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Visual Search for Color and Shape: When Is the Gaze Guided by Feature Relationships, When by Feature Values?

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One of the most widespread views in vision research is that top-down control over visual selection is achieved by tuning attention to a particular feature value (e.g., red/yellow). Contrary to this view, previous spatial cueing studies showed that attention can be tuned to *relative features* of a search target (e.g., redder): An irrelevant distractor (cue) captured attention when it had the same relative color as the target (e.g., redder), and failed to capture when it had a different relative color, regardless of whether the distractor was similar or dissimilar to the target. The present study tested whether the same effects would be observed for eye movements when observers have to search for a color or shape target and when selection errors were very noticeable (resulting in an erroneous eye movement to the distractor). The results corroborated the previous findings, showing that capture by an irrelevant distractor does not depend on the distractor's similarity to the target but on whether it matches or mismatches the relative attributes of the search target. Extending on previous work, we also found that participants can be pretrained to select a color target in virtue of its exact feature value. Contrary to the prevalent feature-based view, the results suggest that visual selection is preferentially biased toward the relative attributes of a search target. Simultaneously, however, visual selection can be biased to specific color values when the task requires it, which rules out a purely relational account of attention and eye movements.

Keywords: relational theory, contingent capture, biased competition, similarity effect, oculomotor capture

Different objects in the visual field are not all appraised at once, with all the information contained in a visual scene processed in parallel. Instead, the eyes are moved to different locations in the visual scene, and information from successive impressions is used to stitch together our rich mental representation of the scene (e.g., Posner, 1980). Given that conscious appraisal of a scene relies on a serial, time-consuming process, it is important to find out which items are selected with the first glance. Previous research has shown that eye movements strongly depend on how attention is allocated to stimuli. Immediately prior to saccade execution, covert attention is shifted to the saccade target location (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Klein, 1980; Kowler, Anderson, Doshier, & Blaser, 1995; Remington, 1980; Rizzolatti, 1983; Sheliga, Riggio, & Rizzolatti, 1995; Shepherd, Findlay, & Hockey, 1986; see also Bichot, Rossi, & Desimone, 2005, and Moore & Armstrong, 2003). Attention is allocated to the

intended saccade location even when observers are instructed to covertly attend to an entirely different location, indicating that attention is always allocated to the intended saccade location (e.g., Deubel & Schneider, 1996). Although it is possible to shift attention covertly, without moving the eyes, such covert attention shifts can only be made while the eyes remain fixated, and will elongate the dwell time or saccade latencies of the coming saccade (because it is not possible to saccade to an unattended location, and covert attention shifts are time consuming; e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Klein, 1980; Kowler et al., 1995; Rizzolatti, 1983; Sheliga et al., 1995; Shepherd et al., 1986). Given this coupling between attention and eye movements, the question of what determines our gaze behavior is closely linked to the question of how we allocate attention.

Guidance of Attention: Theories and Evidence

Attention and eye movements can be guided to particular regions in a goal-directed manner, or they can be reflexively drawn to certain locations in a stimulus-driven manner (e.g., Jonides, 1981; Yantis, 1993, 2000). How top-down and bottom-up mechanisms interact in visual selection is still intensely debated (e.g., Beck & Kastner, 2009; Navalpakkam & Itti, 2006). A widely held view is that salient items with a high feature contrast can automatically attract attention, independently of the intentions and goals of the observer (e.g., Beck & Kastner, 2009; Itti & Koch, 2000; Li, 2002; Navalpakkam & Itti, 2007; Reynolds & Desimone, 2003; Theeuwes, 1994, 2010; Yantis & Egeth, 1999; Zhang, Zhaoping, Zhou, & Fang, 2012).

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On the other hand, visual selection also depends on the goals and intentions of the observer: The intention to find a particular object or feature (e.g., a red-colored item) can override effects of bottom-up saliency and modulate attention to ignore task-irrelevant salient items and select only task-relevant items (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Ludwig & Gilchrist, 2002; Wolfe, 1994).

To study the factors that determine selection, for example, in visual search, previous studies have often added an irrelevant salient item (“distractor”) to the search display, and tested whether the distractor can attract attention while observers search for a predefined target among several nontargets (e.g., Theeuwes, 1992). Distinguishing top-down factors from bottom-up factors in attentional capture can be difficult, as adding a distractor to the search display can alter the bottom-up feature contrasts of the target and the distractor, as well as change the top-down settings themselves (e.g., because observers actively suppress the distractor feature; e.g., Becker, 2007; see also Yantis, 2000). However, studies that systematically varied the features of the irrelevant distractor have uniformly shown that target-similar distractors can attract attention more strongly than target-dissimilar distractors (e.g., Ansorge & Heumann, 2003; Eimer, Kiss, Press, & Sauter, 2009; Folk & Remington, 1998; Ludwig & Gilchrist, 2002). For example, in search for a red target, a red distractor will capture attention more strongly than a green distractor, and in search for a green target, a green distractor will capture more than a red distractor (e.g., Folk & Remington, 1998). Similarly, when observers have to direct their gaze to a predefined target (“saccade task”), the first eye movement is often executed toward a target-similar distractor, whereas a target-dissimilar distractor usually does not capture the observer’s gaze (e.g., Becker, 2010a; Becker, Ansorge, & Horstmann, 2009; Ludwig & Gilchrist, 2002, 2003; Wu & Remington, 2003).

This *similarity effect* has typically been taken to show that visual selection is largely determined by a top-down, feature-specific mechanism (e.g., Folk & Remington, 1998; Folk et al., 1992; Lee, Itti, Koch, & Braun, 1999; Wolfe, 1994, 1998). Most current theories of visual selection propose that top-down mechanisms can bias attention toward particular features by activating or inhibiting specific “feature maps” or “feature detectors”—these are populations of topographically organized sensory neurons that respond preferentially to a specific feature value (e.g., red, green) and thus signal the location of specific features in the visual field (e.g., red, green; e.g., Treisman & Gelade, 1980). Searching for a specific feature will selectively enhance the response gain of those neurons that preferentially respond to this feature, allowing attention to be guided to locations in the visual field containing this feature (e.g., Koch & Ullman, 1985; Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006; Nakayama & Martini, 2011; Navalpakkam & Itti, 2007; Treisman & Sato, 1990; Wolfe, 1994).

