singleton-detection mode, Bacon & Egeth, 1994). Crucially, however, when the target appeared among heterogeneously colored distractors (Experiments 2–5), thereby forcing observers to adopt a set for specific features (i.e., feature-search mode, Bacon & Egeth, 1994), contingent capture emerged: Cues matching one of the two search sets captured attention, whereas cues not matching either set did not.

Roper and Vecera (2012, Experiment 3) further demonstrated that observers can establish an attentional set for two different features that vary on a trial-by-trial basis. Observers searched for a target defined by its color in a central stream of letters and

[1] Adamo et al. (2008) had observers perform a disjunctive search for two color-location conjunctions rather than for two features. Their study is therefore less relevant to the issue at hand. In addition, an alternative interpretation of their findings was possible, according to which cues captured spatial attention to the same extent whether or not their color matched the target template for that location, and the color match affected performance only after attention had been summoned to the cue location. This alternative account was confirmed by the results of a follow-up EEG study by the same group (Adamo, Pun, & Ferber, 2010).

reported its identity. A display including a peripheral color singleton appeared 175 ms before the target. Under such conditions, the appearance of a peripheral distractor is known to disrupt target detection, a phenomenon akin to the "attentional blink" (Folk, Leber, & Egeth, 2002; Raymond, Shapiro, & Arnell, 1992). Importantly, there were three potential target colors but only two of these three colors were designated as potential targets on any given trial. The peripheral distractor captured attention when it was in a cued color, but not when it was in the uncued color, even though this color was a potential task-relevant color on other trials.

The findings reported by Irons et al. (2012) and by Roper and Vecera (2012) indicated that attention was selectively guided by two search templates. However, they do not provide unambiguous evidence that these templates were used simultaneously. Instead, observers might alternate back and forth between the two sets, practically holding only one template at a time, such that any relevant-feature cue would match the currently activated template only on half of trials. This alternative account can be ruled out by comparing the magnitude of contingent capture during single- versus dual-set search. If two search templates can guide search simultaneously, attentional capture should be similar in the two search types.

Grubert and Eimer (2016) recently performed this comparison. In addition to collecting behavioral data, they used the N2pc component (an enhanced negativity observed in the N2 range over posterior scalp electrodes contralateral to the side of an attended stimulus) as a temporal marker for the allocation of attention in visual space (see Eimer, 1996, 1998). They found attentional capture, indexed by both faster RTs and a significant N2pc component, to occur only with cues matching a target feature and not with irrelevant-feature cues. Most critically for the present purposes, such contingent capture was of similar magnitude whether observers searched for one or two possible targets. Grubert and Eimer (2016) concluded that attention can be guided in parallel by two features. They nevertheless also reported poorer overall performance in dual- relative to single-set search (i.e., slower RTs and lower accuracy).

Moore and Weissman (2010) reported compatible findings during temporal search. They compared the magnitude of the attentional blink associated with a peripheral distractor matching a potential target color, when the target was defined by two possible colors versus just one. They found the effects of a relevant-color distractor to be similar in the two search conditions and concluded that participants were able to maintain one and two attentional sets equally well. The authors' main interest was in the finding that during dual-set search, target identification was enhanced when the distractor that preceded the target shared its color relative to when it took on the alternative target color. Based on these and additional findings (Moore & Weissman, 2014), they concluded that multiple attentional sets can be maintained in memory during active search and facilitate the detection of potential targets by boosting the signals of incoming stimuli that possess the target-defining attributes.[2] They further suggested that processing a distractor matching the target color causes this distractor's feature to enter the focus of attention in working memory (the capacity of which is limited to just one item; Oberauer, 2002) and to enhance target identification.

Search for Two Features From Different Dimensions

The findings reviewed above emanated from studies that focused on search for the disjunction of two features within the same dimension, and most often on search for the disjunction of two colors. Thus, the question arises of whether similar findings are observed during search for the disjunction of two features from different dimensions. The main objective of the present study was to address this issue.

It is usually assumed that a search is more difficult for targets defined by two features from the same dimension than from different dimensions (e.g., Grubert & Eimer, 2016; Houtkamp & Roelfsema, 2009; Irons et al., 2012). This claim relies on two main findings. On the one hand, Wolfe and colleagues (Wolfe, Cave, & Franzel, 1989; Wolfe, Yu, Stewart, Shorter, Friedman-Hill, & Cave, 1990) showed that search for a conjunction of two cross-dimensional features (e.g., color and form) can be parallel and more efficient than search for a conjunction of features from the same dimension (e.g., color and color). However, findings pertaining to conjunction search need not apply to disjunctive search, in which the target (defined by one feature) does not benefit from the joint activation of the two search templates.

On the other hand, a seminal study by Treisman and Gelade (1980) demonstrated that although cross-dimensional conjunction search is serial, cross-dimensional disjunction search is parallel. However, it is important to note that in the latter condition, the target was always a singleton on either the color or the shape dimension and could therefore pop out: observers searched for either the color blue or the letter S among green Ts and brown Xs. Thus, observers could search for a singleton in each display instead of maintaining a dual search template, which would explain the flat search slopes observed in that experiment.

By contrast, the dimension-weighting account proposed by Müller and colleagues (e.g., Müller & Krummenacher, 2006) suggests that holding two target templates from different featural dimensions may in fact be more difficult than when these templates belong to the same dimension. Specifically, this model posits that there is a limit to the total attentional weight available to be allocated at any one time to the various dimensions of the target object. It further suggests that potential target-defining dimensions are assigned weights as a function of their importance and of recent attentional allocation history and that weight assignment

[2] In previous spatial-cueing studies (Grubert & Eimer, 2016; Irons et al., 2012) the analysis of spatial capture in the dual-set search condition included a distinction between match and nonmatch relevant-feature cues. For example, in search for either a red target or a circle target, the cue-target sequence "red cue, red target" is an instance of a match relevant-feature cue, whereas "circle cue, red target" is an instance of a nonmatch relevant-feature cue. Moore and Weissman (2010, 2014) reported that target identification is enhanced on match- relative to nonmatch trials and suggested that such set enhancement does not affect attentional guidance but a later stage of target identification. Irons et al. (2012) and Grubert and Eimer (2016) replicated this set enhancement effect and set out to test whether it reflects stronger attentional guidance to the target or the operation of later processes, independent of attention. They supported the latter hypothesis based on the finding that set enhancement did not interact with attentional capture. However, note that as set enhancement occurs *after* the cue has captured attention, it could not possibly enhance the ability of this cue to capture attention. Thus, as set enhancement is unrelated to attentional capture, which is our main interest here, we did not report the analysis of this effect in our results (but see footnote #5).

biases attentional guidance at the pre-attentive stage. Although the dimension-weighting account relies exclusively on findings from cross-dimensional singleton search, it follows from its premises that an attentional set for two features from different dimensions should be less effective in guiding attention than an attentional set for just one feature, because in the former case, the total available weight must be divided between the two dimensions.

Very few studies directly examined the potential costs of simultaneous attentional guidance by two features from different dimensions.[3] Houtkamp and Roelfsema (2009; Experiment 3) observed a dual-target cost in search for either a color or a shape using an RSVP paradigm. However, as for their findings during search for two features within the same dimension (Experiments 1 and 2), this cost may reflect a bottleneck in matching the selected input to search templates stored in working memory. Therefore, it does not necessarily index weaker attentional guidance by two templates relative to just one.

The Present Study

The main objective of the present study was to determine whether two features from different dimensions can simultaneously and selectively guide attention. We addressed this question by comparing contingent attentional capture in dual-set versus single-set search, because this experimental strategy allows one to directly measure potentially deleterious effects of holding two versus one search templates on the selectivity of attentional guidance. If simultaneous guidance by two search templates from different dimensions is as efficient as attentional guidance by just one template, attentional capture should be of the same magnitude in the two search conditions. If only one search template can be applied at a time, this effect should be reduced by about half in dual-set relative to single-set search (because any relevant-feature cue would match the currently activated template only on half of trials).

Observers carried out three tasks in separate experimental blocks: a dual search for the disjunction of two features from different dimensions (color or shape in Experiment 1, color or size in Experiment 2, and size or orientation in Experiment 3) and two single-search tasks (one for each feature). In all conditions, targets appeared among heterogeneous distractors from the same dimension, such that observers had to adopt feature-search mode (Bacon & Egeth, 1994). Cue displays included relevant- and irrelevant-feature cues from the two dimensions (see Figures 1 and 4). Our design involved identical cueing and target displays in all three search types. Thus, the experimental blocks differed only in task demands, which allowed a direct comparison between single and dual search. We expected to observe contingent capture in all search conditions, that is, attentional capture from relevant-feature cues and not from irrelevant-feature cues. Our main interest was in assessing whether such selective guidance by two search templates would prove to be simultaneous, that is, whether the magnitude of attentional capture would be similar in the single- and dual-search tasks.

Data Analyses and Predictions

In all RTs analyses, we used a log transformation to reduce positive skew and to discount the effects of the large overall RT differences between conditions of target dimension (e.g., color vs. shape) and search types (single-set vs. dual-set).

Contingent capture during single-set search. In a first analysis, we verified that contingent capture occurred during single-set search, as has been reported in many previous studies (e.g., Folk et al., 1992). We also verified that irrelevant-feature cues could be ignored to the same extent whether they were singletons in the target-defining dimension or in the alternative dimension. Thus, for instance, in single-set search for a red target, only red cues should capture attention, and a green cue should be ignored as efficiently as a circle- or a diamond-shaped cue.

Comparison of contingent capture in single- versus dual-set search. Then, we moved on to our main analysis, in which we compared contingent capture during single- versus dual-set search. In this analysis, we excluded trials in which the irrelevant-feature cue in the single-set condition was a potential target in the dual-set condition. Such exclusion was necessary to equate the type of irrelevant-feature cues entered in each search-type condition. Consider the case in which a given participant searched only for a circle target and only for a red target in the single-search conditions and for either a red target or a circle target in the dual-set condition. The irrelevant-feature cues included only diamond and green cues in the dual-set search condition, whereas in the single-set condition they also included circle cues in the color search and red cues in the shape search. Thus, for this participant for example, we had to exclude red-cue trials from shape-search data and circle cues from color-search data. Therefore, as the data from the single-set conditions were pooled in this comparison, both the relevant- and irrelevant-cue conditions included two features in the single- and dual-set conditions.

Intertrial priming. Finally, we conducted two analyses of intertrial priming. First, we measured the benefit of searching for a target during the dual-set search when it repeated from the previous trial relative to when it switched from the alternative target. We expected to replicate the well-documented benefit of intertrial repetitions of the target feature (e.g., Maljkovic & Nakayama, 1994) and dimension (e.g., Found & Muller, 1996)—which were confounded in our study. In line with previous findings (e.g., Grubert & Eimer, 2016; Houtkamp & Roelfsema, 2009; Menneer et al., 2007), we also expected to observe an overall dual-search performance cost, namely, overall slower RTs and lower accuracy in the dual- versus single-search tasks. We first established this cost and then examined to what extent it could be accounted for by larger intertrial target repetition benefits in single-set search (in which the target repeats on every trial) relative to dual-set search (in which the target feature switches unpredictably from trial to trial).

