Feature specificity in attentional capture by size and color

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Top-down guidance of visual attention has classically been thought to operate in a feature-specific manner. However, recent studies have shown that top-down visual attention can also be guided by information about target–nontarget feature relations (e.g., larger, redder, brighter). Here we recommend a minimal set of cues for differentiating between relational and feature-specific attentional guidance and examine contrasting predictions for the guidance of attention by size and color stimuli in a spatial cueing paradigm. In Experiment 1 we demonstrate that in search for size, when both feature-specific and relational strategies are available, participants adopt a relational search strategy. Experiment 2 shows that when feature-specific information is the only reliable information to guide attention to the target, participants are able to adopt a feature-specific set for size information. Finally, in Experiment 3 we extend our paradigm to differentiate between feature-specific and relational strategies in search for color. Together, these experiments help to clarify the conditions under which different attentional guidance strategies will be employed, and demonstrate a useful minimum cue requirement for differentiating between these two forms of top-down guidance. Implications for current theories of attention are discussed.

Introduction

It is a relatively undisputed claim that visual attention can be voluntarily shifted to different areas of a scene, either with a movement of the head and eyes (overt orienting; Posner, 1980), or with the eyes fixed on one point and only the "spotlight" of attention shifting (covert orienting; Helmholtz, 1867/1925; Posner, 1980). These voluntary shifts have been termed *endogenous* guidance of attention (Posner, 1980) and are characterized as being directed by factors internal to the agent, and in line with the agent's goals (Folk, Remington, & Johnston, 1992). In counterpoint to this, visual attention can also be guided by factors external to the agent, such as when one's attention is involuntarily drawn to the source of an unexpected loud noise. This has been termed *exogenous* guidance (Posner, 1980), or *attentional capture* (Yantis & Jonides, 1984), and the nature of this guidance has been a somewhat more controversial topic (Awh, Belopolsky, & Theeuwes, 2012; Folk et al., 1992; Rauschenberger, 2003).

Early investigations seemed to support an account of exogenous guidance in which attention was shifted involuntarily, in a manner solely dependent upon the properties of the visual stimuli presented, and insensitive to the intentions of the observer (Jonides & Yantis, 1988; Theeuwes, 1991, 1992; Yantis & Jonides, 1984, 1990). These accounts presumed specialized mechanisms in low-level visual processing that automatically capture attention when triggered by appropriate stimuli. Amongst the stimuli that are supposed to attract attention in a bottom-up, stimulus-driven manner are, for instance, sudden onsets (e.g., Jonides & Yantis, 1988; Yantis & Hillstrom, 1994), and items with a high feature contrast (e.g., Theeuwes, 1991, 1992).

This *bottom-up* account of attentional guidance was challenged by Folk et al. (1992). Adapting the spatial cueing paradigm developed by Posner (1980), they asked participants to report the identity of a target stimulus. Prior to the presentation of the target, a cue was briefly presented at one of the potential target locations. These cues could appear at the target location (*valid trials*) or at a location different to that of the subsequent target (*invalid trials*). Cue locations varied randomly so that the cue provided no informa-

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tion about the location of the upcoming target. Attentional capture is inferred if the responses are faster on valid trials than on invalid trials. This is based on the logic that, if the cue captures attention, then attention is already allocated to the target position on valid trials, which facilitates object identification. However, on invalid trials, attentional capture by the cue would slow responses, because attention is shifted away from the upcoming target location and has to be redeployed to the target in a time-consuming process. This difference between response times for valid and invalid trials is referred to as a *validity effect*, and is the main dependent measure of the Folk et al. (1992) paradigm. A significant validity effect is taken as evidence that a cue has captured attention, while a nonsignificant validity effect suggests that it has not.

In their study, Folk et al. (1992) showed that involuntary attentional capture can still be contingent on top-down task demands: In different blocks, they asked observers to report the identity of a target letter that was either an onset item or a specific color (e.g., red). They found that in blocks where the target was defined by an abrupt onset, only the onset cue captured attention, as indicated by a significant validity effect. Likewise, when the target was defined by a specific color, only the color cue captured attention. Importantly, however, they found no such difference in response times when a color cue was paired with an onset target, or when an onset cue was paired with a color target. From this, Folk et al. (1992) concluded that rather than being driven by bottom-up factors such as salience, attentional capture is driven by the observer's goals, based on the requirements of the task being performed. That is, attentional orienting is contingent on one's top-down attentional control settings. This has come to be known as *contingent capture* (Folk & Remington, 1998, 2008; Folk et al., 1992). Folk and Remington (1998) further clarified the influence of top-down factors on attentional guidance by showing that in search for a red target, red cues captured attention, but green cues did not. These results were reversed when the target was green. This demonstrated that attention could be guided to specific feature values, and not just particular domains such as color or onset.

Recently, Becker (2010) proposed a mode of attentional guidance that is not based on setting for a particular feature value (e.g., red), but by setting for feature relations, such as in a search for redder, larger, or brighter items. Studies testing the relational account against feature-specific accounts confirmed the predictions of the relational account (e.g., Becker, 2010; Becker, Folk, & Remington, 2010, in press). When observers had to search for an orange target among irrelevant yellow nontargets, a red cue captured attention more strongly than an orange cue—despite the fact that the red cue was more dissimilar from the target. When the orange target was embedded among red irrelevant nontargets, a yellow cue captured attention more strongly than a target-similar orange cue, consistent with a relational top-down setting for yellower (e.g., Becker et al., 2010). Across all conditions, the color contrasts of all stimuli were controlled, so that stronger attentional capture by the red or yellow cues could not be explained by bottom-up factors such as feature contrast or visual saliency (Becker et al., 2010; Becker & Horstmann, 2011).

Further support for the relational account of attentional guidance was provided by Becker et al. (in press). They demonstrated that even in search for an orange target surrounded by red and yellow nontargets, where the target was neither the reddest nor the yellowest item in the display, attention was guided in a relational manner. That is, singleton cues that shared the target relation of being between redder and yellower items captured attention, even when competing with target-colored items (e.g., yellow-orange cues presented with yellow and orange context items), while target matching cues did not capture attention if they did not share the target relation of being in-between (e.g., orange cues presented with yellow-orange and yellow context items). This makes a very strong case for attentional guidance by relations rather than features, as it demonstrates how even items that are not at one end of a presented relational continuum can guide attention in a relational manner.

Recently, Kiss and Eimer (2011) demonstrated attentional capture by size cues. In a cueing paradigm similar to that described above, participants were asked to report the orientation (vertical or horizontal) of a target bar that was either Large or Small, and was presented among Medium-sized nontarget bars. The Small and Large target bars were presented in different blocks of trials. Prior to the target display participants were presented with a spatially uninformative singleton cue (henceforth: cue) that was either Large or Small and embedded among five Medium-sized items (henceforth: context items). Kiss and Eimer found that in blocks where the target was Large, significant validity effects emerged for Large cues, but not Small cues, indicating attentional capture by the Large cue. This pattern of results was reversed for blocks containing the Small target. Kiss and Eimer described their results as feature-specific guidance by relative size, as the cues in their experiment were all smaller than their respective targets (e.g., the Large cue was smaller than the Large target), and thus guidance by exact target features was not possible.