The Role of Feature Relationships in Capture

In contrast to these feature-based models, it has been proposed that visual selection could alternatively depend on the *relative attributes* or *feature relationships* between different items. According to this *relational account* (Becker, 2010a), the visual system directly evaluates the feature relationships between features, so that elementary features are encoded relative to other

features in the context (e.g., larger, redder, darker). For instance, an orange item would be encoded as being “redder” when it is surrounded by all-yellow(er) objects, and as “yellower” when surrounded by all-red(der) objects. Because information about the relative features is presumably available very early, attention is correspondingly biased to the relative features of the target (e.g., redder) rather than its absolute feature value (e.g., orange; Becker, 2010a; Becker, Folk, & Remington, 2010). Knowledge or expectations about the features in the context may be conveyed by experience with the task, and/or by our ability to quickly judge the average color, size, or orientation of stimuli present in a given scene (feature averaging; e.g., Chong & Treisman, 2003; Jacoby, Kamke, & Mattingley, 2013).

Deviating from current feature-based accounts, the relational account does not assume a dedicated feature map for each feature that can be top-down selected. Rather, different features can be represented in a continuous feature space (e.g., color space, orientation space, luminance space, size space), and feature relationships can be conceptualized by the direction of vectors that point from one feature to another. Hence, in visual search, we can bias attention to a particular direction in this feature space, which results in an attentional bias for all items that differ in a similar direction from the other items. However, we could not select items in virtue of their specific feature value, independent of the features of the context (for a more detailed description, see Becker, 2010a). An important consequence of biasing visual selection to the relative attribute of the target is that we are prone to select extreme features; for instance, the yellowest item in the visual field when attention is biased to yellower, and the reddest item in the visual field when visual selection is biased to redder.

Most of the currently available behavioral and neurophysiological evidence that has been interpreted in support of a feature-based selection account is consistent with the relational account, as none of the previous studies systematically varied the target–nontarget relationships (e.g., behavioral evidence—e.g., Anderson & Folk, 2012, Ansorge & Heumann, 2003, Eimer et al., 2009, and Folk & Remington, 1998; neurophysiological evidence—e.g., David, Hayden, Mazer, & Gallant, 2008, Maunsell & Treue, 2006, Motter, 1994, Scolari & Serences, 2010, and Spitzer, Desimone, & Moran, 1988, respectively). Hence, it is possible that the frequently reported similarity effect is not due to target–distractor similarity, but to the fact that a similar distractor shares the relative attributes of the target. According to this view, a red distractor captures attention and the gaze in search for a red target, because the target and distractor are both redder than the other context items—not because they are featurally similar.

This view was tested and confirmed in a previous study that used the spatial cueing paradigm (e.g., Becker, Folk, & Remington, 2013). In one block of the experiment, observers had to search for an orange target among three yellow-orange (henceforth, *yorange*) nontargets (target-redder condition). Prior to the search display, we presented a singleton distractor with a unique color that was embedded in a context of three distractors with a different color. The results showed that a singleton distractor with the target color failed to capture when it was yellower than the distractor context (e.g., orange distractor among other red distractors). By contrast, singleton distractors with the nontarget color or an unrelated color captured attention when they matched the target’s relative color (redder; e.g., yorange distractor among other yellow

distractors; red distractor among orange distractors; Becker et al., 2013). In short, capture by the singleton distractor depended only on its relative color (i.e., the color that the singleton distractor had relative to the other distractor colors), and was entirely independent of the specific colors of the singleton distractor and the distractor context.

Taken together, the results demonstrate that a distractor with a target-similar color (orange) can fail to capture attention, whereas a distractor with an unrelated feature (e.g., red) or with the non-target color (yorange) can capture. These results provide very strong evidence for a relational account of the similarity effect and rule out extant feature-based theories of attention (e.g., Duncan & Humphreys, 1989; Folk et al., 1992; Lee et al., 1999; Navalpakam & Itti, 2006; Wolfe, 1994).

Limitations of Previous Studies

Previous studies tested the relational account mostly with the spatial cueing paradigm, because this paradigm permits varying the target-distractor similarity independently of the feature relationships of target and distractor, and allows better control over the bottom-up saliency of different distractors than the visual search paradigm (see previous discussion). However, proponents of the feature-based view could argue that the conditions of previous spatial cueing studies favored a relational selection bias over a feature-based selection bias.

First, in previous spatial cueing studies that tested the relational account, the distractors were presented only very briefly (100 ms) and were rapidly followed by the target display (stimulus onset asynchrony SOA = 200 ms; e.g., Becker et al., 2010, 2013). With this, observers may not have noticed that a selection bias for the relative target color rendered them more susceptible to distraction by target-dissimilar colors. Given that observers may not have been aware of selecting target-dissimilar cues, they probably lacked an incentive to suppress the target-dissimilar cues and/or adopt a more restrictive feature-based selection bias, which would have rendered the target-dissimilar distractors ineffective.¹

In a typical visual search task, on the other hand, both the distractor and erroneous selection of it is potentially more noticeable, because the distractor is typically presented for much longer durations (same duration as the target). In addition, erroneous selection of the distractor can lead to longer delays—especially when the gaze is moved to the distractor location (“oculomotor capture”; e.g., Becker, 2010a; Wu & Remington, 2003). Proponents of a feature-based theory could argue that participants adopted a relational selection bias in previous cueing studies because they were not aware of the distractors and/or the costs of erroneously selecting them, whereas attention would be actively biased against selecting all target-dissimilar distractors when these are more visible and/or their distracting effects are more palpable.

In fact, previous studies using the visual search paradigm have shown that target-dissimilar distractors can be actively inhibited, which significantly modulates capture by salient, target-dissimilar distractors (e.g., Becker, 2007, 2010b; Geyer, Mueller, & Krummenacher, 2008; Sayim, Grubert, Herzog, & Krummenacher, 2010; Theeuwes & Burger, 1998; Zehetleitner, Proulx, & Mueller, 2009; Wolfe, Butcher, Lee, & Hyle, 2003). For example, Geyer and colleagues (2008) found that a salient color distractor captured attention and/or the gaze when it was presented only rarely,

whereas it could be largely ignored when it was presented frequently. These results indicate that a salient distractor can be actively inhibited once it is presented frequently (Sayim et al., 2010; Zehetleitner et al., 2009). Geyer and colleagues (2008) argued that rare salient distractors are not inhibited because observers do not have enough of an incentive to inhibit the feature of the distractor. The same may have been true for the spatial cueing experiments, which tested the relational account: Because the cues were presented so briefly and selection errors may not have been noticeable, participants lacked an incentive to inhibit the target-dissimilar distractor colors and/or adopt a more restrictive feature-specific search strategy. (Because inhibition of target-dissimilar features is indistinguishable from adopting a selection bias for the target feature in the context of the present paradigms, we will use the notions of inhibition and feature-based search interchangeably.)