The second intertrial priming analysis examined whether a match between the target on the previous trial and the cue on the current trial modulated the magnitude of attentional capture by this cue. This analysis allowed us to assess the role of intertrial priming in contingent capture. Several authors have suggested that intertrial priming effects account for contingent capture effects, without the need to

[3] Adamo, Wozny, Pratt, and Ferber (2010) had participants respond to one of two colors when they appeared on one side of the screen and to one of two shapes when they appeared on the opposite side, and to withhold responses to other items. They reported contingent capture, yet the observations described in footnote 1 relative to Adamo et al.'s (2008) study also applies to this study.

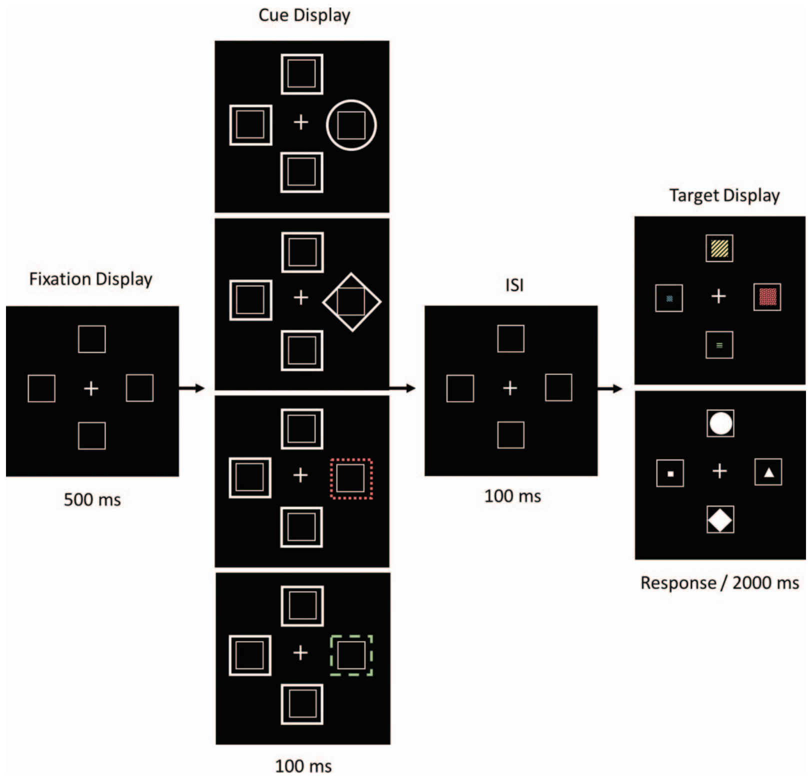

Figure 1. Sequence of events in Experiment 1. The cue was either a color singleton (red [dotted-line frame] or green [dashed-line frame]) or a shape singleton (circle or diamond). In color search, the target was defined by its color (e.g., red [dotted surface]) among three distractors with different colors. In shape search, the target was defined by its shape (e.g., diamond) among three distractors with different shapes. Observers searched for only a specific color in single color-set blocks, for only a specific shape in single shape-set blocks and for either a specific color or a specific shape in the dual-set blocks. In the relevant-cue condition, the unique feature of the cue matched the target feature in the single-search conditions and matched one of the two possible target features in the dual-search condition. In the irrelevant-cue condition, there was no match. See the online article for the color version of this figure.

postulate a role for top-down guidance. For instance, Belopolsky, Schreij, and Theeuwes (2010) noted that the target feature is typically fixed across trials in contingent-capture studies and, therefore, relevant-feature cues always benefit from feature priming from the target on the previous trial whereas irrelevant-feature cues never do. These authors thus suggested that the larger spatial effects elicited by relevant-feature relative to irrelevant-feature cues result from automatic, bottom-up priming from the target feature on the previous trial to the cue feature on the current trial. Although further studies have provided very limited support for this claim (see Lamy & Kristjansson, 2013, for review), the dual-search condition allowed us to compare attentional capture by a relevant cue when this cue matched the previous target relative to when it did not.

Beyond shedding light on the role of intertrial priming on contingent capture, these analyses can also answer important questions with regard to the mechanisms underlying intertrial priming. Several authors posit that intertrial priming enhances the attentional priority of objects possessing a recently attended feature (e.g., Awh, Belopolsky, & Theeuwes, 2012; Becker & Horstmann, 2009; Maljkovic & Nakayama, 1994) or of objects that are salient in a recently attended dimension (e.g., Found & Muller, 1996; Muller & Krummenacher, 2006). Accordingly, these authors predict that a cue should capture attention more strongly if it shares the search-relevant feature or dimension of the target on the previous trial than if it does not. Other authors challenge this claim and suggest that intertrial priming does not affect attentional priority but processes that occur after a candidate target has been detected (e.g., Amunts, Yashar, & Lamy, 2014; Irons et al., 2012; Yashar & Lamy, 2010; Yashar, White, Fang, & Carrasco, 2016). According to this view, responses to the target should be faster if it shares the previous target's feature or dimension but attentional capture by a cue should not be modulated by this cue's match with the previous target's feature or dimension. Preliminary analyses showed that for all experiments, target-cue dimension priming did not occur with irrelevant-feature cues, indicating that attending to a target dimension on trial $n - 1$ did not increase capture by an irrelevant-feature cue in the same dimension on trial *n*. Thus, target-cue priming analyses are reported only for relevant-cue trials.

Experiment 1

Method

Participants. Twenty Tel-Aviv University students (seven females, mean age = 25.7, *SD* = 1.5) volunteered to take part in

Experiment 1. All participants reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus. Stimuli were presented in a dimly lit room on a LCD monitor (23" ASUS SyncMaster) with 1,920 × 1,080 resolution and 120 Hz refresh rate. Responses were collected via the computer keyboard. A chin-rest was used to set viewing distance at 50 cm from the monitor.

Stimuli. The sequence of events is illustrated in Figure 1. Each trial consisted of a fixation display, followed by a cue display, an interstimulus display and a target display. The fixation display contained a 0.5° fixation cross in the center of the screen surrounded by four peripheral boxes (1.2° in side) that appeared at cardinal positions at a center-to-center distance of 3° from fixation. The boxes were drawn in a white 1-pixel thick stroke (RGB = 255,255,255) against a black background.

In the cue display, a larger and thicker (3-pixel) frame was added around each box. Three of these frames were white squares (2° in side). The remaining frame could be a faint red square (RGB = 206,44,49), a faint green square (RGB = 74,162,49), a white diamond (2.82° in height and width) or a white circle (1.2° in radius). The interstimulus display was identical to the fixation display. In the target display, a shape appeared inside each of the four boxes. Two shapes were small and two were large. In the color-search condition, the shapes were four filled squares (small: 0.36° × 0.36°, large: 0.8° × 0.8°) each of a different color: red (RGB = 206,44,49), green (RGB = 74,162,49), blue (RGB = 0,105,156), and yellow (RGB = 206,178,57). In the shape-search condition, the shapes were all white but each had a different form: a triangle (small: 0.23° in side, large: 0.45° in side), a circle (small: 0.23° in radius, large: 0.45° in radius), a diamond (small: 0.45° × 0.45°, large: 1° × 1°) and a square (small: 0.36° × 0.36°, large: 0.8° × 0.8°).

Procedure. On each trial, the fixation display appeared for 500 ms. The cue display immediately followed for 100 ms. The target display appeared after an interstimulus interval of 100 ms and remained visible for 2,000 ms or until response, whichever came first. Each participant underwent two single-set conditions and one dual-set condition. In the single color-set condition, the target was defined by its specific color (red or green, between participants) and in the single shape-set condition it was defined by its specific form (diamond or circle, between participants). In the dual-set condition, the task was a disjunctive search for the same specific color or shape as in the single-set conditions (red or circle, green or circle, red or diamond, or green or diamond, between participants). Accordingly, all target displays were color-target displays in the single color-set condition, shape-target displays in the single shape-set condition and randomly either color-target or shape-target displays in the dual-set condition. Subjects were asked to respond to the target's size by pressing "4" if it was large and "0" if it was small, using their middle and index fingers, respectively, on the numerical keypad. Error trials were followed by a 500-ms beep. If the participant did not respond within 2,000 ms, an error beep was sounded and a new trial began.

Design. The experiment consisted of a 20-trial practice block, followed by 1,024 experimental trials divided into eight blocks: two single color-set blocks, two single shape-set blocks, and four dual-set blocks. Each participant underwent all three search-type conditions with a fixed feature per dimension, which was randomly assigned and counterbalanced between participants. The single-set conditions always occurred one after the other. Their order was counterbalanced across participants and so was the order of the search-type conditions (single vs. dual).

The four possible cue types (red, green, diamond, circle) were equiprobable and randomly mixed within each block of trials, such that all three search-type conditions involved the same cue displays. In both single-set conditions, there was one relevant cue, which matched the feature of the target, and three irrelevant cues. Thus, for instance, if the target was defined as the red item, the red cue was relevant and the green, circle and diamond cues were irrelevant. In the dual-set condition, there were two relevant cues, which matched the two target-defining features, and two irrelevant cues. Thus, for instance, if the target was defined as either the green item or the circle, green and circle cues were relevant (irrespective of which was the actual target on a given trial) and red and diamond cues were irrelevant.

The cue and target locations were randomly assigned, such that the cue appeared at the same location as the target on 25% of the trials and at a different location on 75% of the trials.

The design included six within-participant variables: target type (color vs. shape), cue type (color vs. shape), search type (single-set vs. dual-set), cue relevance (relevant vs. irrelevant), and cue location (same vs. different, relative to the target), and four between-participants variables: search type order (single first vs. dual first), single-set order (color first vs. shape first), target color (red vs. green), and target shape (circle vs. diamond).

Results and Discussion

All RT analyses were conducted on correct trials (96.3% of all trials). Preliminary analyses indicated that none of the between-participants variables interacted with any of the effects of interest (i.e., cue location or its interaction with search type and/or cue relevance). The data were therefore collapsed across all four between-participants variables. We nevertheless present the data as a function of the order to search-type condition (single-set first vs. second) in Table 1. It was not possible to enter target dimension, cue dimension and cue relevance in the same analysis because the task determined the crossing between the other two variables. As our main interest was in contingent capture, that is, in the ability of a cue to capture attention depending on its match with the target template(s) in the single- relative to the dual-set condition, cue dimension (but not target dimension) and cue relevance were entered as factors in the following analyses.

Contingent capture in the single-set condition. We conducted a three-way analysis of variance (ANOVA) with cue dimension (color vs. shape), cue relevance (relevant vs. irrelevant same-dimension vs. irrelevant different-dimension) and cue location (same vs. different, relative to the target) as within-participant variables. Mean RTs and accuracy data are presented in Table 2.