This terminology, referring to relative size as a specific feature, is somewhat confusing. This is because the term "feature-specific" generally refers to an attentional focus on the particular value of a target feature, with all other values in the target domain excluded from the attentional set (e.g., Navalpakkam & Itti, 2007; Treisman & Sato, 1990; Wolfe, 1994). This definition is particularly relevant to the discussion of attentional guidance by size stimuli because "large" and "small" are not properties intrinsic to the object, as are color and shape, but are "features" defined in relation to other objects. A large object is only large when paired with smaller objects, and the same size that is considered large in one context could be considered small if surrounded by even larger objects. As such, when this paper refers to "feature-specific" guidance, it will be using the above definition of guidance by a match of absolute feature values. When we wish to discuss guidance by relative features we will refer to "relational" guidance, or guidance by "target–nontarget feature relations" (Becker, 2010).

By the above definitions, the results of Kiss and Eimer (2011) seem to be due to relational guidance. However, Kiss and Eimer did not design their experiment to differentiate between feature-specific and relational guidance, and thus their results can only be suggestive of a relational guidance strategy. As stated above, the cues they employed were a different absolute size to their corresponding targets, so there was no possibility for evidence of feature-specific guidance in their experiment.

To examine the relative contributions of feature-specific and relational strategies to attentional guidance, and indeed to truly establish the guidance strategy being employed under such conditions, simply testing the target features is not sufficient. This is because attentional capture by target-similar cues can be caused by both relational and feature-specific settings. To establish that a guidance strategy is feature-specific or relational, a minimum of four cue conditions is required. Two of these should test attentional capture by the target feature, once with it embedded in items of one relational direction (e.g., target size among larger context items), and once embedded in items of the other relational direction (e.g., target size among smaller context items). In addition to this, two more cue conditions that do not match the target feature should test the relational dimensions involved (e.g., a larger cue among target sized context items, and a smaller cue among target sized context items). If attention is set for the exact target feature value then only the two target-similar cues should capture attention, regardless of whether the cues are embedded among larger or smaller context items (and regardless of the size of the nontargets). If, on the other hand, attention is set for the relative size of the target, then only the two cues that have the same relative size (e.g., larger) should capture attention—regardless of whether the cue has the same size as the target or the nontargets. Only by examining the combined behavior across these four cue conditions will it be determined whether participants' attention is being guided by the specific target features, by target–nontarget relational information, or a combination of these.

The aim of the present studies was to determine the conditions under which feature-specific mechanisms will guide attentional capture by size (Experiments 1 and 2), and color (Experiment 3). Experiment 1 was similar to Kiss and Eimer (2011) except for a few key differences. Here, observers always had to search for a Medium target, and this was presented among either Large or Small nontargets in separate blocks. Also, a subset of cue stimuli employed in Experiment 1 was identical to the target stimuli, and thus absolutely matched the target size. This allowed us to orthogonally vary relational and feature-specific characteristics of the stimuli, allowing for the possibility of a results pattern that definitively indicated relational or feature-specific guidance. Preempting our results, Experiment 1 found attentional capture exclusively by cues that matched the target–nontarget relations in each block. No contribution of feature-specific attentional guidance was found. Experiment 2 sought to examine whether attentional guidance by feature-specific size information was possible by embedding a Medium target among larger or smaller nontargets that varied from trial to trial, such that the feature-specific information was the only consistent information by which the target could be identified. Under these conditions participants were able to adopt a feature-specific attentional set for size, and no contribution of relational guidance (e.g., from the previous trial) was found. Finally, Experiment 3 employed this paradigm to extend on previous work demonstrating relational guidance by color (Becker et al., 2010, in press). Participants were required to report an Orange target among either Yellow or Red nontarget items that randomly varied from trial to trial. Contrary to previous studies showing consistently relational guidance by color, the present results showed that participants were setting only for the specific target feature (Orange; e.g., Becker et al., 2010, in press).

Experiment 1

The aim of Experiment 1 was to clarify whether search in the size domain was driven by relational or feature-specific guidance mechanisms when the targets were presented under blocked conditions. The design was similar to that of Kiss and Eimer (2011), except cues were employed that could definitively differentiate between attentional capture by target features, and by target–nontarget relational information. This was achieved by having Small, Medium, and Large stimuli that were identical in both cue and target displays. Targets in this experiment were presented by blocks and were either Medium among Large nontargets or Medium among Small nontargets. These were cued by four cue conditions: two that matched the target feature (Medium among either Large context items or Small context items), and two that did not share the target feature (Small or Large cue among Medium context items). Two cues always matched the target's relational properties (e.g., a Medium target among Small nontargets is larger than its context, and this property is shared by both the Medium cue among Small context items, and the Large cue among Medium context items), and two cues had the opposite relation (e.g., Medium cue among Large context items and Small cue among Medium context items are both smaller).

If guidance in this experiment is relational, we would expect attention to be captured by both cues that share the target–nontarget relations, as demonstrated by significant validity effects in these conditions. No attentional capture would be expected by cues with the opposite relational properties (e.g., smaller cues in search for a larger target). However, if guidance is feature-specific we would expect attention to be captured only by those cues that share the target feature. That is, Medium cues among Large or Small context items should produce validity effects, but not Small or Large cues among Medium context items.

As we are interested in covert shifts of attention, eye tracking was employed in all experiments to ensure that the results were due to covert shifts of attention and not overt shifts of the eyes. Correspondingly, trials were excluded from analysis if participants moved their eyes more than 1.5° from fixation during the trial. Across all experiments this led to a loss of less than 2% of data.

Methods

Participants

Ten volunteers (five females, mean age $= 24.5$ years, $SD = 6.0$ years) from the University of Queensland, Australia, took part in Experiment 1. All participants had normal or corrected-to-normal vision and were given course credit or compensated at a rate of $10 per hour for their participation.

Apparatus

Stimuli were displayed on a 19-in. CRT color monitor (Samsung SyncMaster 957DF, Samsung, Seoul, South Korea) with a resolution of 1152×864 pixels and a refresh rate of 85Hz, controlled by an Intel Core 2 Quad CPU 2.83 GHz computer. A video-based infrared eye-tracking system was used (Eyelink 1000, SR Research, Ontario, Canada) with a spatial resolution of 0.10° of visual angle and a temporal resolution of 500 Hz. Participants were seated in a normally lit room, with their heads supported by the eye tracker's chin rest and forehead support, and they viewed the screen from a distance of 60 cm. For registration of manual responses, a standard USB mouse was used. Event scheduling and response time (RT) measurement were controlled by Matlab (The Mathworks, Inc., Natick, MA), using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007) on Windows XP (Microsoft Corporation, Redmond, WA).