A second possible limitation of previous studies was that the distractors were presented in a separate cueing display prior to the target (e.g., Becker et al., 2010, 2013). With this, the target could be located by discriminating the target color from the nontarget color. The situation is markedly different in the visual search paradigm: In visual search, the distractor is typically presented together with the target in the same display, so that successful target selection requires discriminating the target feature not only from the nontarget features but also from the distractor feature(s). The requirement to distinguish the target from all distractors could provide a strong incentive to adopt a more fine-grained, feature-specific bias. For this reason, and the reasons mentioned earlier, we cannot assume that the relational selection bias observed in the spatial cueing experiments will generalise to a standard visual search task.

Evidence From Visual Search

To date, only a single study has compared capture by a relationally better distractor to capture by a target-similar distractor in a visual search task, in which the distractor was presented in the same display as the target, and the target and distractors were continuously visible (Becker, 2010a). In this study, observers had to search for a target defined by size. In one block, the target was a medium item, presented among large nontargets, and in another block, it was a large item among medium nontargets. Observers had to make a fast eye movement to the target and ignore an irrelevant salient distractor that was always presented at an irrelevant position never occupied by the target. The distractor could be small, medium, large, or extra large. Hence, one distractor always had the same size as the target, two distractors had more extreme features and shared either the relative attributes of the target or the nontargets, and one distractor had the same size as the nontargets. The results showed that the observers' gaze was often captured by the target-similar distractor, but even more frequently captured by the relationally better distractors that shared the target's relative

¹ Naturally, the presumed differences between the spatial cueing task and the visual search paradigm can be eliminated by shortening the target display duration in visual search and/or shortening the SOA between distractor and target display in spatial cueing tasks (e.g., Ansorge & Heumann, 2003; Chen & Mordkoff, 2007). These modified spatial cueing tasks may not differ from the visual search paradigm with regard to the incentive to inhibit an irrelevant distractor.

size but not its absolute size. Specifically, in search for the medium, relatively smaller target, the small distractor captured most strongly, and in search for the large target, the extra-large distractor attracted attention and the gaze most strongly (Becker, 2010a, Figure 7a). The finding that these target-dissimilar distractors can attract the gaze more strongly than a target-similar distractor is in line with the relational account and indicates that visual selection was biased to the relative size of the target (i.e., larger) rather than the target's actual size (e.g., large; see also Harris, Remington, & Becker, 2013).

Although the study showed that visual selection is biased to the relative rather than the absolute size of the target in visual search, proponents of feature-based accounts could argue that these results may be specific to size search. In search for a size target, attention could be generally biased to the relative size of the target rather than its physical size, because the retinal size of an object greatly varies with its distance. By contrast, the relative size of an object is quite invariant, and hence a search strategy relying on the relative size may be more reliable, but this would not generalize to other stimulus dimensions.

Overview of the Present Experiments

The aim of the present study was to test whether selection would also be biased to the relative attributes of the target in a visual search task for more categorical features when observers have to make an eye movement to the target. To assess possible differences between the spatial cueing paradigm and visual search, Experiment 1 assessed capture by target-similar versus target-dissimilar distractors in a color search task using the same colors and conditions as previously used in the spatial cueing studies (e.g., Becker et al., 2010). In Experiment 2, visual selection was tested in a new shape search task, in which the target, nontarget, and distractor were star-like stimuli that systematically differed in the number of spikes (see Figure 1 for an example).

Testing the relational account in a shape search task was deemed interesting, because (a) capture by target-similar versus target-

dissimilar distractors has not been tested in search for shape, and (b) an object's shape can be regarded as a higher order property that consists of multiple lower level features (e.g., orientation, edges). Hence, a shape target can be expected to be encoded independently of the shape of irrelevant nontargets (in a nonrelational manner).

In Experiments 1 and 2, we used a paradigm that has been extensively used in previous research (e.g., Ludwig & Gilchrist, 2002, 2003), and tested capture by an irrelevant distractor in very similar conditions as in Becker's (2010a) size search experiment. Participants had to make a fast eye movement to a search target defined by color (Exp. 1) or shape (Exp. 2), while they had to ignore an irrelevant distractor placed at a nontarget position. Four different types of distractors were tested (target-similar, nontarget-similar, relationally better, or relationally opposite distractor), and capture by the distractor was assessed by measuring the proportion of first eye movements to the distractor. If visual selection is biased toward the exact target feature value, then only the target-similar distractor should be able to attract attention and eye movements, whereas observers should be able to (largely) ignore all target-dissimilar distractors. By contrast, if visual selection is biased toward the target–nontarget feature relations, then both the target-similar distractor and the relationally better distractor should capture attention and the observer's gaze, with more capture by the relationally better distractor than the target-similar distractor. Such a results pattern would correspond to earlier findings from the spatial cueing paradigm (Becker et al., 2010, 2013). However, it is unclear whether observers will indeed adopt a relational search strategy in the present visual search task. Of note, a relational selection bias would render observers vulnerable to capture by two types of distractors—the target-similar distractor and the relationally better distractor, which were together present on 50% of all trials. By contrast, a feature-specific selection bias would prevent capture by all target-dissimilar distractors and render observers vulnerable only to the target-similar distractor, which was present on 25% of all trials. Hence, contrary to the previous spatial cueing

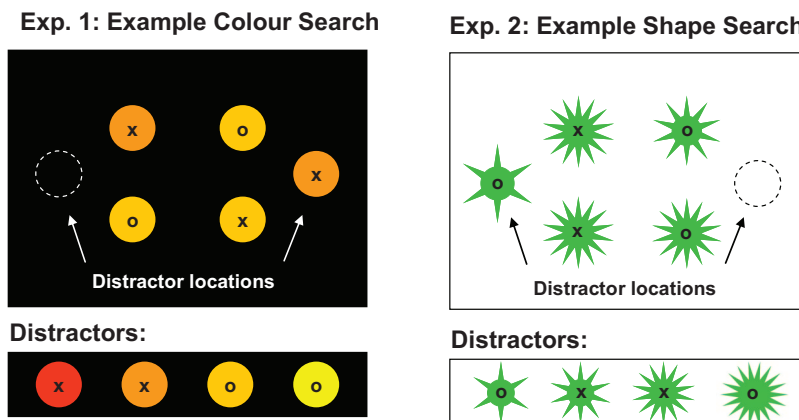


Figure 1. Example of the stimuli and the design used in Experiment 1 (left) and Experiment 2 (right). The task was to make a fast and precise eye movement to the odd-one-out target that could appear at one of the four center positions, and to respond to the item located inside the target (O or X). Each trial contained one of the four possible irrelevant distractors depicted at the bottom, which were presented at one of the two lateral positions and had to be ignored. Deviating from the figure, the background was light gray in Experiment 1.

studies, the present experiments favored a feature-specific selection strategy over a relational search strategy.