Reaction times. The main effects of cue location and cue dimension were significant, indicating that RTs were faster on same- than on different-location trials, $F(1, 19) = 4.83$, $p = .04$, $\eta_p^2 = .20$, and on color- than on shape-cue trials, $F(1, 19) = 48.44$,

Table 1
Mean Location Effect and Standard Deviation of the Reaction Times (RTs; Milliseconds) and Accuracy Rates (%) in Experiments 1–3 as a Function of Search-Type Order (Single-Search First vs. Dual-Search First), Search Type, and Cue Relevance

			Single set		Dual set	
Experiment and order	Cue type	Cue relevance	RT	Accuracy	RT	Accuracy
Experiment 1						
Single-set first	Color	Relevant	33 (40)	.6 (3.8)	36 (41)	1.4 (4.2)
		Irrelevant	9 (33)	.4 (3.6)	27 (25)	−.5 (2.8)
	Shape	Relevant	9 (59)	.0 (3.2)	−1 (27)	−.3 (2.6)
		Irrelevant	−10 (52)	−2.2 (3.9)	−19 (33)	−1.0 (2.2)
Dual-set first	Color	Relevant	41 (36)	−.4 (4.4)	32 (64)	−3.3 (4.0)
		Irrelevant	16 (33)	−3.1 (2.2)	18 (64)	−4.3 (5.2)
	Shape	Relevant	31 (51)	−1.9 (3.7)	4 (33)	1.4 (3.3)
		Irrelevant	−5 (28)	2.7 (4.4)	−6 (41)	1.5 (5.0)
Experiment 2						
Single-set first	Color	Relevant	81 (51)	−2.6 (5.9)	74 (51)	1.6 (3.9)
		Irrelevant	−5 (39)	.3 (6.7)	27 (30)	1.6 (4.6)
	Size	Relevant	43 (42)	3.1 (9.9)	32 (30)	−2.1 (1.9)
		Irrelevant	−16 (19)	−2.3 (5.7)	−22 (59)	−.3 (3.2)
Dual-set first	Color	Relevant	30 (71)	.5 (5.3)	44 (45)	−2.6 (3.4)
		Irrelevant	−7 (37)	−.4 (3.7)	−7 (43)	−2.2 (2.8)
	Size	Relevant	49 (47)	−1.0 (5.8)	25 (39)	.8 (8.9)
		Irrelevant	−5 (37)	.1 (3.4)	17 (50)	−1.4 (3.1)
Experiment 3						
Single-set first	Orientation	Relevant	26 (41)	−1.2 (8.9)	−2 (38)	.9 (3.5)
		Irrelevant	−16 (47)	−.6 (3.5)	50 (48)	.1 (5.3)
	Size	Relevant	40 (89)	−1.8 (3.2)	43 (48)	−1.2 (3.0)
		Irrelevant	30 (56)	.7 (3.6)	−16 (43)	1.0 (3.1)
Dual-set first	Orientation	Relevant	41 (72)	−2.1 (5.8)	−12 (34)	−1.2 (4.8)
		Irrelevant	−23 (43)	−.7 (3.5)	17 (46)	1.7 (3.2)
	Size	Relevant	47 (32)	1.8 (4.2)	40 (33)	−1.8 (4.6)
		Irrelevant	16 (42)	.8 (3.4)	8 (36)	2.2 (5.9)

Note. The location effect was calculated as the mean performance on different-location trials minus the mean performance on same-location trials for RTs, and vice versa for accuracy.

$p < .0001$, $\eta_p^2 = .71$. The interaction between cue location and cue relevance, which indexes contingent capture, was highly significant, $F(2, 38) = 10.39$, $p = .0003$, $\eta_p^2 = .35$. Paired comparisons indicated that relevant-feature cues captured attention, $F(1, 19) = 25.80$, $p < .0001$, $\eta_p^2 = .58$, whereas irrelevant-feature cues did not, $F < 1$. In addition, there was no significant difference in the location effect associated with irrelevant-feature cues within versus outside the target dimension, $F < 1$. The three-way interaction between cue location, cue relevance and cue dimension was not significant, $F(2, 38) = 1.24$, $p = .38$, $\eta_p^2 = .06$. Separate comparisons confirmed that contingent capture was significant for both color cues, $F(1, 19) = 19.60$, $p = .0003$, $\eta_p^2 = .50$, and shape cues, $F(1, 19) = 4.48$, $p = .05$, $\eta_p^2 = .19$.

Accuracy. Only the three-way interaction approached significance, $F(2, 38) = 2.53$, $p = .09$, $\eta_p^2 = .12$. Follow-up analyses indicated that on the accuracy measure, contingent capture was significant for shape cues, $F(1, 19) = 5.14$, $p = .04$, $\eta_p^2 = .22$, but not for color cues, $F < 1$.

Contingent capture in single-set versus dual-set search. We conducted a four-way ANOVA with search type (single-set vs. dual-set), cue dimension color versus shape), cue relevance (relevant vs. irrelevant) and cue location (same vs. different, relative to the target) as within-participant variables. Trials of the single-set conditions in which the cue had a feature that served as a target feature in the dual-set condition were excluded from this analysis (see the *Data Analysis and Predictions* section for a detailed explanation of the rationale for this exclusion). Mean RTs and accuracy data are presented in Table 3. Mean location effects are presented in Figure 2.

Reaction times. Reaction times were faster in the single-set than in the dual-set condition, $F(1, 19) = 17.43$, $p = .0005$, $\eta_p^2 = .48$, on same-location relative to different-location trials, $F(1, 19) = 16.95$, $p = .0006$, $\eta_p^2 = .47$, and with color cues than with shape cues, $F(1, 19) = 44.63$, $p < .0001$, $\eta_p^2 = .70$. The interaction between cue dimension and cue location was also significant, $F(1, 19) = 14.96$, $p = .001$, $\eta_p^2 = .44$, indicating that capture by color cues was stronger than capture by shape cues.[4] The interaction between cue location and cue relevance, which reflects contingent

[4] The interactions between cue dimension and cue relevance, and between search type and cue dimension were both significant and modulated by a three-way interaction between cue dimension, cue relevance and search type, $F(1, 19) = 44.51$, $p < .0001$, $\eta_p^2 = .70$, $F(1, 19) = 66.65$, $p < .0001$, $\eta_p^2 = .78$, $F(1, 19) = 51.56$, $p < .0001$, $\eta_p^2 = .73$, respectively in Experiment 1, $F(1, 15) = 5.48$, $p = .03$, $\eta_p^2 = .27$, $F(1, 15) = 15.12$, $p = .002$, $\eta_p^2 = .50$, $F(1, 15) = 11.14$, $p = .004$, $\eta_p^2 = .42$, respectively in Experiment 2 and $F(1, 14) = 58.18$, $p < .0001$, $\eta_p^2 = 81$, $F(1, 14) = 61.92$, $p < .0001$, $\eta_p^2 = 82$, $F(1, 14) = 18.71$, $p = .001$, $\eta_p^2 = 57$, respectively in Experiment 3. However, as these interactions do not involve location they are not relevant for the current purposes and are not reported in the body of the analyses to improve readability.

Table 2
Mean and Standard Deviation of Reaction Times (RTs; Milliseconds) and Accuracy Rates (%) in Single-Search Condition in Experiments 1–3 as a Function of Cue Type, Cue Relevance, and Cue Location Relative to the Target

Experiment and cue type	Cue relevance	Cue location	RT	Accuracy
Experiment 1				
Color	Relevant	Same	537 (92)	97.2 (4.3)
		Different	575 (92)	97.3 (2.7)
	Irrelevant same-dimension	Same	562 (98)	97.8 (3.1)
		Different	555 (83)	97.1 (2.2)
	Irrelevant different-dimension	Same	717 (107)	96.7 (3.6)
		Different	725 (106)	96.1 (4.0)
Shape	Relevant	Same	722 (110)	96.9 (5.2)
		Different	743 (109)	95.9 (4.5)
	Irrelevant same-dimension	Same	729 (129)	95.0 (6.6)
		Different	725 (107)	96.9 (3.5)
	Irrelevant different-dimension	Same	562 (89)	95.9 (3.9)
		Different	558 (86)	98.0 (1.9)
Experiment 2				
Color	Relevant	Same	571 (105)	94.9 (6.9)
		Different	627 (83)	93.9 (7.1)
	Irrelevant same-dimension	Same	597 (99)	94.1 (7.7)
		Different	591 (75)	95.2 (5.0)
	Irrelevant different-dimension	Same	689 (90)	92.8 (6.9)
		Different	691 (75)	92.9 (6.8)
Size	Relevant	Same	653 (75)	93.8 (10)
		Different	699 (84)	94.8 (4.8)
	Irrelevant same-dimension	Same	702 (99)	94.1 (6.6)
		Different	684 (84)	93.1 (7.1)
	Irrelevant different-dimension	Same	583 (75)	95.1 (5.5)
		Different	589 (75)	95.1 (4.1)
Orientation	Relevant	Same	793 (134)	96.3 (6.2)
		Different	827 (130)	94.6 (4.7)
	Irrelevant same-dimension	Same	782 (109)	95.4 (5.0)
		Different	768 (128)	94.7 (4.4)
	Irrelevant different-dimension	Same	657 (141)	96.0 (3.2)
		Different	641 (129)	95.4 (3.4)
Experiment 3				
Size	Relevant	Same	671 (147)	97.1 (4.0)
		Different	627 (129)	97.2 (2.8)
	Irrelevant same-dimension	Same	628 (135)	95.0 (5.4)
		Different	643 (132)	96.0 (4.6)
	Irrelevant different-dimension	Same	766 (135)	94.0 (4.9)
		Different	780 (138)	95.3 (3.6)

capture, was significant, $F(1, 19) = 11.58$, $p = .003$, $\eta_p^2 = .38$, indicating that while the location effect was highly significant on relevant-cue trials, $F(1, 19) = 22.19$, $p = .0002$, $\eta_p^2 = .54$, it was nonsignificant on irrelevant-cue trials, $F < 1$. The three-way interaction between cue relevance, cue location, and search type did not reach significance, $F(1, 19) = 2.35$, $p = .14$, $\eta_p^2 = .11$ (see Figure 2). However, additional comparisons indicated that although contingent capture was highly significant in the single-set condition, $F(1, 19) = 12.85$, $p = .002$, $\eta_p^2 = .40$, it was nonsignificant in the dual-set condition, $F(1, 19) = 1.55$, $p = .23$, $\eta_p^2 = .08$.

Although the nonsignificant four-way interaction, $F < 1$, indicated that the effect of holding one versus two search sets on contingent capture was not modulated by cue dimension, it was important to verify that the pattern of results was similar for the two cue dimensions when examined separately. Contingent capture was significant during single-set search with color cues, $F(1, 19) = 12.58$, $p = .002$, $\eta_p^2 = .40$, and approached significance with shape cues, $F(1, 19) = 3.66$, $p = .07$, $\eta_p^2 = .16$, but was not significant during dual-set search with either color cues, $F < 1$, or shape cues, $F(1, 19) = 1.75$, $p = .20$, $\eta_p^2 = .08$, with no significant difference between the two cue dimensions, $F < 1$. Further analysis of dual-set search performance revealed that disruption of contingent capture showed a different pattern for color and for shape cues. Color cues captured attention both when they shared the relevant color, $F(1, 19) = 8.35$, $p = .009$, $\eta_p^2 = .31$, and when they did not, $F(1, 19) = 4.24$, $p = .05$, $\eta_p^2 = .18$, whereas shape cues did not capture attention when they shared the relevant shape, $F < 1$, and showed a numerical trend toward a same-location cost when they had an irrelevant shape, $F(1, 19) = 2.36$, $p > .14$, $\eta_p^2 = .11$.