Stimuli

Throughout the experiment the screen background was set to black (RGB: 0, 0, 0; xyY: 0.324; 0.282; 1.02). The task consisted of a series of displays (Figure 1) beginning with a fixation display, composed of a central white fixation cross ($0.30° \times 0.30°$; RGB: 255, 255, 255; xyY: 0.275; 0.282; 32.78) and four boxes ($2.00° \times 2.00°$), of which only the thin white outlines were visible (0.05° width). The boxes were placed at the 12, 3, 6, and 9 o'clock positions, 5.7° from the center of the display (measured to the center of the boxes).

The cue display consisted of the fixation display with the addition of a single white arrowhead beside each of the boxes, on the side of the box closest to the fixation cross (see Figure 1). The arrowheads were located at a distance of 0.60° from the edge of each box, and randomly pointed left or right. Three sizes of arrowheads were used: Small ($0.45° \times 0.40°$), Medium ($0.80° \times 0.70°$), and Large ($1.10° \times 1.00°$). On all cue trials the size of one arrowhead (designated the "cue") differed from those at the other three locations. We employed four cue conditions: Small cue among Medium context items (relationally smaller, target dissimilar), Medium among Large context items (relationally smaller, target similar), Medium among Small context items (relationally larger, target similar), and Large among Medium context items (relationally larger, target dissimilar). Thus, these four conditions provided two cues that were relationally smaller, two that were relationally larger, and two that matched the target feature (targets were Medium in size—see below).

The target display consisted of the fixation display with the addition of a leftward or rightward pointing arrowhead located centrally in each of the boxes. Identical arrowheads were used for both cue and target displays to ensure that the size of the cues exactly matched the size of the targets. The target was always Medium and was presented among either three Large nontargets (target smaller condition) or three Small nontargets (target larger condition). There were always two leftward and two rightward pointing arrowheads in the target display.

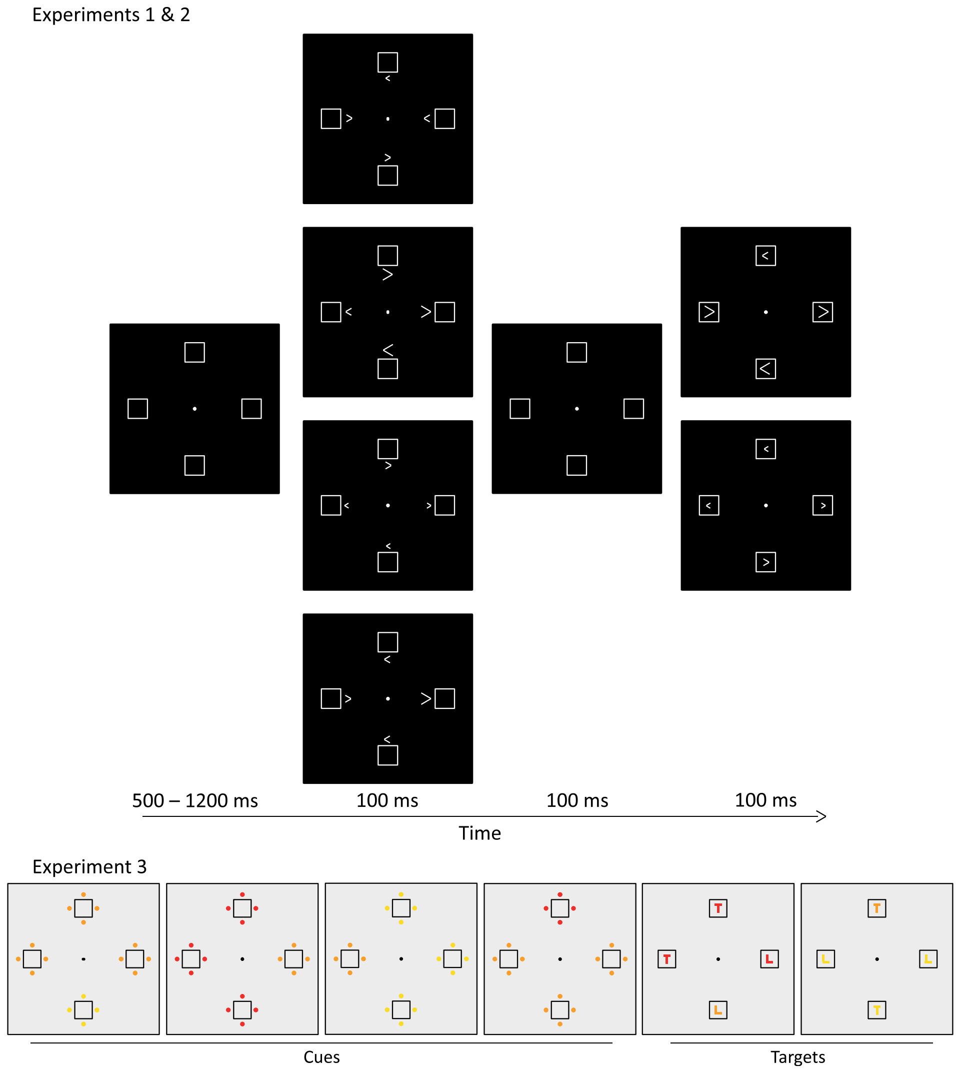

Figure 1. Stimuli from Experiments 1, 2, and 3. In Experiments 1 and 2, cues were Small among Medium context items, Medium among Large context items, Medium among Small context items, and Large among Medium context items, and targets were Medium among Large nontargets and Medium among Small nontargets. In Experiment 3 cues were Yellow among Orange context items, Orange among Red context items, Orange among Yellow context items, and Red among Orange context items, and targets were Orange among Red nontargets and Orange among Yellow nontargets.

Design

Across the experiment, target conditions (larger vs. smaller target) were blocked and the order of target conditions was counterbalanced across participants. The four cue conditions were presented randomly within each block. The target and cue locations were controlled so that each target type appeared with each cue in each position an equal number of times. As a result of this (controlled) randomization procedure, the location of the unique cue was uncorrelated with the target location, such that they appeared at the same location on 25% of trials. This also ensured that the cue was uninformative as to the location of the subsequent target, so that any evidence for attentional capture by the cue cannot be attributed to the deliberate use of a predictive cue. A complete crossing of all cue and location combinations gave a total of 128 trials per block (2 target types $\times$ 4 target positions $\times$ 4 cue positions $\times$ 4 cue displays). Each participant completed six blocks (three in each target condition), giving a total of 768 trials per experiment. This resulted in a total of 96 trials per cue/target combination (Small cue among Medium context items, Medium target among Large nontargets; Medium cue among Large context items, Medium target among Large nontargets; etc.).