A remaining complication is that results commensurate with the relational account would not be inconsistent with a combined top-down/bottom-up feature-based theory: Note that the relationally better distractor probably has a higher bottom-up saliency than the target-similar distractor (e.g., orange), because the relationally better distractor has a unique color and therefore has a higher feature contrast than the target-similar distractor (which has the same color or shape as the target). Hence, more capture by a relationally better distractor could be attributed to bottom-up processes rather than a top-down bias for feature relationships.

Experiment 3 critically tested whether the relationally better distractors can be successfully ignored when observers are primed to select the target in virtue of its specific feature value. To that aim, a subgroup of observers in Experiment 3 was trained to select the target in virtue of its specific color in a feature search task, and performance of this group was compared with a naïve, untrained group in a pop-out search task similar to Experiment 1. If pretraining can successfully induce feature search, then observers who first completed the feature search task should be able to successfully ignore the target-dissimilar distractors. A corresponding result would demonstrate that capture by relationally better distractors is not due to an inability to ignore the more salient, target-dissimilar distractors, but to differences in top-down search strategies.

Apart from investigating the effects of different distractors on visual search performance and eye movement behavior, we also examined possible effects of repeating the distractor feature and the distractor location on distractor selection rates. Previous studies have shown that an irrelevant distractor captures less when the distractor feature is repeated over consecutive trials, indicating that inhibition of the distractor feature can automatically carry over to the next trial and modulate visual selection (e.g., Becker, 2007, 2010b; Geyer et al., 2008; Lamy & Yashar, 2008; Sayim et al., 2010; Zehetleitner et al., 2009). It is difficult to distinguish these automatic carryover effects from top-down strategies to inhibit the irrelevant distractor (or a feature-specific selection strategy), because automatic carryover effects can be cumulative and increase in strength as the number of repetitions increases (e.g., Becker, 2007, 2010b; see also Maljkovic & Nakayama, 1994). In the present study, we compared distractor selection rates when the distractor feature (e.g., color) or the distractor location (e.g., right) from the previous trial was repeated versus not repeated, to assess whether and to what extent the ability to ignore the distractor may be mediated by carryover effects of short-lived inhibition of the distractor feature or its position (see, e.g., Geyer et al., 2008, for a similar approach).

Previous studies have not assessed possible short-lived effects of inhibition of the distractor feature in this paradigm. Yet this was deemed important, because these analyses can shed new light on how a feature-specific selection bias is achieved: Observing a reduction in distractor selection rates after repetitions of the distractor feature would indicate that observers had inhibited the distractor feature on the previous trial, indicating that distractor inhibition may play a role in adopting a feature-specific selection bias. As mentioned previously, it is currently unclear whether and to what extent inhibition of task-irrelevant features can contribute to the selection of task-relevant features in this paradigm (but see

Arita, Carlisle, & Woodman, 2012; Geyer et al., 2008; Lamy & Yashar, 2008; Sayim et al., 2010; Zehetleitner et al., 2009).

Second, we also analyzed carryover effects of inhibition of the distractor position in the experiment, by comparing capture by the distractor when it was presented at the same location as on the previous trial versus a different location. These effects were mainly assessed as a precaution. As mentioned by Mulckhuysse, van Zoest, and Theeuwes (2008), observers have an incentive to inhibit the possible distractor locations in the present paradigm, as there are only two possible distractor locations. Analogous to the case of distractor inhibition, previous studies have found evidence for inhibition of the distractor location that transfers to the subsequent trial and modulates distractor selection (e.g., Geyer, Mueller, & Krummenacher, 2007). Despite the fact that the present visual search task has been extensively used in research, it has never been assessed whether short-lived inhibition of the distractor location contributes to the results pattern. Given that the distractors differed in their bottom-up feature contrast as well as in their physical similarity to the target, we cannot assume that the distractors will all be suppressed to the same extent. Hence, we analyzed carryover effects of distractor inhibition and location inhibition to rule out that more capture by one type of distractor arises as a secondary consequence of being shielded from inhibition.

In addition, we analyzed possible effects of the spatial distance between target and distractor on distractor selection rates by comparing capture by the distractor on trials in which the target and distractor were located in the same hemifield (ipsilateral condition) versus when they were located in opposite hemifields (contralateral condition). Several theories have proposed that selection is strongly modulated by interitem distance. According to the Guided Search 2.0 model (Wolfe, 1994), for instance, bottom-up saliency computations are limited to directly adjacent items, because bottom-up saliency is thought to depend mainly on the *local* feature contrasts between items (see also Bravo & Nakayama, 1992; Desimone, 1998; Julesz, 1986; Koch & Ullman, 1985).² Most theories assume that items compete more strongly for visual selection when they are in close spatial proximity because neurons that respond to the same feature value inhibit each other via lateral inhibitory connections (e.g., Desimone, 1998).

In the present study, the distractor was located close to the target in the same hemifield on half of all trials. Moreover, the relationally better distractor also probably had a larger bottom-up feature contrast than the target. Hence, it is possible that a relationally better distractor would dominate selection only when it is presented in the same hemifield as the target (e.g., Bravo & Nakayama, 1992; Julesz, 1986; Koch & Ullman, 1985; Wolfe, 1994). A corresponding result would indicate that the relationally better distractor was selected because it suppressed the target signal when target and distractor were presented in close spatial proximity. Such a result would be contrary to the claim of the relational account that relationally better distractors can attract attention because of a top-down attentional bias for feature relationships that

² See, for example, Wolfe (1994, p. 207): “The bottom-up activation for an item is based on comparison with all of the item’s neighbors in a 5×5 array centered on the item. For each neighbor, we compute the difference between the output of each broadly tuned channel for the item and that neighbor. Items outside the 5×5 array do not influence the bottom-up activation of the item.”

operates across the entire visual field. In the present study, we assessed hemifield effects to index possible contributions of bottom-up feature contrast to visual selection of the distractor and to distinguish the relational account from other models of visual search.