Accuracy. The main effect of search type was significant, $F(1, 19) = 12.12$, $p = .003$, $\eta_p^2 = .38$, with higher accuracy during single- than during dual-set search. The interaction between cue location and cue dimension was significant, $F(1, 19) = 5.16$, $p = .03$, $\eta_p^2 = .21$, and was modulated by a three-way interaction with

Table 3
Mean and Standard Deviation of Reaction Times (RTs; Milliseconds) and Accuracy Rates (%) in Experiments 1–3 as a Function of Search Type, Cue Type, Cue Relevance, and Cue Location Relative to the Target

			Single set		Dual set	
Experiment and cue type	Cue relevance	Cue location	RT	Accuracy	RT	Accuracy
Experiment 1						
Color	Relevant	Same	537 (92)	97.2 (4.3)	700 (106)	95.6 (4.2)
		Different	575 (92)	97.3 (2.7)	734 (88)	94.6 (3.9)
	Irrelevant	Same	632 (89)	98.0 (2.7)	698 (82)	97.3 (3.6)
		Different	644 (84)	96.6 (2.8)	720 (92)	94.9 (3.9)
Shape	Relevant	Same	722 (110)	96.9 (5.2)	715 (97)	94.7 (5.3)
		Different	743 (109)	95.9 (4.5)	717 (92)	95.2 (4.3)
	Irrelevant	Same	647 (99)	95.0 (4.8)	717 (90)	94.8 (5.4)
		Different	640 (83)	97.4 (2.3)	704 (90)	96.1 (3.3)
Experiment 2						
Color	Relevant	Same	571 (105)	94.9 (6.9)	718 (107)	93.0 (8.9)
		Different	627 (83)	93.9 (7.1)	777 (104)	92.4 (7.4)
	Irrelevant	Same	643 (71)	93.9 (6.5)	726 (120)	93.4 (6.9)
		Different	637 (60)	93.9 (5.4)	736 (106)	93.0 (6.6)
Size	Relevant	Same	653 (75)	93.8 (6.7)	713 (114)	93.0 (8.8)
		Different	699 (84)	94.8 (4.8)	741 (103)	92.3 (6.1)
	Irrelevant	Same	644 (83)	94.9 (4.1)	739 (102)	94.1 (5.3)
		Different	634 (65)	93.8 (6.7)	737 (111)	93.3 (6.4)
Experiment 3						
Orientation	Relevant	Same	793 (134)	96.3 (6.2)	818 (125)	94.6 (4.0)
		Different	827 (130)	94.6 (4.7)	810 (117)	94.4 (4.1)
	Irrelevant	Same	718 (113)	95.6 (2.8)	771 (120)	93.8 (4.7)
		Different	698 (116)	95.0 (3.3)	804 (124)	94.7 (2.5)
Size	Relevant	Same	671 (147)	97.1 (4.0)	791 (136)	95.0 (4.7)
		Different	627 (129)	97.2 (2.8)	833 (129)	93.5 (4.4)
	Irrelevant	Same	691 (120)	94.4 (4.5)	806 (117)	91.9 (6.3)
		Different	713 (128)	95.1 (4.1)	803 (137)	93.5 (3.8)

cue relevance, $F(1, 19) = 8.85$, $p = .008$, $\eta_p^2 = .31$. Follow-up analyses clarified this interaction: Although across search types, contingent capture was significant with shape cues, $F(1, 19) = 7.05$, $p = .02$, $\eta_p^2 = .27$, there was a nonsignificant trend toward a reverse contingent capture effect with color cues, $F(1, 19) = 2.50$, $p = .13$, $\eta_p^2 = .12$. There was no other significant effect.

Dual- versus single-set search cost and intertrial target repetition effects. Across experiments the effect of successive intertrial target repetitions in the dual-set condition reached its asymptote after a maximum of four target repetitions. We thus conducted an ANOVA with target repetition (0, 1, 2, 3 or 4) and target dimension (color vs. shape) as within-subject factors during dual-set search. Then, we compared mean performance during single-set search to mean performance during dual-set search after four target repetitions in an ANOVA with search type and target dimension as within-subject factors. Mean RTs and accuracy rates are presented in Figure 3.

Response times. The mean RT decreased as the number of successive identical targets increased, $F(4, 76) = 20.05$, $p < .0001$, $\eta_p^2 = .51$. This effect did not interact with target dimension, $F < 1$. Further analyses indicated that RTs decreased with up to 2 successive repetitions and did not decrease further with either three or four repetitions. Mean RTs remained significantly slower in the dual-set condition after four target repetitions than in the single-set condition, $F(1, 19) = 5.03$, $p = .04$, $\eta_p^2 = .21$. This effect did not interact with target dimension, $F < 1$.

Accuracy. The interaction between target repetition and target dimension was significant, $F(4, 76) = 2.78$, $p = .04$, $\eta_p^2 = .13$, indicating that unlike with RT data, target repetition increased performance accuracy for shape targets, $F(4, 76) = 3.03$, $p = .02$, $\eta_p^2 = .14$, but not for color targets, $F(4, 76) = 1.68$, $p = .16$, $\eta_p^2 = .08$. Mean accuracy during dual-set search after four target repetitions did not significantly differ from mean accuracy during single-set search, $F < 1$. The interaction between search type and target dimension approached significance, $F(1, 19) = 3.00$, $p = .10$, $\eta_p^2 = .14$, but follow-up analyses indicated that the effect of search type was significant with neither color nor shape targets, $F(1, 19) = 2.7$, $p = .12$, $\eta_p^2 = .13$, and $F < 1$, respectively.

Target-cue intertrial priming. We conducted an ANOVA with cue dimension (color vs. shape), target-cue dimension priming (priming vs. no priming, that is, the cue on the current trial shared vs. did not share the feature of the target on the previous trial), and cue location (same as target vs. different) as within-subject factors on relevant-cue trials of the dual-set search condition.

Reaction times. The interaction between target-cue priming and cue location was not significant, $F(1, 19) = 3.14$, $p = .09$, $\eta_p^2 = .14$, despite a numerical trend toward larger capture for primed relative to unprimed cues (24 vs. 13 ms, respectively), and did not interact with cue dimension, $F < 1$.

Accuracy. The interaction between cue location and target-cue priming was not significant, $F(1, 19) = 1.98$, $p = .18$, $\eta_p^2 = .09$,

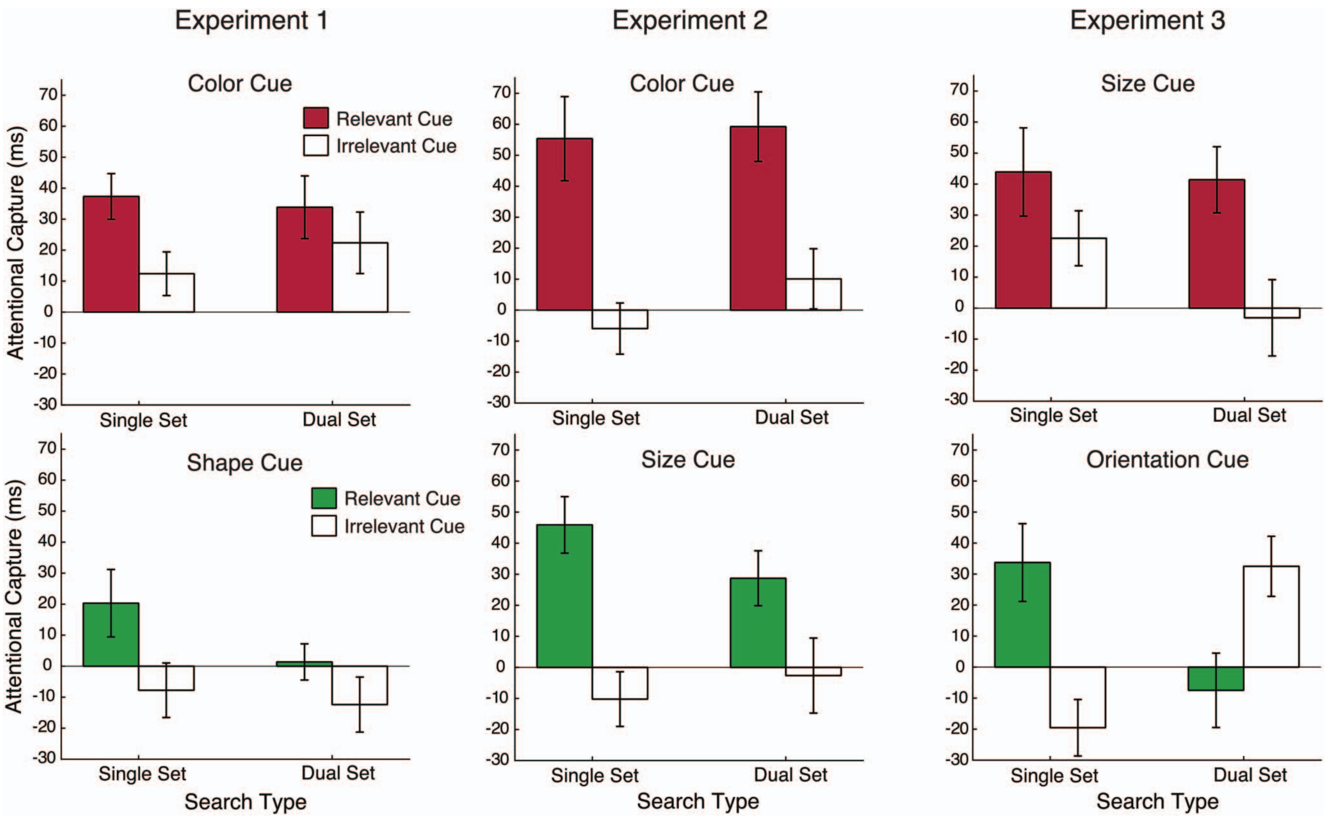

Figure 2. Attentional capture (the mean RT on different-location trials minus the mean RT on same-location trials) in milliseconds, as a function of cue dimension (color, shape, size and orientation), search type (single set vs. dual set), and cue relevance (relevant cue vs. irrelevant cue, relative to target location) in Experiments 1–3. Error bars represent within-subject standard errors (Cousineau, 2005). See the online article for the color version of this figure.

yet showed the opposite trend relative to the RT data. Thus, the numerical trends showed a speed–accuracy trade-off.

Discussion

In this experiment, we replicated previous reports of contingent capture when participants searched for a target defined by one feature (whether it was color or shape): Only cues sharing the target's defining feature captured attention. Although the interaction between contingent capture and search type did not reach significance (both across cue dimensions and for each cue dimension considered separately), numerical trends showed that for identical cueing and target displays attentional capture was smaller under conditions of dual-set search, and in fact did not reach significance for either color or shape cues.