Procedure

Participants were tested individually. Written and oral instructions were given prior to commencing the task. Participants were informed that their target was the oddly sized arrowhead in the display and that it

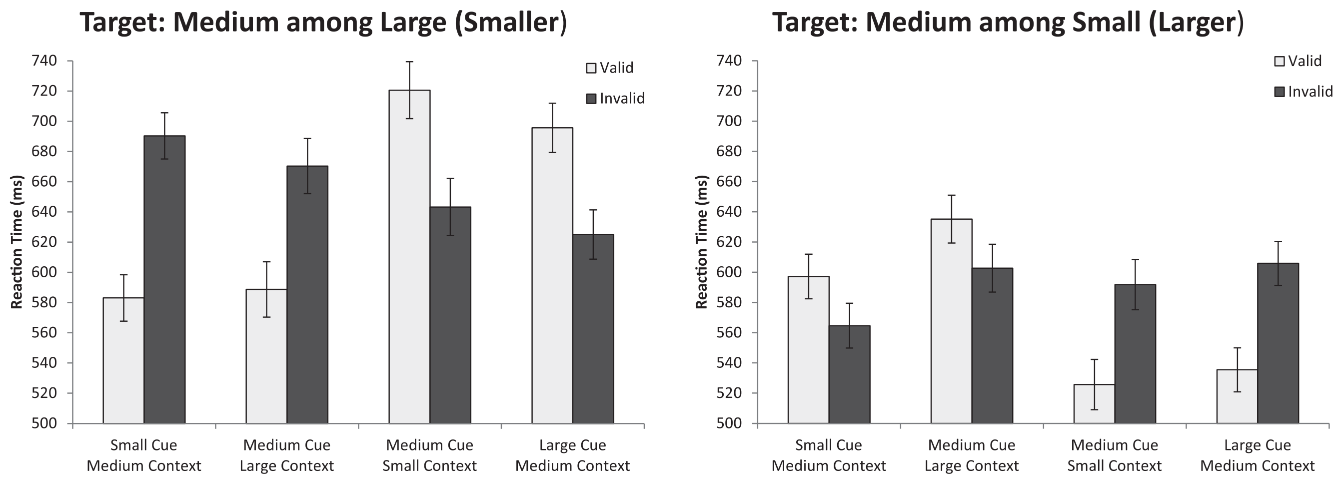

Figure 2. Results for Experiment 1. Note that the two cue conditions on the left are relationally smaller, the cue conditions on the right are larger, and the two cue conditions in the center match the target feature. Error bars represent *SEM* (Loftus & Masson, 1994).

would always be Medium in size. An example of a leftward and rightward arrowhead of each size was presented with the task instructions. They were instructed to ignore the cues that were presented outside the boxes and to respond to the target as quickly and accurately as possible, by pressing the left mouse button when the target pointed left, and the right mouse button when the target pointed right. Participants were instructed to maintain fixation on the central cross at all times, and eye tracking was employed to ensure compliance with this instruction (see fixation control below).

After receiving the instructions, participants were calibrated in the eye-tracker with a randomized nine-point calibration, after which the experimental trials began. The beginning of each trial was indicated by the appearance of the fixation display. Directly following this, a fixation control was implemented to ensure that participants maintained central fixation. The fixation control lasted up to 2000 ms, and a trial would only begin once the participant's gaze had been within 1.5° of the central fixation cross for 500 ms. If a participant's gaze did not rest on the fixation cross for 500 ms within this 2000 ms period, they were calibrated anew and the trial would begin again with the fixation control. Once participants had been fixating on the cross for 500 ms, the cue display was presented for 100 ms, followed by the fixation display for 100 ms, and then the target display for 100 ms. The target display was followed by a blank black screen, which remained visible until participants made their response. Immediately after responding, participants received written feedback consisting of "Correct" or "Wrong" printed in white (Arial Black, 15 point) at the center of the screen. Feedback was presented for 500 ms on correct trials and 1500 ms on incorrect trials. After an intertrial interval of 250 ms, during which a blank black screen was presented, the next trial again started with the fixation control.

Participants were encouraged to take a short break after every 128 trials. The first 30 trials from each participant were discarded as practice trials. On average, it took 45 min to complete the experiment.

Results

The mean RT for each cue and target condition is depicted in Figure 2, and the mean errors for Experiment 1 are displayed in Table 1, together with the error comparison statistics. Error trials (12.33% of trials) were excluded from the RT analyses. In addition, RTs shorter than 200 ms or longer than 1200 ms were excluded from all analyses, which led to a loss of 3.04% of all data.

RT data were analyzed in a mixed model ANOVA, incorporating the within-participants factors of target (two levels: Medium among Large, and Medium among Small), cue condition (four levels: Small among Medium, Medium among Large, Medium among Small, and Large among Medium; Figure 1), validity (two levels: valid and invalid), and the between-participants factor of block order (two levels: Target Larger followed by Target Smaller, or vice-versa). The main effect of block order was not significant, nor did it enter into any significant interactions ($ps > 0.146$), suggesting the pattern of attentional capture within each target condition was the same regardless of whether it was the first or second target condition participants were exposed to. However, a significant three-way interaction between target, cue, and validity emerged, $F(3, 24) = 39.36$, $p < 0.001$, $\eta_p^2 = 0.83$ (Figure

Experiment 1				
Target = Medium among Large				
Cue	S in M	M in L	M in S	L in M
Valid	6.75 (1.33)	5.77 (2.24)	22.30 (3.65)	23.42 (4.82)
Invalid	25.00 (4.28)	16.51 (3.34)	13.11 (2.28)	13.49 (2.70)
t(9)	4.06	3.44	3.88	2.75
p	0.003	0.007	0.004	0.023
Target = Medium among Small				
Cue	S in M	M in L	M in S	L in M
Valid	5.56 (1.25)	8.49 (3.28)	2.29 (1.07)	5.55 (1.32)
Invalid	4.39 (0.80)	8.42 (2.94)	9.77 (2.10)	14.74 (2.87)
t(9)	1.00	0.03	3.31	2.93
p	0.346	0.975	0.009	0.017
Experiment 2				
Cue	S in M	M in L	M in S	L in M
Valid	11.06 (2.23)	6.26 (1.47)	8.59 (1.47)	11.48 (2.83)
Invalid	12.25 (2.15)	13.70 (2.72)	15.37 (2.25)	13.10 (3.24)
t(9)	0.60	3.61	4.98	0.79
p	0.566	0.006	0.001	0.452
Experiment 3				
Cue	Y in O	O in R	O in Y	R in O
Valid	5.85 (1.50)	4.55 (0.94)	4.72 (1.19)	5.74 (1.06)
Invalid	6.23 (1.09)	6.53 (0.90)	6.89 (1.21)	6.42 (1.12)
t(15)	0.27	2.31	2.03	0.75
p	0.795	0.036	0.060	0.467

Table 1. Mean error scores (percentages) and 1 *SEM* (in brackets) of valid and invalid trials for Experiments 1, 2, and 3, presented with the results of paired-samples *t* tests between valid and invalid conditions for each cue. *Notes*: Cues: S in M = Small cue among Medium context items. M in L = Medium cue among Large context items. M in S = Medium cue among Small context items. L in M = Large cue among Medium context items. Y in O = Yellow cue among Orange context items. O in R = Orange cue among Red context items. O in Y = Orange cue among Yellow context items. R in O = Red cue among Orange context items.