Experiment 1

In Experiment 1, observers had to search for a predefined color target, and it was tested whether visual selection would be biased toward the target color or the color that the target had relative to the nontargets (e.g., redder/yellower). In different blocks, observers searched either for an orange target among three yorange (yellow-orange) nontargets (redder target), or for a yorange target among three orange nontargets (yellower target). The target could appear at one out of four possible positions that were located at the corners of an imaginary rectangle, whereas the remaining positions were occupied by nontargets that all had the same color. On each trial, an irrelevant distractor was presented either to the right or left of the imaginary rectangle (see Figure 1; Becker, 2010b; Ludwig & Gilchrist, 2002, 2003), and observers were instructed to ignore all items presented at these locations, as the target would never appear there. The irrelevant distractor could have one out of four possible colors—red, orange, yorange, or yellow—the same colors as used in a previous spatial cueing study that tested capture in analogue conditions (Becker et al., 2010).

The observers' task was to make a fast eye movement to the target and to ignore all items presented at an irrelevant position to the right or left of the imaginary rectangle.

After selecting the target, observers had to respond to the item located inside the target with a button press (X and O; left and right button, respectively). The response-related items were included to ensure that eye movements were always targeted to the center of the search items and to discourage saccadic undershoot, which would complicate the assignment of eye movements to individual search stimuli. The search stimuli all remained visible until the observer made a button-press response.

If visual selection is biased toward the target feature value, we would expect the target-similar distractor to capture most strongly; namely, in search for the orange target, the orange distractor should capture most, and in search for the yorange target, the

yorange distractor should capture most. On the other hand, if visual selection is biased to the relative color of the target (i.e., the target–nontarget feature relationships), the target-dissimilar distractor matching the target–nontarget relations should capture most. That is, in search for the orange and redder target, the red distractor should capture the observer's gaze more strongly than the orange distractor, and in search for the yorange and yellower target, the yellow distractor should capture most and significantly more than the yorange distractor.

In addition, if capture by the distractor is modulated by short-lived inhibition of the distractor feature or the distractor location, capture should be reduced on trials in which distractor color or the distractor position is repeated. Moreover, to assess whether and to what extent capture by the irrelevant distractor(s) is affected by the spatial distance between target and distractor, capture was compared between displays in which the target and distractor were in the same hemifield (ipsilateral condition) versus different hemifields (contralateral condition).

Capture by the irrelevant distractor was assessed by measuring the proportion of first eye movements to each of the different distractors. In addition, we report the manual response times (RTs) and error scores (see Tables 1 and 2). The manual responses were not analyzed in detail, but served only as a manipulation check to assess whether erroneous selection of the distractor indeed noticeably delayed manual responses.

Other eye movement measures are also reported; in particular, the distractor fixation latencies, that is, the time from the onset of the search display to the initiation of an eye movement to the distractor. These were assessed because it has been proposed that a salient distractor can elicit a fast, reflexive orienting to the distractor, which is only later modulated by a top-down, feature specific bias (e.g., Theeuwes, 1993; Theeuwes, Atchley, & Kramer, 2000; van Zoest & Donk, 2005; van Zoest, Donk, & Theeuwes, 2004). If selection of the relationally better distractor is (in part) due to fast, reflexive orienting to salient items, distractor fixation latencies should be significantly shorter for eye movements to the dissimilar, salient distractors than to the target-similar and nontarget-similar distractors.

The latencies of first eye movements to the target were also assessed to ensure that more frequent eye movements to one

Table 1
Mean Response Time and Percent of Errors for Experiments 1 and 2

Target		Distractor			
Experiment 1					
RT (ms)	Orange	Red 782 [45.9]	Orange 754 [45.4]	Yorange 692 [40.8]	Yellow 688 [37.1]
	Yorange	656 [23.8]	662 [27.7]	718 [29.3]	749 [27.9]
Percent errors (%)	Orange	7.6% [1.5]	5.3% [1.1]	5.7% [1.3]	6.3% [1.2]
	Yorange	5.5% [1.3]	5.1% [1.6]	7.3% [2.3]	7.3% [1.8]
Experiment 2					
RT (ms)	10-spike	6-spike 1,191 [65.4]	10-spike 1,093 [67.5]	14-spike 1,008 [62.9]	18-spike 1,013 [68.0]
	14-spike	883 [57.6]	887 [64.0]	952 [79.6]	1073 [108.7]
Percent errors (%)	10-spike	10.8% [3.5]	8.0% [2.4]	5.3% [5.3]	4.2% [1.4]
	14-spike	5.9% [2.0]	5.5% [1.1]	7.7% [2.1]	7.2% [1.5]

Note. Mean RT and percent of errors for the color search task of Experiment 1 and the shape search task of Experiment 2, depicted separately for the different search conditions and distractor features. Numbers in brackets describe the standard error of the mean. RT = response time.

Table 2
Mean Percent of Errors For Experiment 3

	Distractor				
	Red	Red-Ora	Orange	Yorange	Yellow
Target redder					
Feature first	5.5% [1.4]	6.0% [2.0]	9.7% [3.1]	5.1% [1.9]	4.0 [1.4]
Pop-out first	7.5% [1.9]	7.5% [2.5]	5.7% [2.0]	7.2% [3.1]	4.0 [1.3]
Target yellower					
Feature first	4.5% [1.3]	5.2% [1.5]	13.2% [4.1]	6.1% [1.4]	6.8% [1.7]
Pop-out first	4.8% [1.5]	8.0% [2.0]	7.3% [3.1]	5.6% [1.5]	10.2% [3.3]

Note. The mean error scores for Experiment 3 are depicted as a function of the search task (target redder vs. target yellower condition) and pretraining (feature first vs. pop-out first group), separately for each distractor condition (red, red-orange, orange, yorange, and yellow distractor). Numbers in brackets describe the standard error of the mean.

distractor could not be ascribed to a speed–accuracy trade-off (e.g., Findlay, 1997). Analyzing the target fixation latencies also allowed testing for possible dissociations between overt and covert capture. As mentioned previously, covert attention shifts to the distractor should either trigger a saccade to the distractor or delay the first eye movement (because covert attention has to be allocated to the saccade target location prior to the saccade). On the basis of previous studies, we did not expect a dissociation between oculomotor capture (as indexed by the proportion of eye movements to the distractor) and attentional capture (as indexed in the elevated target fixation latencies). However, such a dissociation would be detectable in the present paradigm as a discrepancy between the two measures. For example, observing the longest target fixation latencies with one type of distractor and the strongest oculomotor capture by a different type of distractor would indicate that attention and eye movements are affected differently by differently colored distractors.