In addition, maintaining two sets impaired overall performance: responses to the target were slower and less accurate during dual-set than during single-set search. This cost was reduced, yet not eliminated, when the effect of target repetitions was discounted. Finally, during dual-set search, a relevant-feature cue did not capture attention more strongly when it shared the feature of the target on the previous trial than when it did not. The nonsignificant trend toward stronger capture by primed relevant-feature cues on the RT measure was counteracted by a reverse trend on accuracy indicating a speed–accuracy trade-off.

Experiment 2

The findings of Experiment 1 suggest that observers show less selectivity when searching for two features from different dimensions simultaneously than when searching for just one feature. However, the data were relatively noisy: on the one hand, contingent capture was significant during single-set search but not during dual-set search. On the other hand, the interaction between contingent capture and search type was not significant. It may be noteworthy that compared to previous studies using the spatial cueing paradigm, the location effects observed for relevant cues in Experiment 1 were relatively small: 38 ms and 21 ms in the single-set condition for color and shape cues, respectively (as compared to about 50–60 ms in Grubert and Eimer's (2016) study, for instance). This observation raises the possibility that attentional guidance may break down during dual-set search only when attentional guidance in single-set search is relatively weak. The goal of Experiment 2 was to bolster contingent capture in single-set search to test this hypothesis. This experiment was similar to Experiment 1, except for four main changes: (a) the displays were

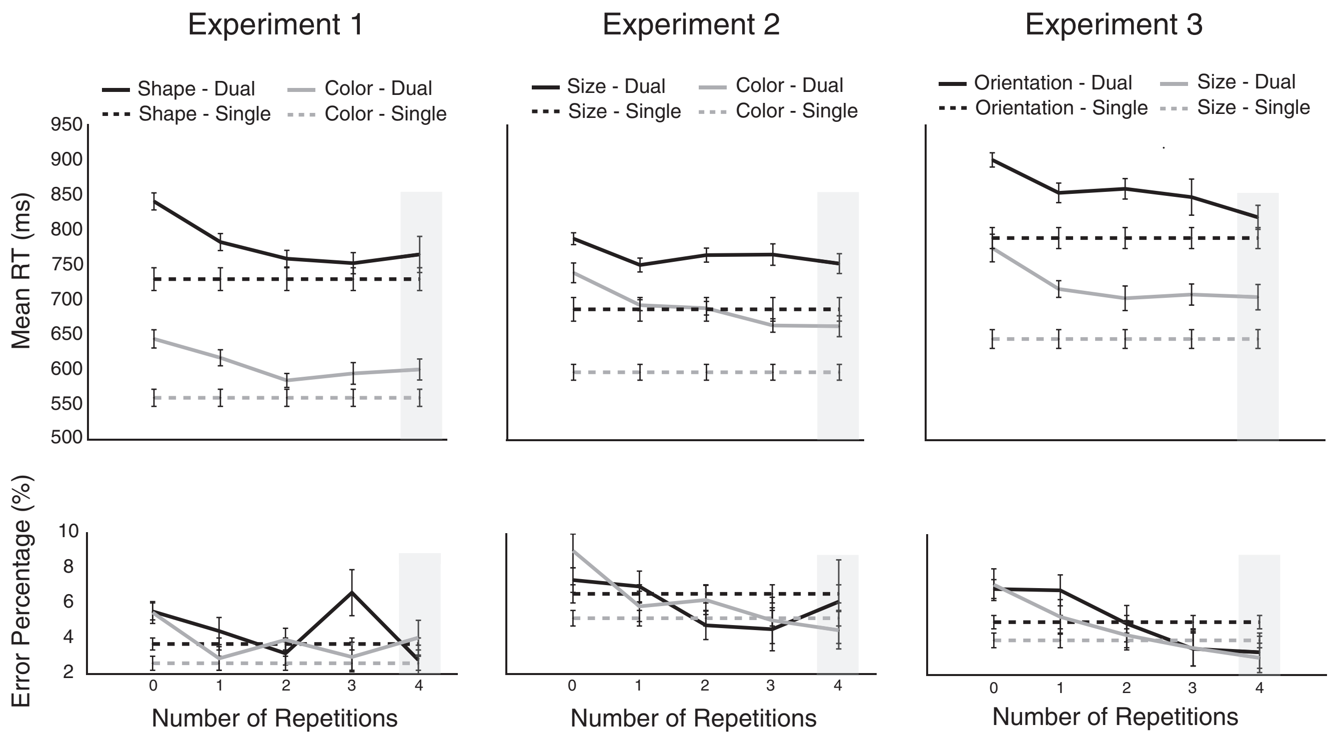

Figure 3. Mean RTs (reaction times) in milliseconds (top panel) and error percentage (bottom panel) as a function of the number of consecutive target repetitions in the single-set (dashed line) and dual-set (full line) conditions for each cue dimension (color, shape, size, and orientation) in Experiments 1–3. Error bars represent within-subject standard errors (Cousineau, 2005).

more similar to those used in typical contingent capture paradigms (e.g., Folk et al., 1992; Irons et al., 2012); (b) the shape cues and targets were replaced with size cues and targets; (c) the color cues were more salient; and (d) the target display included two unique-feature items among two similar items, to make the distinction between the various items' sizes easier.

Method

Participants. Sixteen Tel-Aviv University students (13 females, mean age = 25.3, *SD* = 3.6) took part in the experiment for a $10 payment. All participants reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, stimuli, procedure and design. Experiment 2 was similar to Experiment 1, except for the following changes (see Figure 4). The four boxes were 1.4° in side (instead of 1.2°) and distant from fixation by 4.7° center to center (instead of 3°). In the cue display, each box was surrounded by a group of four dots positioned in diamond configuration (with a distance of 0.8° from box-side to dot-center), three of which were white with a dot size of 0.3° in radius (medium size). On size-cue trials, the remaining dot group (the cue) was colored white and differed from the other groups only in size: its dots were either small (0.09° in radius) or large (0.48° in radius). On color-cue trials, the cue was medium in size (0.3 in radius) and differed from the other groups only in color: it was either red (RGB: 210,50,50) or green (RGB: 80,160,50). The target display consisted of the fixation display with either an "=" or an "X" presented at the center of each box. In the size-search condition, symbols were all white, and one symbol was large (0.5° × 0.74°), one small (0.1° × 0.15°) and the remaining two were medium sized (0.25° × 0.37°). In the color-search condition, the symbols were all medium sized (0.25° × 0.37°), and one was red (RGB: 210,50,50), one green (RGB: 80,160,50), and the other two were white.

The target was defined by its specific color (red or green, between participants) in the single color-set condition, its specific size (large or small, between participants) in the single size-set condition, and by either its specific color or its specific size (red or large, green or large, red or small, or green or small, between participants) in the dual-set condition. Subjects reported whether the target was an "=" or an "X" using the "m" and "x" keys with the left and right index fingers, respectively.

Results

All RT analyses were conducted on correct trials (93.9% of all trials). Preliminary analyses indicated that none of the between-participants variables interacted with any of the variables of interest. The data were therefore collapsed across all four between-participants variables.

Contingent capture in the single-set condition. We conducted a three-way ANOVA with cue dimension (color vs. size), cue relevance (relevant vs. irrelevant same-dimension vs. irrelevant different-dimension) and cue location (same vs. different,

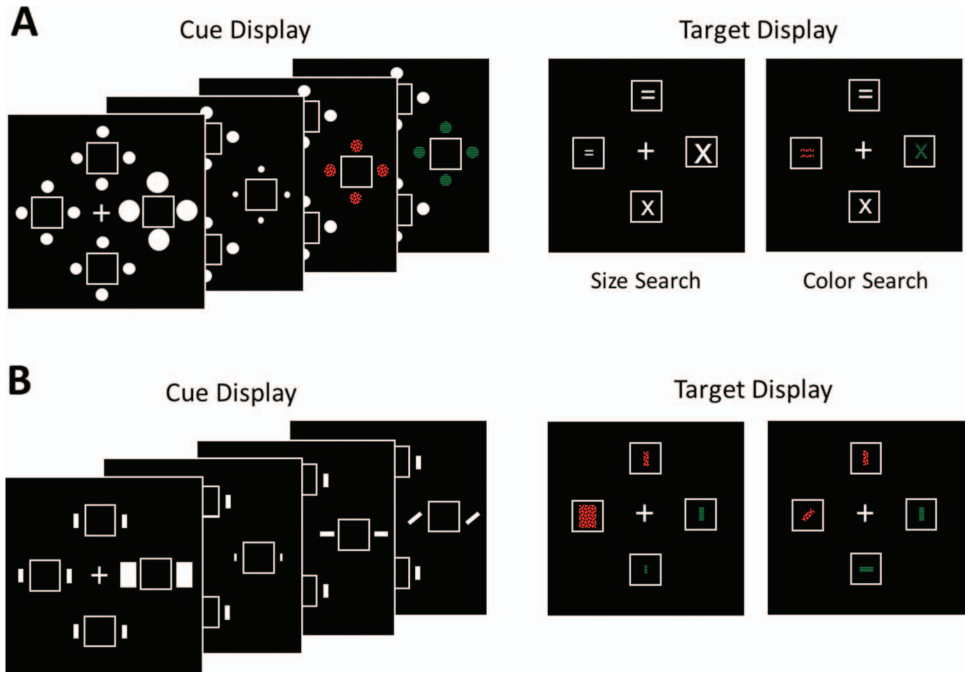

Figure 4. Cue and target displays in Experiments 2 (A, top panel) and 3 (B, bottom panel). In Experiment 2, cues and targets were defined on the size dimension (large or small) or on the color dimension (red [dotted-line surfaces] or green [horizontally striped surfaces]). In Experiment 3, cues and targets were defined on the size dimension (large or small) or on the orientation dimension (horizontal or tilted). See the online article for the color version of this figure.

relative to the target) as within-participant variables. Mean RTs and accuracy data are presented in Table 2.

Reaction times. The main effects of cue dimension and cue location were significant, indicating that RTs were faster on same- than on different-location trials, $F(1, 15) = 7.53$, $p = .02$, $\eta_p^2 = .33$, and on color- than on size-cue trials, $F(1, 15) = 8.40$, $p = .01$, $\eta_p^2 = .36$. The interaction between cue location and cue relevance, which indexes contingent capture, was significant, $F(2, 30) = 18.31$, $p < .0001$, $\eta_p^2 = .55$. Paired comparisons indicated that relevant-feature cues captured attention, $F(1, 15) = 25.91$, $p = .0001$, $\eta_p^2 = .63$, whereas irrelevant-feature cues did not, $F < 1$. In addition, there was no significant difference in the location effect from irrelevant-feature cues within versus outside the target dimension, $F(1, 15) = 1.49$, $p = .24$, $\eta_p^2 = .09$. The three-way interaction between cue location, cue relevance, and cue dimension was not significant, $F < 1$. Separate comparisons confirmed that contingent capture was significant both for color cues, $F(1, 15) = 22.64$, $p = .0003$, $\eta_p^2 = .60$, and for size cues, $F(1, 15) = 16.63$, $p = .001$, $\eta_p^2 = .53$.