2). To examine this interaction we conducted paired-samples *t* tests.

When the target was Medium among Large nontargets, valid trials were significantly faster than invalid trials for Small cues among Medium context items, $t(9) = 6.99$, $p < 0.001$, and Medium cues among Large context items, $t(9) = 4.47$, $p = 0.002$. In contrast to this, valid trials were significantly slower than invalid trials for Medium cues among Small context items, $t(9) = 4.10$, $p = 0.003$, and Large cues among Medium context items, $t(9) = 4.34$, $p = 0.002$. That is, when the target was relationally smaller than the nontargets, participants' attention was captured by smaller cues, and was not systematically influenced by the specific target feature.

When the target was Medium among Small nontargets, valid trials were marginally slower than invalid trials for Small cues among Medium context items, $t(9) = 2.20$, $p = 0.056$, and Medium cues among Large context items, $t(9) = 2.06$, $p = 0.070$. However, valid trials were significantly faster than invalid trials for Medium cues among Small context items, $t(9) = 3.97$, $p = 0.003$, and Large cues among Medium context items, $t(9) = 4.84$, $p = 0.001$. That is, when the target was relationally larger than the nontargets, participants' attention was captured by larger cues, and again was not systematically influenced by the specific target feature.

The mean error scores mimicked the RT results, indicating that the results were not due to a speed-accuracy trade-off (see Table 1).

Discussion

The aim of Experiment 1 was to clarify whether search in the size domain was driven by relational or feature-specific guidance mechanisms when the targets were presented under blocked conditions. The results were clear. Those cues that matched the target relation captured attention, while those that matched the specific features of the target did not guide attention unless they also matched the target relation. Thus, no support was found for feature-specific guidance in Experiment 1. This was the case even after the direction of the target–nontarget relation was reversed halfway through the experiment.

Interestingly, in both target conditions, cues that had the opposite feature relation to the target produced a reverse validity effect, with participants slower to respond on valid trials than invalid. We can speculate that this may be due to attention being captured to one of the context items (which all shared the target–nontarget relation), or to the broad region occupied by the three context items, and then needing to be redeployed to the location of the target in a time-consuming manner. Another possibility is that locations with the "wrong" feature relations were inhibited, delaying attentional deployment to targets that subsequently appear in these locations (Eimer, Kiss, Press, & Sauter, 2009; Lamy, Leber, & Egeth, 2004). The current data do not clearly favor one interpretation over the other.

Experiment 1 provided clear evidence of relational guidance, with no evidence that attentional capture was modulated by exact feature matches. A question Experiment 1 leaves unanswered is whether feature-specific attentional guidance is possible for stimuli defined by size. It is conceivable that calibrating the attentional system for a specific size may not be possible, as objects in the world present a different retinal size at different distances from the observer, making specific size an unreliable metric to search by. Indeed, it may be that in searching for an item defined by size, only relational guidance is used, as the size of an object relative to its surroundings rarely changes. Experiment 2 was conducted to examine this possibility.

Experiment 2

The aim of Experiment 2 was to determine whether it is possible to calibrate the attentional system to respond to a specific size. As in Experiment 1, the target in Experiment 2 was always Medium sized, but to encourage a feature-specific attentional set, the nontarget items in the target frame were randomly varied between Small and Large, rather than being blocked as they were in Experiment 1. We hypothesized that participants should adopt a feature-specific setting for the specific size of the target in this experiment, as the target size always remained constant while the size of the surrounding items randomly varied, rendering feature relations unreliable. If a feature-specific attentional set for size is possible, only the target matching cues will capture attention. However, if observers are unable to adopt a feature-specific setting in search for size, then we would expect the pattern of results to be ambiguous, with relational set potentially varying from trial to trial.

Method

Participants

Thirteen volunteers (nine female, mean age = 22.08 years, $SD = 2.62$ years) from the University of Queensland, Australia, took part in Experiment 2. All participants had normal or corrected-to-normal vision and were compensated with course credit or at a rate of $10 per hour for their participation.

Apparatus

The apparatus in Experiment 2 were the same as those used in Experiment 1.

Stimuli

The stimuli in Experiment 2 were identical to those used in Experiment 1.

Design

The design of Experiment 2 was identical to Experiment 1, except that the two target conditions were randomly intermixed throughout the entire experiment. That is, the target was always a Medium item, and on half of all trials this target was presented among Large nontargets, and on the other half the target was presented among Small nontargets. The total number of trials, and the number of trials for each target, and cue/target combination, were identical to Experiment 1.

Procedure

The procedure for Experiment 2 was identical to that of Experiment 1. As in Experiment 1, participants were informed that they had to search for the Medium-sized arrowhead target and to respond to its orientation, while their gaze remained fixated on the central fixation cross. Participants were also informed that the target was randomly presented among Small or Large nontargets.

Results

Three participants were excluded from Experiment 2 for having more than 30% errors. The error statistics for the remaining participants are displayed in Table 1. Error trials were excluded from RT analyses, leading to a loss of 12.53% of trials. In addition, RTs shorter than 200 ms or longer than 1200 ms were excluded from all analyses, which led to a further loss of 4.61% of all data. As order of target presentation was randomized,

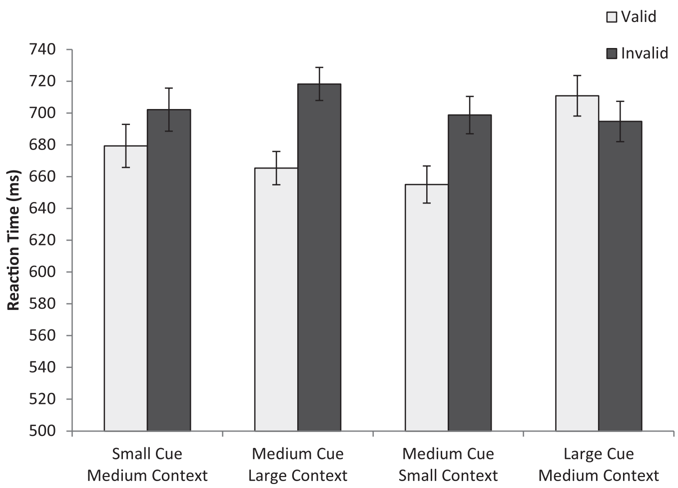

Figure 3. Results of Experiment 2. Note that the two cue conditions on the left are relationally smaller, the two cue conditions on the right are larger, and the two cue conditions in the centre match the target feature. Error bars represent *SEM* (Loftus & Masson, 1994).

all data were collapsed across target condition to increase statistical power.