Method

Participants. Nine participants took part in Experiment 1. All participants were paid \$10 for their participation, were naïve as to the purpose of the experiment, and had normal or corrected-to-normal vision.

Materials. An Intel Duo 2 CPU 2.4GHz computer with a 17-in. LCD color monitor was used to generate and display the stimuli and to control the experiment. Stimuli were presented with a resolution of 1280×1024 pixels and a refresh rate of 75Hz. A video-based infrared eye-tracking system was used (Eyelink 1000, SR Research, Ontario, Canada) with a spatial resolution of 0.1 and a temporal resolution of 500Hz. Participants were seated in a normally lit room, with their head fixated by the eyetracker’s chin rest and forehead support, and viewed the screen from a distance of 62 cm.

Stimuli. All stimuli were displayed against a light gray background (79.9 cd/m^2). Stimulus displays consisted of five disks (diameter = 2.0°), four of which were presented at the corners of an imaginary rectangle ($9.6^\circ \times 8.4^\circ$), with the distractor located to the right or left of the sides of the imaginary rectangle (see Figure 1). The disks were colored either red (255, 0, 0; $Y_{xy} = 10.5, .398, .528$), orange (255, 102, 0; $Y_{xy} = 15.8, .330, .537$), yorange (255, 152, 0; $Y_{xy} = 23.1, .259, .546$), or yellow (255, 195, 0; $Y_{xy} = 50.5, .212, .552$). All search displays consisted either of an orange target

disk and three yorange nontarget disks or one yorange target disk among three orange nontarget disks that were positioned at the corners of the imaginary rectangle and a single distractor to the right or left of this formation (red, orange, yorange, or yellow).

All stimuli contained a small black “o” or “x” (in Arial black, 10pt) as a response-defining item ($0.2^\circ \times 0.2^\circ$). The response-related items were included to ensure that eye movements were always aimed at the center of a stimulus and to discourage saccadic undershoot.

Design. The experiment consisted of two blocked conditions. In one block, the target was orange and presented among three yorange nontargets, whereas in the other block, the color assignment was reversed. In each block, the target position (1 through 4), distractor color (red, orange, yorange, yellow), distractor position (left, right), and response (left, right) were varied orthogonally ($4 \times 4 \times 2 \times 2 = 64$ trials). Participants completed 512 trials, 256 trials in each blocked condition; the order of blocks was counter-balanced across participants.

Procedure. Prior to the experiment, participants were instructed to make a fast and precise eye movement to the predefined target and to ignore the irrelevant distractor, as attending to it would harm their performance. Before each block, participants were given written instructions about the possible target and nontarget features of the next block.

Participants were calibrated with a randomized 9-point calibration. Each trial started with the presentation of a small black fixation cross and a fixation control: The search display was only presented if the tracking was stable (no blinks) and the gaze was within 50 pixels (0.5°) of the center of the fixation cross, for at least 500 ms (within a time window of 2,000 ms). Otherwise, participants were calibrated anew (9-point calibration) and the next trial started again with the fixation control.

Upon presentation of the stimulus display, the fixation cross disappeared and participants were required to make an eye movement to the target and respond to the item inside, pressing the right mouse button if the response-indicative item located inside the target square was an “o” and the left mouse button when it was an “x.” The stimulus display remained on screen until response, and was immediately succeeded by a feedback display. The feedback consisted in the black printed words “right” or “wrong” (Arial, 12 pt.), which were presented centrally against a light gray background and remained on screen for 500 ms. After an intertrial

interval of 250 ms, in which a blank gray screen was presented, the next trial started with the presentation of the fixation cross.

Results

Data. Eye movements were parsed into saccades, fixations, and blinks using the standard parser configuration of the Eyelink software, which classifies an eye movement as a saccade when it exceeds a velocity of 30°/s or an acceleration of 8,000°/s. The first eye movement on a trial was assigned to the target or the distractor if the gaze was within 100 pixels (1.0°) of the center of the search item. Thus, only fixations within the boundary of the search stimuli (diameter = 2°) were assigned to the target or the distractor, ensuring that the results were not unduly influenced by center-of-gravity fixations (e.g., Findlay, 1997). Despite this rather strict criterion, 94.60% of first fixations could be assigned to the target, the distractor, or a nontarget in Experiment 1.

In Experiment 1, one participant had to be excluded because she always selected one of the nontargets prior to the target in one condition. Trials with anticipatory eye movements (<100 ms) and trials in which the target had not been fixated within 3,000 ms from the onset of the search display were excluded from all analyses, which led to a loss of 0.78% of all data (0.05% because of anticipatory eye movements).

Proportion of distractor fixations.

Repeated versus nonrepeated distractor color. As shown in Figure 2A, the proportion of first fixations on the distractors was strongly modulated by the distractor color. For analysis, separate 4×2 ANOVAs comprising the variables distractor color (red vs. orange vs. yorange vs. yellow) and distractor repetition (distractor color repeated vs. not repeated) were computed first over the orange target block and then the yorange target condition.

In both search conditions, only the color of the distractor modulated capture (orange target, $F(3, 21) = 54.1, p < .001, \eta^2 = .89$; yorange target, $F(3, 21) = 27.1, p < .001, \eta^2 = .80$), with most fixations being recorded on the relationally better distractor, followed by the target-similar distractor and the remaining distractors (nontarget-similar distractor and relationally opposite distractor). Repeating the distractor color had no effect and did not interact with the distractor color, all $ps > .10$. For the analysis of the distractor effect, data from repeated and nonrepeated distractor trials were pooled to increase the power.