Accuracy. No effect approached significance, all $ps > .18$

Contingent capture in single-set versus dual-set search. We conducted a four-way ANOVA with search type (single-set vs. dual-set), cue dimension color versus size), cue relevance (relevant vs. irrelevant), and cue location (same vs. different, relative to the target) as within-participant variables. Trials of the single-set conditions in which the cue had a feature that served as a target feature in the dual-set condition were excluded from this analysis. Mean RTs and accuracy data are presented in Table 3. Mean location effects are presented in Figure 2.

Reaction times. Reaction times were faster in the single-set than in the dual-set condition, $F(1, 15) = 35.58$, $p < .0001$, $\eta_p^2 = .70$, on same-location relative to different-location trials, $F(1, 15) = 24.03$, $p = .0002$, $\eta_p^2 = .62$, and for color cues than for size cues, $F(1, 15) = 4.70$, $p = .05$, $\eta_p^2 = .24$. The interaction between cue type and cue location was also significant, $F(1, 15) = 7.65$, $p = .01$, $\eta_p^2 = .34$, indicating that capture by color cues was stronger than capture by size cues. The interaction between location and cue relevance, which reflects contingent capture, was significant, $F(1, 15) = 38.33$, $p < .0001$, $\eta_p^2 = .72$, indicating that the location effect was highly significant on relevant-cue trials, $F(1, 15) = 44.94$, $p < .0001$, $\eta_p^2 = .75$, and nonsignificant on irrelevant-cue trials, $F < 1$. The three-way interaction between cue relevance, cue location and search type was significant, $F(1, 15) = 4.57$, $p = .05$, $\eta_p^2 = .23$, indicating that contingent capture across cue dimensions was smaller during dual- than during single-set search. Follow-up comparisons indicated that contingent capture was nevertheless highly significant during both single- and dual-set search, $F(1, 15) = 35.40$, $p < .0001$, $\eta_p^2 = .70$, and $F(1, 15) = 14.40$, $p = .002$, $\eta_p^2 = .49$, respectively.

Although the four-way interaction was nonsignificant, $F < 1$, we verified that the pattern of results was similar for the two cue dimensions examined separately. Contingent capture was significant during both single- and dual-set search with color cues, $F(1, 15) = 22.80$, $p = .0002$, $\eta_p^2 = .60$, and $F(1, 15) = 9.21$, $p = .008$, $\eta_p^2 = .38$, respectively, with no significant difference between the two search conditions, $F(1, 15) = 1.88$, $p = .19$, $\eta_p^2 = .11$. Likewise, contingent capture was significant during both single-and dual-set search with size cues, $F(1, 15) = 19.29$, $p = .0005$, $\eta_p^2 = .56$, and $F(1, 15) = 5.29$, $p = .04$, $\eta_p^2 = .26$, respectively, with no significant difference between the two search conditions, $F(1, 15) = 1.88$, $p = .19$, $\eta_p^2 = .11$.

Accuracy. No significant effect involved cue location and target-cue priming, all Fs < 1.

Dual- versus single-set search cost and intertrial target repetition effects. We first conducted an ANOVA with target repetition (0, 1, 2, 3, or 4) and target dimension (color vs. size) as within-subject factors during dual-set search data. Then we compared mean performance in the dual-set search condition after four target repetitions to mean performance during single-set search in an ANOVA with search type and target dimension as within-participant variables. Mean RTs and accuracy rates are presented in Figure 3.

Response times. The mean RT decreased as the number of successive identical targets increased, $F(4, 60) = 8.94$, $p < .0001$, $\eta_p^2 = .37$. This effect interacted with target dimension, $F(4, 60) = 3.08$, $p = .04$. $\eta_p^2 = .17$, indicating that the effect of target repetition was larger for color than for size targets. Further analyses indicated that RTs decreased with one repetition and did not significantly decrease with further repetitions. Mean RTs remained significantly slower in the dual-set condition after four target repetitions than in the single-set condition, $F(1, 15) = 17.85$, $p = .0007$, $\eta_p^2 = .54$. This effect did not interact with target dimension, $F < 1$.

Accuracy. There was no significant effect, all ps $> .13$.

Target-cue intertrial priming. We conducted an ANOVA with cue dimension (color vs. size), target-cue dimension priming (priming vs. no priming) and cue location (same as target vs. different) as within-subject factors on relevant-cue trials of the dual-set search condition.

Reaction times. The interaction between target-cue priming and cue location was not significant, $F < 1$ and tended to be modulated by cue type, $F(1, 15) = 2.52$, $p = .13$. Follow-up analyses showed that capture tended to be larger for primed versus unprimed cues in the color dimension, $F(1, 15) = 2.70$, $p = .11$, $\eta_p^2 = .12$, but not for cues in the size dimension, $F < 1$.

Accuracy. No effect involving cue location and target-cue priming was significant, all Fs < 1.

Discussion

The changes we introduced in the present experiment relative to Experiment 1 were effective: Attentional capture by relevant-feature cues in the single-set condition reached an order of magnitude similar to that reported in analogous previous studies (56 and 46 ms for color and size cues, respectively), with no attentional capture by irrelevant-feature cues (0 and −2 ms, respectively). Although contingent capture remained very strong in the dual-set search condition for both cue dimensions, its magnitude slightly yet significantly decreased relative to the single-set search condition (yet this impairment did not reach significance when each condition was considered in isolation). A between-experiment analysis confirmed that contingent capture was indeed weaker in Experiment 1 than in Experiment 2, $F(1, 34) = 5.06$, $p = .031$, $\eta_p^2 = .13$, yet while the modulation of contingent capture by search type was significant across the two experiments, $F(1, 34) = 5.97$, $p = .020$, $\eta_p^2 = .15$, it did not significantly differ between them, $F < 1$. Thus, the disruption of attentional guidance by two target templates from different dimensions relative to just one generalized across conditions in which guidance by each individual template in single-set search was weak (Experiment 1) or strong (Experiment 2).

The other findings of Experiment 1 were thoroughly replicated. (a) An overall performance cost in dual- relative to single-set search was found and was reduced, yet not eliminated, when the effect of target repetitions was discounted. (b) During dual-set search, a relevant-feature cue did not capture attention more strongly when it shared the feature of the target on the previous trial than when it did not.

The objective of Experiment 3 was to further establish the findings of Experiments 1 and 2 with a different pair of dimensions, namely, orientation and size.

Experiment 3

Participants

Sixteen Tel-Aviv University students (13 females, mean age = 22.6, $SD = 1.3$) took part in the experiment for course credit. All participants reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, Stimuli, Procedure, and Design

Experiment 3 was similar to Experiment 2 except for the following changes (see Figure 4). In the cue display, each box was surrounded by a pair of white lines positioned on the right and left sides of the box. Three pairs consisted of two vertical lines, 0.6° in height and 0.2° in width (medium size). On size-cue trials, the remaining pair of lines was vertical and could either be large (1.2° × 0.6°) or small (0.25° × 0.1°). On orientation-cue trials, the two lines were medium-sized and could be either horizontal or tilted to the right by 45°.

The target display included the fixation display with four color lines presented in the center of each box. Two lines were red (RGB: 210,50,50), and two were green (RGB: 80,160,50). In the size-search condition, all lines were vertical, one line was large (1.1° × 0.6°), one small (0.25° × 0.1°) and the remaining two were medium-sized (0.6° × 0.2°). In the orientation-search condition, the lines were all medium sized, and one was horizontal, one tilted to the right by 45°, and the remaining two were vertical.

The target was defined by its specific size (large or small, between participants) in the single-set size-target condition, its specific orientation (right or horizontal, between participants) in the single-set orientation-target condition, and by either its specific size or its specific orientation (large or right, small or right, large of horizontal, small or horizontal, between participants) in the dual-set condition. Subjects reported whether the target was colored red or green using the "3" and "z" keys with the right and left index fingers, respectively.

Results

All RT analyses were conducted on correct trials (95.3%). The data from one participant were excluded from all analyses because his mean accuracy was lower than the group's by more than 2 standard deviations (M = 87.8% vs. M = 95.3%, *SD* = 2.6%). The pattern of results remained the same when the data from this subject were included. Preliminary analyses indicated that none of the between-participants variables interacted with any of the variables of interest. The data were therefore collapsed across all these variables.

Contingent capture in the single-set condition. We conducted a three-way ANOVA with cue dimension (size vs. orientation), cue relevance (relevant vs. irrelevant same-dimension vs. irrelevant different-dimension), and cue location (same vs. different, relative to the target) as within-participant variables. Mean RTs and accuracy data are presented in Table 2.

Reaction times. The main effect of cue dimension was significant, $F(1, 14) = 56.83$, $p < .0001$, $\eta_p^2 = .80$, with faster RTs on size- than on orientation-cue trials. This effect interacted with cue location, $F(1, 14) = 5.03$, $p = .04$, $\eta_p^2 = .26$, indicating that attentional capture by size cues was larger than attentional capture by orientation cues. The interaction between cue location and cue relevance, which indexes contingent capture, was also significant, $F(2, 28) = 6.78$, $p = .004$, $\eta_p^2 = .33$, indicating that relevant-feature cues captured attention, $F(1, 14) = 10.2$, $p = .02$, $\eta_p^2 = .42$, whereas irrelevant-feature cues did not, $F < 1$. In addition, there was no significant difference in the location effect from irrelevant-feature cues within versus outside the target dimension, $F < 1$. The three-way interaction between cue location, cue relevance and cue dimension was not significant, $F < 1$. Separate comparisons confirmed that contingent capture was significant both for orientation cues, $F(1, 14) = 6.96$, $p = .02$, $\eta_p^2 = .33$, and for size cues, $F(1, 14) = 7.65$, $p = .02$, $\eta_p^2 = .35$.

Accuracy. No effect was significant, all ps $> .14$.

Contingent capture in single-set versus dual-set search. We conducted a four-way ANOVA with search type (single-set vs. dual-set), cue dimension size versus orientation), cue relevance (relevant vs. irrelevant), and cue location (same vs. different, relative to the target) as within-participant variables. Trials of the single-set conditions in which the cue had a feature that served as a target feature in the dual-set condition were excluded from this analysis. Mean RTs and accuracy data are presented in Table 3. Mean location effects are presented in Figure 2.

Reaction times. Reaction times were faster in the single-set than in the dual-set condition, $F(1, 14) = 29.61$, $p < .0001$, $\eta_p^2 = .68$, on same-location than on different-location trials, $F(1, 14) = 14.64$, $p = .002$, $\eta_p^2 = .51$, and with size cues than with orientation cues, $F(1, 14) = 45.20$, $p < .0001$, $\eta_p^2 = .76$. The interaction between cue dimension and cue location was significant, $F(1, 14) = 6.04$, $p = .03$, $\eta_p^2 = .30$, indicating that attentional capture by size cues was larger than attentional capture by orientation cues. The interaction between cue location and cue relevance, which reflects contingent capture, was significant, $F(1, 14) = 11.51$, $p = .004$, $\eta_p^2 = .45$. The interaction between search type, cue relevance and cue location was significant, $F(1, 14) = 5.16$, $p = .04$, $\eta_p^2 = .27$, and the interaction between cue dimension, cue relevance and cue location approached significance, $F(1, 14) = 4.16$, $p = .06$, $\eta_p^2 = .23$. The two interactions were modulated by a four-way interaction, $F(1, 14) = 6.73$, $p = .02$, $\eta_p^2 = .32$.