RT data were analyzed with a 4 (cue condition: Small among Medium, Medium among Large, Medium among Small, and Large among Medium) × 2 (validity: valid and invalid) within-participants ANOVA. The results revealed a significant main effect of cue, $F(3, 27) = 4.83$, $p = 0.013$, $\eta_p^2 = 0.35$, and a significant main effect of validity, $F(1, 9) = 11.17$, $p = 0.009$, $\eta_p^2 = 0.55$. These were qualified by a significant interaction between cue and validity, $F(3, 27) = 8.03$, $p = 0.003$, $\eta_p^2 = 0.47$ (Figure 3). Paired samples *t* tests were conducted to examine this interaction and revealed that participants were significantly faster to respond on valid trials, compared to invalid trials, when the cue was Medium among Large context items, $t(9) = 5.08$, $p = 0.001$, and when the cue was Medium among Small context items, $t(9) = 3.74$, $p = 0.005$. However, there was no difference between response times to valid and invalid trials when the cue was Small among Medium context items, or Large among Medium context items ($ps > 0.12$). That is, when the target was consistently the same size, but the target–nontarget size relations changed regularly, cues captured attention only when they exactly matched the target size. These results were mirrored in the error data (Table 1).

Previous studies (e.g., Folk & Remington, 2008) have looked at the effects that target condition on trial $n - 1$ might have on the attentional capture by the cue on trial *n*, when two target conditions are randomly intermixed. It is plausible that relational information could be having some influence on the pattern of attentional capture in this experiment, such that exposure to a particular target–nontarget relation induces a matching relational set until a target of the opposite relation is encountered. This effect may be masked by averaging across opposite effects in the different target conditions. To examine the data for possible intertrial effects, we divided our trials into two groups, depending on the target on the previous trial (Medium among Large or Medium among Small). These were entered into a 4 (cue condition) × 2 (validity) × 2 (previous target) within-participants ANOVA of reaction times, which found no interaction between previous target and cue condition, and no three way interaction ($ps > 0.41$). This suggests that the pattern of attentional capture on a given trial was not significantly influenced by the target condition on the previous trial.

Discussion

Experiment 2 sought to determine whether a feature-specific set for size stimuli could be adopted by the attentional system. The results show clearly that it can. The nonsignificant trend towards faster reaction times on valid trials than invalid trials for the Small cue among Medium context items (Figure 3) may suggest participants lapsed into relational capture on a small number of trials. However, this possibility does not alter our primary conclusion that on at least the majority of trials, participants' attention was captured by only those stimuli that shared the specific target size.

It is interesting to note that, though Experiment 2 demonstrates that unreliable target–nontarget relations can lead to a feature-specific search strategy if the target feature remains constant, participants in Experiment 1 did not adopt a feature-specific strategy in the second block, when the target–nontarget relations were reversed. This suggests that a single change in the target–nontarget relations in a blocked design is not sufficient to induce a feature-specific attentional set with the current stimuli. In this respect, the results are similar to those of Leber and Egeth (2006) who observed that once subjects adopted a search mode they tended to perseverate in that mode even when the changed situation favored a different mode. Other than our results and those of Leber and Egeth (2006), the issue of switching attentional sets has received little attention and will require more research to fully understand the factors that determine which set subjects adopt. Our results and those of Leber and Egeth (2006) suggest that past history, not just the immediate task requirements, contribute substantially to determining the attentional setting.

Experiment 3

In Experiment 2, participants were able to adopt a feature-specific attentional set in a size search task. The aim of Experiment 3 was to critically test whether a feature-specific setting can also be adopted in the color domain. Of note, most studies that have compared the relational account to feature-based views have used color search tasks, all of which consistently showed relational results (Becker, Folk, & Remington, 2010, in press; but see Becker, Harris, Venini, & Retell, in press). Here, we used similar colors as in previous studies and tested capture of attention in our new paradigm that allows distinguishing relational capture from feature-specific capture when the nontarget colors randomly vary. With this, Experiment 3 serves to apply the current paradigm to a domain other than size to examine its utility in differentiating between feature-specific and relational results patterns among other feature domains.

In Experiment 3, participants had to search for an Orange target among three nontargets that were randomly all Yellow or all Red. With this, the target was randomly and unpredictably either redder or yellower than the nontargets, preventing successful localization of the target in virtue of its feature relationships. Attentional capture was tested by a unique colored cue in four different cueing conditions, where the cue was an Orange singleton presented among three Red or three Yellow context items or was a Red or Yellow singleton presented among three Orange context items.

If attention can be set for the specific target color (Orange), only the Orange cues should capture attention, independently of the colors of the other context items in the cueing display. If, on the other hand, attention can only be set for the target–nontarget relationships in search for color, then all cues should capture attention equally strongly (as they were all either redder or yellower than their context items), with relational set potentially varying from trial to trial. Finally, in the absence of a constant feature relation, attention could be set for the odd color regardless of its specific feature value or its relative color (Bacon & Egeth, 1994; Eimer & Kiss, 2010; Folk & Anderson, 2010). In this situation all singleton cues should capture attention, with no evidence of intertrial effects present.

Method

Participants

Sixteen volunteers (10 female, mean age = 23.25 years, $SD = 9.08$ years) from the University of Queensland, Australia, took part in Experiment 3. All participants had normal or corrected-to-normal vision and reported normal color vision. Participants were compensated with course credit or at a rate of $10 per hour for their participation.

Apparatus

The apparatus for Experiment 3 were the same as reported previously.

Stimuli

The display background for Experiment 3 was gray (RGB: 240, 240, 240; xyY: 0.275; 0.280; 28.10), and the fixation cross and boxes were black.

The cue display consisted of the fixation display with the addition of four dots (0.40° × 0.40°) around each of the boxes, at a distance of 0.30° from the edge of each box (Figure 1). All cueing displays consisted of one set of dots (the cue) with a color different from the dots at the other three locations, which all had the same color (the context items). The target, nontargets, and cues could have three colors, Red (RGB: 255, 0, 0; xyY: 0.584; 0.339; 7.07), Orange (RGB: 255, 160, 0; xyY: 0.480; 0.452; 13.27), or Yellow (RGB: 255, 220, 0; xyY: 0.432; 0.502; 20.84). Altogether four cue conditions were tested: a Yellow cue among Orange context items (relationally yellower, target dissimilar), Orange cue among Red context items (relationally yellower, target similar), Orange cue among Yellow context items (relationally redder, target similar), and Red cue among Orange context items (relationally redder, target dissimilar). Thus, these four conditions provided two cues that were relationally yellower than their surroundings, two that were redder, and two that matched the target feature (the target was Orange—see below).

The target display consisted of the fixation display with the addition of a "T" or an "L" located centrally in each of the boxes (Figure 1). The target was always Orange and was presented among either three Red nontargets or three Yellow nontargets.

Design

The design of Experiment 3 was identical to Experiment 2, except using the above cue and target conditions.