Pairwise two-tailed t tests showed that in search for the orange target, the red distractor was selected most frequently, significantly more often than the orange distractor, $t(7) = 5.2, p = .001$ (see Figure 2). In addition, the target-similar orange distractor was selected more frequently than the yorange distractor, $t(7) = 6.1, p = .001$, whereas the yorange and yellow distractors did not differ ($p > .30$).

In search for the yorange target among the orange nontargets, the yellow distractor was more often selected than the target-similar yorange distractor, $t(7) = 2.5, p = .039$. Moreover, distractor selection rates were higher for the target-similar yorange distractor than for the nontarget-similar orange distractor, $t(7) = 6.5, p < .001$, whereas the orange distractor did not differ from the red distractor ($p > .90$). In sum, relationally better distractors captured the gaze more strongly than target-similar distractors, both when the target was orange and when it was yorange,

whereby gaze capture was not modulated by repeating the distractor color across trials.

Repeated versus nonrepeated distractor position. To assess whether capture is modulated by short-lived inhibition of the distractor position, 4×2 ANOVAs comprising the variables distractor color and position repetition (repeated vs. nonrepeated distractor position) were computed over the data from the orange target block and yorange target block. The corresponding results are depicted in Figure 2B.

In the orange target block, capture was significantly modulated by the distractor color, $F(3, 21) = 51.9, p < .001, \eta^2 = .88$, and by repetitions of the distractor position, $F(1, 7) = 57.0, p < .001, \eta^2 = .89$. Repetition also significantly interacted with distractor color, $F(3, 21) = 3.9, p = .044, \eta^2 = .36$. Follow-up two-tailed t tests showed that capture was significantly attenuated for the red distractor, $t(7) = 2.9, p = .23$, as well as for the orange distractor, $t(7) = 4.3, p = .004$, when the distractor position was repeated, but not for the other distractors ($ps > .22$).

In the yorange target block, only the distractor color modulated capture, $F(3, 21) = 32.7, p < .001, \eta^2 = .82$, whereas repetitions of the distractor position did not modulate capture and did not interact with distractor color ($ps > .09$). Numerically, distractor selection rates were attenuated at repetitions of the distractor; however, two-tailed t tests did not show any significant differences between repeated and nonrepeated distractors ($ps > .07$).

Ipsilateral versus contralateral target-distractor displays. To assess whether spatial proximity between target and distractor modulates distractor selection rates, a 4×2 ANOVA comprising the variables distractor color (red, orange, yorange, yellow) and hemifield (ipsilateral vs. contralateral target-distractor positions) was computed over the proportion of first distractor fixations (see Figure 2C).

In search for the orange (redder) target the results showed a significant main effect of the distractor color, $F(3, 21) = 55.8, p < .001, \eta^2 = .88$, and of hemifield, $F(1, 7) = 39.3, p < .001, \eta^2 = .85$, reflecting that the proportion of distractor fixations was significantly higher in the ipsilateral condition, in which target and distractor were in the same hemifield ($M = 30.2\%$) than the contralateral condition ($M = 16.8\%$). Pairwise two-tailed t tests confirmed that distractor selection rates were significantly higher in the ipsilateral condition than the contralateral condition, for all distractors, all $ts > 5.6, ps < .022$.

The same analysis conducted for the yorange target condition showed a significant main effect of the distractor color, $F(3, 21) = 31.7, p < .001, \eta^2 = .82$, of hemifield, $F(1, 7) = 24.7, p = .002, \eta^2 = .78$, as well as a significant interaction between the variables, $F(3, 21) = 6.1, p = .014, \eta^2 = .47$. The interaction was due to the fact that distractor selection rates were significantly higher in the ipsilateral condition for all distractors, all $ts > 2.8, ps < .027$, except for the target-similar yorange distractor, $t(7) = 2.0, p = .083$.

Mean latencies of the first eye movements to target and distractor. The mean latencies of first eye movements to the distractor and the target are listed in Table 3. The analysis of the distractor fixation latencies had to be limited to the relationally better distractor and the target-similar distractor, as the remaining distractors were too rarely selected (<5 times) to obtain valid estimates of the mean latencies. Moreover, as the target and distractor were selected as the first item on only a portion of the trials, there were not sufficient data to analyze effects of repetition or hemifield on the fixation latencies.