To clarify the four-way interaction we conducted a separate ANOVA for each cue dimension. With size cues, the interaction between cue relevance and cue location was significant, $F(1, 14) = 10.97$, $p = .005$, $\eta_p^2 = .44$, indicating significant capture by relevant-feature cues, $F(1, 14) = 26.81$, $p = .0001$, $\eta_p^2 = .66$, but not by irrelevant-feature cues, $F(1, 14) = 1.99$, $p = .18$, $\eta_p^2 = .12$, and was not modulated by search type, $F < 1$. If anything, as is clear from Figure 2, contingent capture was numerically larger during dual- than in the single-set search for size cues. With orientation cues, the three-way interaction between search type, cue relevance, and cue location was significant, $F(1, 14) = 9.86$, $p = .007$, $\eta_p^2 = .41$. The traditional contingent capture effect was observed during single-set search, $F(1, 14) = 7.77$, $p = .01$, $\eta_p^2 = .36$, that is, significant capture with relevant-orientation cues, $F(1, 14) = 5.34$, $p = .04$, $\eta_p^2 = .28$, and a nonsignificant trend toward a same-location cost with irrelevant-feature cues, $F(1, 14) = 3.52$, $p = .08$, $\eta_p^2 = .20$. The reverse pattern was observed during dual-set search, $F(1, 14) = 6.92$, $p = .02$, $\eta_p^2 = .33$, attentional capture was observed with irrelevant-orientation cues, $F(1, 14) = 10.81$, $p = .005$, $\eta_p^2 = .44$, but not with relevant-orientation cues, $F < 1$.

Accuracy. The main effect of search type was significant, $F(1, 14) = 19.93$, $p = .0005$, $\eta_p^2 = 59$, indicating that accuracy was higher during single- than during dual-set search. The interaction between cue relevance and cue location approached significance, $F(1, 14) = 3.99$, $p = .07$, $\eta_p^2 = .22$, indicating a trend toward contingent capture that mirrored the RT data. No other interaction involving cue location and search type was significant, all ps $> .26$.

Dual- versus single-set search cost and intertrial target repetition effects. We first conducted an ANOVA with target repetition (0, 1, 2, 3, or 4) and target dimension (orientation vs. size) as within-participant variables during dual-set search data. We then compared mean performance during single-set search to mean performance in the dual-set search condition after four repetitions in an ANOVA with search type and target dimension as within-participant variables. Mean RTs and accuracy rates are presented in Figure 3.

Response times. The mean RT decreased as the number of successive identical targets increased, $F(4, 56) = 10.14$, $p < .0001$, $\eta_p^2 = .42$. Mean RTs decreased with one repetition and did not decrease significantly further with 2 or more repetitions. The effect of target repetition did not interact with target dimension, $F < 1$. Mean RTs remained significantly slower in the dual-set condition after four target repetitions than in the single-set condition, $F(1, 14) = 7.13$, $p = .02$, $\eta_p^2 = 34$. This effect interacted with target dimension, $F(1, 14) = 5.39$, $p = .04$, $\eta_p^2 = .28$; RTs were slower during dual-set search after four target repetitions with size targets, $F(1, 14) = 11.07$, $p = .005$, $\eta_p^2 = .44$, but not with orientation targets, $F(1, 14) = 2.47$, $p = .14$, $\eta_p^2 = .15$.

Accuracy. The main effect of target repetition was significant, $F(4, 56) = 5.58$, $p = .0007$, $\eta_p^2 = .28$, indicating that performance improved as the number of target repetitions increased. This effect did not interact with target dimension, $F < 1$. Accuracy tended to be higher in dual-set search after four target repetitions than in the single-set condition, $F(1, 14) = 4.04$, $p = .06$, $\eta_p^2 = .22$, thus indicating a speed–accuracy trade-off.

Target-cue intertrial priming. We conducted an ANOVA with cue dimension (size vs. orientation), target-cue dimension priming (priming vs. no priming), and cue location (same as target vs. different) as within-subject factors on relevant-cue trials of the dual-set search condition.

Reaction 5imes. No significant effect involved cue location and target-cue priming, all *F*s < 1.

Accuracy. No significant effect involved cue location and target-cue priming, all *F*s < 1.

Discussion

In the present experiment, contingent capture was again observed during single-search task for both orientation and size cues. Although as in the previous two experiments, attentional guidance was impaired during disjunction search for two target features from different dimensions, this was true only for orientation cues. In fact, during dual-set search, orientation cues did not capture attention when they matched the target-defining orientation and captured attention when they did not match it. This pattern of results is surprising. One would expect failure to maintain an attentional set for orientation during dual-set search to manifest in one of two ways: (a) capture by both relevant and irrelevant-feature cues, which would suggest that observers lose their ability to filter out salient yet irrelevant information or (b) no capture by either relevant or irrelevant cues, which would suggest that they maintain only the set for the size target.

We further scrutinized the data to determine whether the disruption of contingent capture might differ between the two orientation-target groups (horizontal vs. tilted). However, in both groups the pattern of results was similar: The significant interaction between cue relevance and cue-target location indicating reverse contingent capture during dual-set search (i.e., attentional capture by irrelevant-orientation cues but none by relevant-orientation cues) did not interact with the specific target orientation (horizontal vs. tilted), $F(1, 14) = 2.64$, $p = .13$, $\eta_p^2 = .16$, although the pattern tended to be stronger with tilted than with horizontal cues. We have no explanation for why this pattern was observed. However, because contingent capture was observed for orientation cues in the single-set search (and was similar in magnitude to contingent capture by size cues), these findings nevertheless clearly indicate that attentional guidance was disrupted during dual- relative to single-set search.

The other findings of Experiments 1 and 2 were again replicated. (a) An overall performance cost in dual- relative to single-set search was observed. It was reduced, yet not eliminated, when the effect of target repetitions was discounted. (b) During dual-set search, a relevant-feature cue did not capture attention more strongly when it shared the feature of the target on the previous trial than when it did not.

General Discussion

Impaired Attentional Guidance During Disjunctive Search for Features From Different Dimensions

In the present study, we investigated whether two features from different dimensions can simultaneously and selectively guide attention. We had observers search for either the disjunction of two features from different dimensions (color or shape in Experiment 1 and color or size in Experiment 2, and size or orientation in Experiment 3) or for just one feature on those dimensions, in a spatial-cueing paradigm. In the single-set search condition the results of the three experiments showed a very high degree of convergence: There was clear evidence for contingent capture in each experiment and for each cue dimension, thus replicating the well-documented finding that when searching for a target defined by its known feature only cues matching this feature capture attention, whereas irrelevant-feature cues do not.

In the dual-set search condition, which involved identical cue and target displays as the single-set search condition, contingent capture was impaired across experiments, as reflected by the significant interaction between search type, cue relevance and cue-target location, $F(1, 48) = 11.41$, $p = .002$, $\eta_p^2 = .19$. A Bayesian inference analysis (Masson, 2011) of the critical interaction provided strong evidence against the null hypothesis, $\Delta\text{BIC} = -6.94$, Bayes factor (BF01) = 0.031, $p(\text{H0|D}) = 0.03$. Nevertheless, contingent capture remained significant during dual-set search, $F(1, 48) = 10.16$, $p = .003$, $\eta_p^2 = .17$ (see Table 4). The weakening of contingent capture mainly resulted from reduced ability of either one or both target features to capture attention (i.e., capture by relevant-feature cues was weaker): the magnitude of the spatial cueing effect dropped from 38 ms to 25 ms overall, $F(1, 48) = 7.02$, $p = .02$, $\eta_p^2 = .13$, in the single- relative to the dual-search task condition, respectively. In addition, efficiency at filtering out irrelevant features tended to be reduced (i.e., capture

Table 4
Mean and Standard Deviation of Reaction Times (RTs; Milliseconds) and Accuracy Rates (%) Across Experiments as a Function of Search Type, Cue Relevance, and Cue Location Relative to the Target

	Single set		Dual set	
Cue relevance and cue location	RT	Accuracy	RT	Accuracy
Relevant				
Same	648 (101)	96.1 (5.1)	739 (117)	94.4 (5.6)
Different	686 (102)	95.7 (3.9)	764 (109)	93.8 (4.8)
Location effect	36	.4	25	.6
Irrelevant				
Same	660 (97)	95.4 (3.3)	740 (108)	94.4 (4.8)
Different	659 (94)	95.5 (4.3)	747 (109)	94.4 (4.4)
Location effect	−1	−.1	7	0

Note. The location effect was calculated as the mean performance on different-location trials minus the mean performance on same-location trials for RTs, and vice versa for accuracy.

by irrelevant-feature cues tended to be stronger), $F(1, 48) = 3.62$, $p = .06$, $\eta_p^2 = .07$. However, it is important to note that observers were nevertheless able to guide their attention relying on both target features simultaneously on at least part of the trials because spatial capture by relevant-feature cues was overall reduced by less than half - and in Experiment 2, for instance, it was reduced by less than 15% (see Figure 2).

One may also argue that since target-defining features remained constant within experimental blocks in our experiments, the corresponding templates may have been transferred from working memory to long-term memory (e.g., Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Olivers, & Meeter, 2016; Thompson, Underwood, & Crundall, 2007). However, if sets were maintained in long-term memory it is not clear why attentional guidance was impaired (although only partially) when two instead of one search template had to be stored. In addition, one would expect long-term memory effects to manifest in carry-over effects from the dual-set search blocks to the single-set search blocks. Specifically, the long-term representation of a feature that served as a target during dual-set search should be stronger than the representation of a feature that was never searched for. One would therefore predict that participants who were administered the dual-set search condition first should be less successful at ignoring a cue in the second half of the experiment (i.e., in single-set search), when this cue's feature was previously relevant relative to when it was always irrelevant.

To test this possibility, we conducted an analysis of single-set search trials in participants for which this condition followed the dual-set search condition, with irrelevant-feature type (was previously a relevant target vs. was not), cue-target location, and experiment as factors. None of the interactions involving cue-target location and irrelevant-feature type was significant, all $F\text{s} < 1$, even when the analysis was limited to the first single-set search block that followed the dual-set search condition, all $F\text{s} < 1$. Nevertheless, in future research, it would be useful to directly compare the disruption of attentional guidance in cross-dimensional dual-set search relative to single-set search when the target features are set on a trial-by-trial basis relative to when they are constant.

Heterogeneity of the Patterns of Guidance Disruption During Dual-Search Task

Contingent capture during dual-set search broke down to various degrees and following different patterns for each experiment and cue dimension. In Experiment 1, observers' attention was captured by both relevant and irrelevant-color cues and by neither relevant nor irrelevant-shape cues, although for both cue dimensions, the location effect was numerically larger for relevant- than for irrelevant-feature cues. In that experiment, cues were relatively faint, which raised the possibility that attentional guidance might break down during dual-set search only when it is already weak during single-set search. Experiment 2 involved stronger cues but contingent capture was again disrupted in the dual- relative to the single-set condition, although not strongly so. Finally, in Experiment 3, contingent capture was disrupted for the orientation dimension but not for the size dimension.