Procedure

The procedure for Experiment 3 was identical to that of Experiment 1, except that participants were informed their targets would be the oddly colored letter and that this letter would always be Orange. Participants were required to press the left mouse button if the Orange letter was an "L" and the right mouse button if it was a "T."

Results

Error statistics for Experiment 3 are displayed in Table 1. Error trials were excluded from analyses, leading to a loss of 6.18% of trials. In addition, RTs shorter than 200 ms or longer than 1200 ms were excluded from all analyses, which led to a further loss of 1.47% of all data. As nontarget color changed randomly from trial to trial, data were collapsed across the two target conditions (Orange target among Red nontargets and Orange target among Yellow nontargets).

RT data were analyzed in a 4 (cue condition: Yellow cue among Orange context items, Orange cue among Red context items, Orange cue among Yellow context items, and Red cue among Orange context items) × 2 (validity: valid and invalid) within-participants ANOVA. This revealed a significant main effect of cue, $F(3, 45) = 3.62$, $p = 0.031$, $\eta_p^2 = 0.19$, and a significant main effect of validity, $F(1, 15) = 17.18$, $p = 0.001$, $\eta_p^2 = 0.53$. These were qualified by a significant interaction between cue condition and validity, $F(3, 45) = 10.27$, $p = 0.002$, $\eta_p^2 = 0.41$ (Figure 4). Paired-samples *t* tests were conducted to examine this interaction and revealed that participants were significantly faster to respond on valid trials, compared to invalid trials, when the cue was Orange among Red context items, $t(15) = 4.50$, $p < 0.001$, or when it was Orange among Yellow context items, $t(15) = 4.22$, $p = 0.001$. There was no difference between the RTs of valid and invalid trials when the cues were Yellow among Orange context items or Red among Orange context items (*p*s > 0.2). That is, when the target was consistently Orange and was randomly paired with either Red or Yellow nontargets, and thus was randomly redder or yellower than the nontargets, cues captured attention only when they exactly matched the target color Orange. Analyses of error data matched this pattern of results (Table 1).

Again, we analyzed intertrial effects by dividing our trials into two groups, depending on the target on the previous trial (Orange among Yellow nontargets or Orange among Red nontargets). These were entered into a 4 (cue condition) × 2 (validity) × 2 (previous target) within-participants ANOVA, which found no interaction between previous target and cue condition, and no three-way interaction (*p*s > 0.31). This suggests that the pattern of attentional capture on a given trial was not significantly influenced by the target condition on the previous trial.

Discussion

Experiment 3 sought to extend the findings of Experiment 2 to the color domain and thus provide a

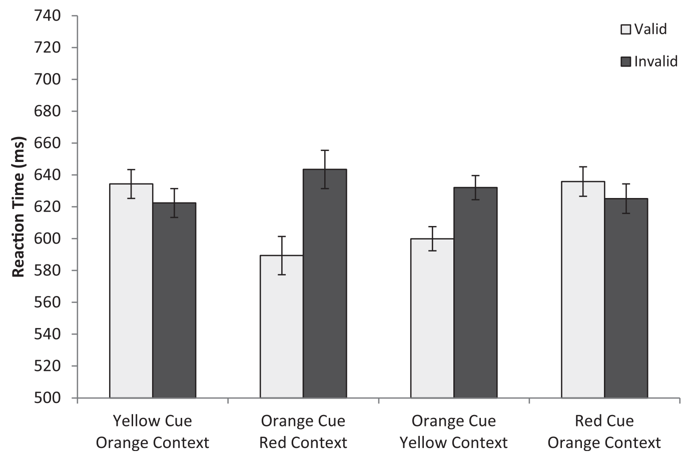

Figure 4. Results of Experiment 3. Note that the two cue conditions on the left are relationally yellower, the two cue conditions on the right are redder, and the two cue conditions in the centre match the target feature. Error bars represent *SEM* (Loftus & Masson, 1994).

definitive demonstration of feature-specific contingent capture for color when the colors being tested vary along a relational continuum. Here we employed the continuum of Yellow through Orange to Red, and tested participants' attentional control settings when the target was always the same color (Orange), while its surrounding colors (Red or Yellow) varied, rendering target–nontarget relations unreliable.

We found results consistent with the predictions of a feature-specific set, with attentional capture demonstrated only by singleton cues that shared the target color. These results unequivocally show that a feature-specific setting for a particular color is possible. Given that a feature-specific setting was standardly assumed in many previous studies on contingent capture (e.g., Ansorge & Heumann, 2003; Becker, Ansorge, & Horstmann, 2009; Folk & Remington, 1998, 2006; Ludwig & Gilchrist, 2002), this outcome may not seem too surprising. Yet, all of these studies were consistent with a set for the target–nontarget relationship (e.g., Becker, 2010). Some other studies have shown attentional capture by target-similar cues under conditions in which the underlying target–nontarget relations were unclear and a feature-specific bias for the target seemed perhaps more probable than a bias for feature relationships (e.g., Eimer, Kiss, Press, & Sauter, 2009; Irons, Folk, & Remington, 2012; Lamy, Leber, & Egeth, 2004). However, this is the first study that has used appropriate cue conditions to demonstrate feature-specific search for color and size while ruling out an alternative set for relational properties. The absence of intertrial effects in this study rules out any possibility of guidance attributable to a rapidly updating attentional setting for target–nontarget feature relations. As such, this is the first study that clearly invalidates a strong version of the relational account that all instances of feature-specific search are due to top-down tuning to the target's relative feature (e.g., Becker, 2010, in press). The present results clearly demonstrate that relational search is not ubiquitous and can be abolished by rendering the target–nontarget relationships unreliable.

General discussion

The broad aim of the present study was to examine the nature of feature-specificity as regards top-down attentional control settings. Participants were required to report the identity of a search target defined either by its unique size (Experiments 1 and 2), or by its color (Experiment 3). Target–nontarget relations were varied either across blocks (Experiment 1), or randomly from trial to trial (Experiments 2 and 3). In all three experiments, targets were randomly pre-cued by one of four cue displays. The singleton in these cue displays could have the same or opposite feature relation to the target–nontarget relation (Experiments 1 and 2: larger or smaller; Experiment 3: redder or yellower), and could have the same defining feature as the target (Experiments 1 and 2: Medium size; Experiment 3: Orange), or a different feature. This allowed us to contrast two previously established forms of top-down attentional capture: feature-specific contingent capture (Folk et al., 1992), and relational capture (Becker, 2010; Becker et al., 2010, in press).

In Experiment 1 we hypothesized that if participants' attention was being guided by relational information, then in each block significant validity effects would be produced for the two cues that match the target–nontarget relation for that block (e.g., Small cue among Medium context items and Medium cues among Large context items, when the target was Medium among Large nontargets, and thus smaller), but not for the two cues that had the opposite relation. Alternately, if attention was set for the specific target feature, then in both blocks validity effects would be produced by the two cues that matched the target feature (Medium cues among Large context items and Medium cues among Small context items), but not by the two cues that differed from the target feature. The results of Experiment 1 unambiguously supported relational guidance as the attentional mechanism being employed. In each target condition, both of the cues matching the target–nontarget relation produced significant validity effects, while no support was found for feature-specific capture.