The variety of patterns in which disruption on attentional guidance manifested during dual-search task suggests that observers may resort to different strategies in order to cope with the challenge posed by holding two simultaneous attentional sets. For instance, they may switch from one set to the other across trials, search displays serially, or intermittently let go of both sets and become momentarily vulnerable to attentional capture by salient irrelevant objects. Alternatively, such variance may be determined by the specific dimensions in which the target features are defined or by their specific combination: here, for instance, attentional guidance was more impaired during dual-set search for a shape target (Experiment 1) or for an orientation target (Experiment 3) and less impaired in search for a color target (Experiments 1 and 2) or for a size target (Experiments 2 and 3). These results nicely dovetail the findings reported by Menneer et al. (2007) who showed that relative to color, the dual-target cost for orientation and shape was very large. Finally, the variance may reflect individual differences in observers' ability to maintain an attentional set for two features. Characterizing the variables that determine the extent and pattern of the impairment at maintaining two simultaneous sets is beyond the scope of the present study but opens interesting avenues for future research.

Dual-Set Search Within Versus Between Dimensions

The results from previous studies that used a spatial capture paradigm to probe attentional guidance by two features from the same dimension led to the conclusion that such guidance is possible (Irons et al., 2012; Roper & Vecera, 2012) and is unimpaired relative to guidance by a single feature (Grubert & Eimer, 2016; Moore & Weissman, 2010). By contrast, here, we found that when the two features are defined in different dimensions, attentional guidance is weakened during dual- relative to single-set search. Taken together, these findings might suggest that attentional guidance by two features from different dimensions is subject to capacity limitations that do not accrue to attentional guidance by two features within the same dimension. Or do they? A closer comparison between previous findings and the present ones suggests that this conclusion may be premature.

Irons et al. (2012) reported contingent capture during dual-set search. In the present study, this finding was replicated across experiments. It was not observed for each dimension in each experiment, but when looking at capture by color cues in Experiment 2 (the colors of which, unlike in Experiment 1, were comparable to the colors used by Irons et al., 2012), contingent attentional capture was highly significant during dual-set search. As explained in the introduction, however, to assess whether simultaneous attentional guidance by two features is possible, it is necessary to compare contingent capture during single- versus dual-set search.

Grubert and Eimer (2016) conducted the critical comparison with single-set search. They reported that "behavioral and electrophysiological markers of task-set contingent attentional capture are virtually identical when task sets contain one or two possible target colors, which strongly suggests that attentional guidance processes can operate equally efficiently during single-feature and multiple-feature search." However, closer scrutiny of their data raises the possibility that differences in the magnitude of contingent capture during single- versus dual-set search may have gone undetected. In their Experiment 4 (which is most similar to our study), the interaction between search type, cue relevance and cue-target location showed a nonsignificant numerical trend ($p = .17$) toward stronger contingent capture during single- relative dual-set search, with a spatial cueing effect from relevant-color cues of roughly 50 ms versus 30 ms, respectively. These findings resulted from analyses of the raw RT data and therefore did not take the significant difference in base RTs between single-and dual-set search into account (508 ms vs. 587 ms, respectively). To illustrate, in Experiment 2 of the present study, where the magnitude of contingent capture during single-set search was similar to that observed by Grubert and Eimer (2016), the critical interaction that was diagnostic of weaker contingent capture during dual-set search was significant with analyses of the log-transformed data (which factored out differences in base RTs), $p = .05$, but was not significant with analyses of the raw RTs, $p = .21$.

Likewise, Moore and Weissman (2010) reported that "participants were able to maintain one and two attentional sets equally well." The conclusion that the attentional blink induced by a relevant-color distractor did not differ during search for one versus two colors was based on the nonsignificant interaction between distractor (same-color relevant vs. irrelevant), search type (single vs. dual set) and SOA (Stimulus-onset-asynchrony: 116, 233, 350, 466 ms). However, again, target identification accuracy during the attentional blink (i.e., at the 116-ms distractor-target SOA, which is the only SOA at which the distractor impaired performance during single-set search) was numerically much larger during search for one color relative to two (approximately 18% vs. 11%, respectively), a difference that was not tested for significance.

Finally, although we investigated attentional guidance by two properties on a variety of dimensions, previous contingent-capture research on search for two features focused exclusively on the color dimension (Grubert & Eimer, 2016; Irons et al., 2012; Moore & Weissman, 2010; Roper & Vecera, 2012). Relative to the shape and orientation dimensions, we found guidance in dual-set search to be only mildly weaker than in single-set search for the color dimension. Thus, it would be important to determine whether attention can be guided with similar efficiency by two search templates defined within the same dimension other than the color dimension.

Taken together, the above observations suggest that the jury is still out with regard to whether simultaneous guidance of attention by two features within the same dimensions is possible and with regard to how it compares to guidance by features from different dimensions. If further research reveals that contingent capture is also weakened in search for multiple features from the same dimension, the apparent discrepancy between studies relying on overall performance and eye movements (e.g., Houtkamp & Roelfsema, 2009; Menneer et al., 2007; Stroud et al., 2012; but see Beck et al., 2012) versus studies relying on attentional capture (e.g., Grubert & Eimer, 2016; Moore & Weissman, 2010) would be resolved.

An Overall Dual-Set Search Cost

Our results showed that in addition to weakening attentional guidance, maintaining two sets incurred an overall performance cost (see also e.g., Grubert & Eimer, 2016; Houtkamp & Roelfsema, 2009). This cost was reduced, yet not eliminated when the effect of target repetitions was taken into account. The overall dual-target cost may result at least in part from the extra time it takes to match the selected candidate target against two instead of just one search template to verify that it is indeed the target before responding.

Note that the dual-target cost may be underestimated in our study because target displays differed considerably for each potential target. In Experiment 1, for instance, display items on color-target trials differed in color but were homogenously shaped and conversely, display items on shape-target trials differed in shape but were homogenously colored. This aspect of the design may have induced observers to search for both targets at the beginning of the trial but as soon as they detected that the target display was heterogeneous on the color dimension, for instance, they ceased to maintain the representation of the alternative target property (e.g., the task-relevant shape) and searched only for the task-relevant color. This would improve overall performance, because in this case, observers would need to match the target to only one search template.[5]

Although this aspect of the design may have influenced overall target identification performance and magnified target–target intertrial priming, it is unlikely to have affected attentional capture since observers did not know which target would appear when their attention was captured by the cue. It is also unlikely that this aspect of the design induced participants to wait for the target display to activate the appropriate search template because if so, no attentional capture whatsoever would be expected during dual-set search. This was clearly not the case.

Implications for the Mechanisms Underlying the Effects of Selection History

Our findings also shed light on the mechanisms underlying the effects of selection history (see Lamy & Kristjansson, 2013 for review). Several authors suggested that attending to a specific defining feature (e.g., Awh et al., 2012; Becker & Horstmann, 2009; Maljkovic & Nakayama, 1994) or dimension (e.g., Found & Muller, 1996; Muller & Krummenacher, 2006) induces an early perceptual bias, such that subsequent stimuli with that feature are prioritized over other stimuli during initial encoding. For instance, Awh et al. (2012) suggested the existence of a priority map that

[5] The fact that target displays for each potential target differed conspicuously in our study (unlike in previous studies probing attentional guidance by two features from the same dimension) may have an additional implication. Although it was not the focus of the present study, we examined the set enhancement effect reported in previous studies (e.g., Grubert & Eimer, 2016; Irons et al., 2012; Moore & Weissman, 2010, 2014), that is, the effect of the congruency between the cue and target features for relevant-feature cues. For instance, in the dual-set condition of Experiment 1, if an observer searched for either a red item or a circle and the target happened to be a circle, the set-enhancement effect would refer to faster RTs when the cue was also a circle relative to when it was red. Across all three experiments, although target identification tended to be faster when the target matched the cue feature, this effect did not reach significance, $F(1, 48) = 2.73$, $p = .10$, $\eta_p^2 = .05$. Our failure to replicate the set-enhancement effect reported in within-dimension dual-search can be easily explained if observers relied on the global characteristics of the target display to narrow their search to just one template. Indeed, it is reasonable to assume that such information boosted the current target feature to a larger extent than did priming by the cue, thereby overriding the set-enhancement effect. It would be useful to determine in future research whether set enhancement arises when target displays are heterogeneous on both target dimensions, such that display-wide properties do not differ between tasks.

integrates three distinct categories of selection bias: current goals, selection history and physical salience. The results of the present study argue against this view. Specifically, they demonstrate that current goals (i.e., attentional settings) and selection history (i.e., intertrial priming) do not affect the same processes.

In the dual-search condition, the target feature on the current trial was either the same as on the previous trial or different. We found intertrial target repetition to have a strong impact on overall performance. This finding is novel because it extends earlier findings from singleton search (e.g., Maljkovic & Nakayama, 1994) to feature-guided search. However, this effect does not allow one to determine whether such priming induced an early perceptual bias or improved target processing after this target had been selected. Examining whether the match between a relevant-feature cue and the feature of the target on the previous trial increased the ability of this cue to summon attention to its location allowed us to resolve this ambiguity.

We found that intertrial target-cue repetition did not enhance attentional capture by the cue, unlike its match with the target's defining features, on which capture was contingent. Although there was a numerical trend for a priming benefit in Experiment 1 and for color cues in Experiment 2, across experiments this effect was not significant on the RT measure and was in the reverse direction on the accuracy measure, $F < 1$ and $F(1, 48) = 3.60$, $p = .064$, $\eta_p^2 = .07$, respectively. A Bayesian inference analysis (Masson, 2011) on the interaction between target-cue priming and cue location provided strong evidence supporting the null hypothesis on the RT measure, $\Delta BIC = 3.93$, $BF = 7.13$, $p(H0|D) = 0.88$ and inconclusive evidence for smaller capture by primed cues on the accuracy measure, $\Delta BIC = .25$, $BF = 1.13$, $p(H0|D) = 0.53$.

If current goals and selection history both affected the pattern of activations on the priority map, they should have had similar effects, that is, both should have boosted attentional capture. Yet, this was not the case. Taken together, these findings suggest that while current goals affect pre-attentive attentional guidance, intertrial priming affects later, postselection processes (see Amunts et al., 2014; Irons et al., 2012; Yashar & Lamy, 2010; Yashar, White, Fang, & Carrasco, 2016, for evidence converging on the same conclusion).

Conclusions

Taken together, our findings suggest that although we have some ability to maintain two simultaneous attentional sets during visual search, attentional guidance by these sets is weaker than during search for only one target feature. In addition, the magnitude of this dual-target cost in attentional guidance seems to vary substantially between target dimensions and observers. To determine whether this pattern of results is specific to cross-dimensional disjunctive search or also occurs in within-dimension search, more research is needed, using the contingent-capture spatial cueing paradigm with a larger variety of dimensions.

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