In Experiment 2 we created conditions that favored a feature-specific search strategy over relational search, to determine whether participants were able to tune attention to the physical size of the target, independently of the size of context items. To do this we randomized the presentation of target conditions from trial to trial, so the target–nontarget relationships became an unreliable source of guidance, while the target feature remained constant. Using the same cue conditions as in Experiment 1, attentional capture in Experiment 2 was only observed for those cues that matched the target feature, confirming that feature-specific size information is indeed available for use in guiding attention.

In Experiment 3 we sought to further validate the current design by applying it to a different feature domain, and in doing so extend the results of previous studies that have demonstrated relational guidance for color. Experiment 3 tested guidance by feature-specific color information in analogous conditions to Experiment 2—with the nontarget colors varied randomly. The results showed that, in these conditions, only cues matching the target color (Orange) captured attention. These results provide the first demonstration of feature-specific color search in conditions that allow detection of relational strategies.

Combined with previous results demonstrating relational capture in color search when target conditions are blocked (Becker et al., 2010), the experiments presented here paint a picture whereby relational strategies are employed when searching for a specific target under blocked nontarget conditions, and feature-specific strategies are employed in search for a specific target when target–nontarget feature relations become unreliable. Notably, relational strategies seem to be employed under blocked conditions (Experiment 1 and Becker et al., 2010), despite a consistent and reliable target feature being present on all trials in these conditions, and despite the fact that feature-specific information is clearly able to guide attention under certain circumstances (e.g., Experiment 2). Thus, relational strategies seem to be preferred to feature-specific strategies when both are available.

It is also worth noting that nothing about the target was changed from trial to trial in these experiments. The only trial-to-trial differences were in the ensemble of nontargets on the target frame. Thus, the use of a relational search strategy in Experiment 1, and a feature-specific strategy in Experiments 2 and 3, is evidence that the attentional set is strongly driven by the demands of target–nontarget discrimination, not by target identification alone, and that the attentional system has some flexibility in how it achieves this. The value of this finding is not only in its new view of attentional capture, but also in its implications for the interpretation of existing work.

The present experiments also have implications for feature map theories of visual search, such as Feature Integration Theory (FIT; Treisman & Gelade, 1980) and Guided Search (GS; Wolfe, 1994, 2007). These theories posit that features perceived by the visual system are processed in parallel, activating a number of specific "feature maps." Red items in a display will activate regions of a feature map dedicated to red, horizontal things will activate regions of a horizontal feature map, and so on. Finally, these maps are summed (using the term in a colloquial, rather than a strictly computational sense) to form a master activation map, applying some multiplicative weighting to the contribution of those feature maps that are relevant to the current task (top-down influence). Attention is allocated to the region of the master map that has the highest activation.

However, the present results provide a problem for these theories. Some feature map theories (e.g., FIT; Treisman & Gelade, 1980) posit maps for each individual feature, with top-down influence achieved by weighting relevant feature maps. It is unclear how these theories would explain the results of Experiment 1 and other research demonstrating relational results (e.g., Becker et al., 2010, in press; Hodsoll & Humphreys, 2001; Hodsoll, Humphreys, & Braithwaite, 2006; Kiss & Eimer, 2011; Kiss, Grubert, & Eimer, 2012). A key issue here is that for relational guidance to occur, the item furthest along the relevant continuum must draw attention (e.g., the largest item). Thus, in relational guidance weights cannot be applied to pre-specified feature values, as there is no way to determine in advance, for example, the size of the largest item in the display. Thus, for relational capture to take place in these models there needs to be a step between the activation of specific feature maps and their integration into a master map, that compares all maps in the relevant relational dimension and applies the weighting to the activated map that lies furthest along the continuum. There is currently no such step in these models. Furthermore, it is unclear how relational dimensions might be incorporated into such a model when one can imagine a seemingly endless list of possible target–nontarget relations.

The present results also seem inconsistent with other theories of visual attention such as the GS model that assume that attention can only be tuned very broadly to a limited number of basic color categories (red, yellow, blue, and green; Wolfe, 1994, 2007). Similarly, the results seem inconsistent with models claiming that feature-specific selection is achieved by segregating feature space into a to-be-attended and to-be-ignored region (feature divider account, Huang & Pashler, 2005). These models may be able to explain relational results by the application of weighting to the dimension furthest along the relational search continuum (e.g., red, in search for redder items); however, it is unclear how these models would explain the feature-specific results of Experiments 2 and 3. For example, the target in Experiment 3 was Orange and was directly sandwiched between the possible nontarget colors of Red and Yellow. With this, the target could not be selected by virtue of a red or yellow channel but would require a dedicated channel signaling the presence of orange. Similarly, across trials, the target color was nonlinearly separable from the nontarget colors; that is, it was not possible to delineate the target from the possible nontarget colors by drawing a single straight line through feature space (e.g., D'Zmura, 1991; see also Bauer, Jolicoeur, & Cowan, 1996a, 1996b). Thus, the target could not be located by tuning attention to any broadly defined area in feature space. The fact that only Orange cues captured attention suggests that attention was set for a narrow interval in color feature space, which contained Orange and excluded both Yellow and Red (e.g., Navalpakkam & Itti, 2007). Such a setting would require a nonlinear classifier, or the ability to tune attention fine-grainedly to specific regions in feature space, which is at odds with the assumption that attention can only be tuned to broad categorical channels (e.g., Red, Yellow; Wolfe, 1994, 2007), or to broad regions of feature-space (Huang & Pashler, 2005).

In sum, the present results showing both relational and fine-grained feature-specific search present a problem for current models of attention, because relational search is difficult to explain with a fine-grained model proposing a multitude of different feature maps, whereas feature-specific search is difficult to explain with a broad, categorical account.

The experiments in this paper employed manipulations of size (Experiments 1 and 2) and color (Experiment 3) to explore the nature of feature-specificity in top-down guidance of attention. We introduced a minimal set of cue conditions required to differentiate between feature-specific and relational guidance. In Experiment 1 we applied these conditions to determine whether attention was guided by feature-specific or relational strategies in search for a target defined by size. The results suggested that when target conditions were blocked, a relational search strategy was employed. Experiment 2 further validated the use of these cue conditions to demonstrate that a feature set for size is indeed possible when a relational strategy is discouraged, and that in this scenario, no trial-by-trial carryover of relational information contributes to guidance. Experiment 3 extended these results to the color domain. Together these experiments, coupled with past studies (Becker et al., 2010, in press) suggest that when both relational and feature-specific strategies are possible to complete a search task, relational strategies will be employed. However, feature-specific strategies can be employed when the specific target feature is the only reliable information available to the attentional system.

Keywords: attentional capture, spatial cueing, feature-specific, relational, feature attention

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