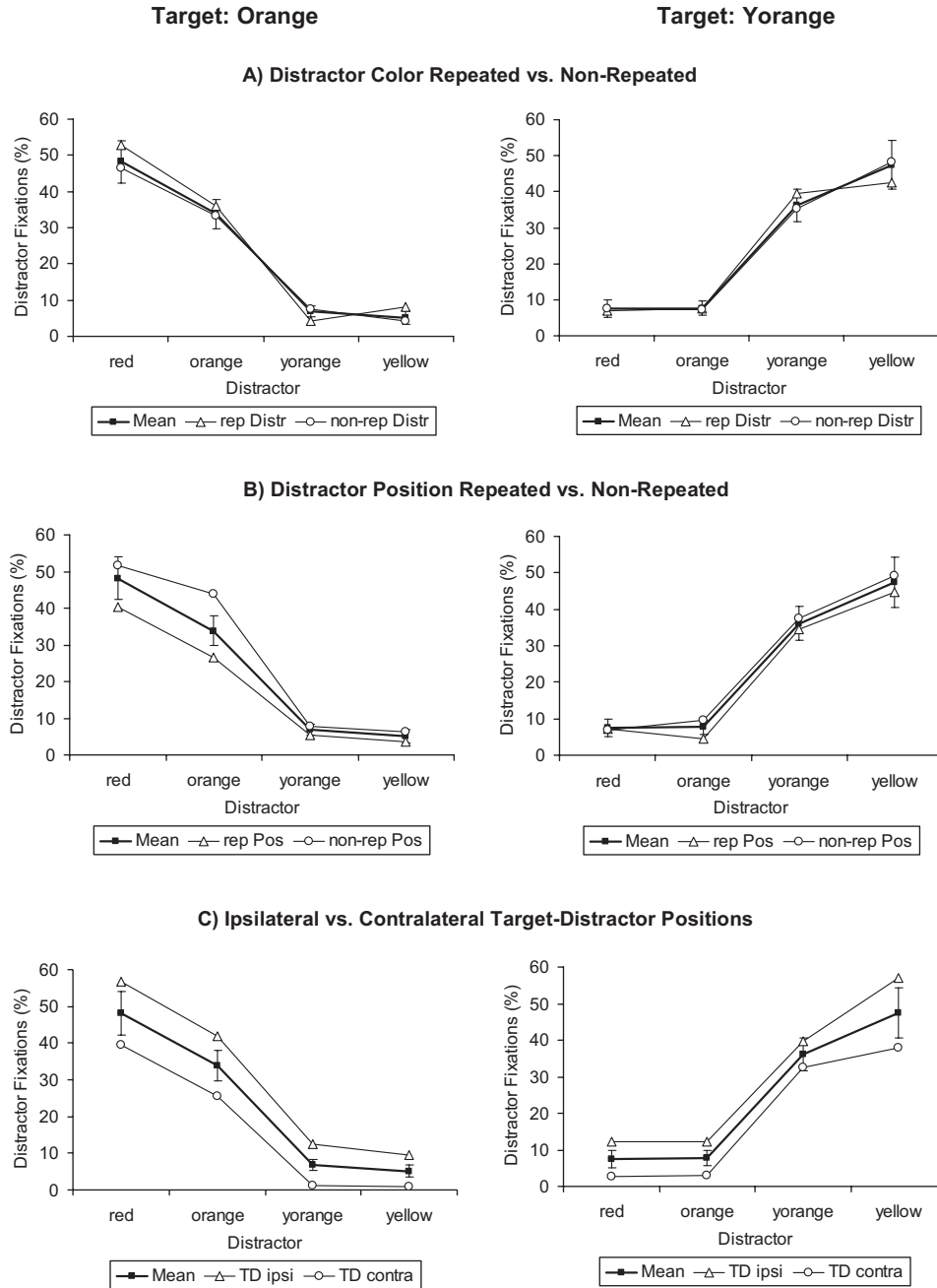


Figure 2. The mean proportion of first eye movements to each distractor in search for the orange, redder target (left panels) and the yorange, yellower target (right panels) in Experiment 1. (A) Distractor selection rates are depicted separately for trials in which the distractor had the same color as on the previous trial (*rep Distr*; triangle symbols) and in which the distractor color was different (*nonrep Distr*; circle symbols). (B) Proportions of first distractor fixations are depicted separately for trials in which the distractor was presented in the same location as on the previous trial (*rep Pos*; triangles) and in which it occupied a different position (*nonrep Pos*; circles). (C) Distractor selection rates as a function of the relative positions of target and distractors. *TD ipsi* denotes trials in which the target and distractor were presented in the same hemifield; *TD contra* trials where target and distractor were positioned in different hemifields. Error bars present ± 1 standard error of the mean and are only shown for the mean proportion of distractor fixations.

Table 3

Mean Proportion and Latencies for First Fixations on the Target and Distractor in Experiments 1 and 2

	Target		Distractor		
Experiment 1					
		Red	Orange	Yorange	Yellow
Prop. target fix (%)	Orange	31.4% [3.2]	41.4% [2.0]	68.4% [6.1]	68.3% [3.7]
	Yorange	73.5% [4.6]	72.3% [5.2]	42.8% [4.3]	30.6% [3.1]
Target latency (ms)	Orange	237 [6.2]	240 [6.4]	240 [7.0]	236 [5.4]
	Yorange	240 [3.9]	245 [5.5]	245 [6.6]	250 [5.1]
Distr. latency (ms)	Orange	222 [6.6]	219 [7.2]	217 [9.0]	230 [14.6]
	Yorange	242 [17.7]	212 [4.0]	220 [5.6]	217 [5.1]
Experiment 2					
		6-spike	10-spike	14-spike	18-spike
Prop. target fix (%)	10-spike	25.5% [3.6]	33.2% [4.7]	35.6% [4.9]	35.4% [5.1]
	14-spike	49.7% [5.3]	49.5% [5.9]	35.8% [7.1]	26.9% [5.2]
Target latency (ms)	10-spike	288 [26.0]	278 [18.1]	290 [20.1]	276 [19.7]
	14-spike	274 [6.5]	276 [6.0]	278 [9.9]	274 [7.1]
Distr. latency (ms)	10-spike	265 [13.6]	256 [3.8]	237 [4.3]	244 [5.0]
	14-spike	243 [5.8]	246 [8.9]	249 [7.1]	260 [8.3]

Note. The results are depicted as a function of the target feature and the distractor features (organized in columns). Numbers in brackets describe the standard error of the mean. Numbers in italics indicate that averages were based on few trials per cell or that individual data were missing. Distr. latency = latency of first eye movements to the distractor; Prop. target fix = mean proportion of first fixations on the target; Target latency = latency of first eye movements to the target.

To assess whether eye movements to the target were delayed in one of the distractor conditions, one-way ANOVAs were first computed over the target fixation latencies when a red, orange, yorange, or yellow distractor was present. However, the target fixation latencies were unaffected by the color of the irrelevant distractor, both in the orange target block, $F < 1$, and in the yorange target block, $F(3, 21) = 1.3, p = .31$. Hence, the results show no indication that the distractors elicited differences in covert attentional capture.

Analysis of the latencies of eye movements to the irrelevant distractor did not show any evidence for faster selection of target-dissimilar distractors than target-similar distractors. In search for the orange target, latencies of saccades to the red distractor ($M = 222$ ms) were not shorter than latencies of saccades to the orange distractor ($M = 219$ ms), $t(7) = 1.1, p = .29$. In search for the yorange target, eye movements to the yellow distractor ($M = 217$ ms) similarly were not elicited earlier than eye movements to the yorange distractor ($M = 220$ ms), $t < 1$. Hence, there is no indication that saccades to the target-similar distractor and the relationally better distractor are driven by processes with different time courses.

Discussion

Experiment 1 showed several interesting findings. First, the experiment showed that, in search for color, a relationally better distractor captured the observers' gaze more strongly than a target-similar distractor. These results are in line with the relational account and indicate that visual selection of the target was based on the target's relative color rather than its feature value. Extending on previous studies that have predominately used the spatial cueing paradigm, the present study demonstrates that relationally better, target-dissimilar distractors do not only fleetingly capture covert attention but also capture an observer's gaze. In the present study, visual selection was biased to feature relationships despite the facts that (a) the conditions did not favor a relational selection

bias over a feature-specific selection bias, (b) the irrelevant distractor was presented in the same display as the target and had to be discriminated from the target color for successful target selection, and (c) capture by the relationally better distractor resulted in a large number of erroneous eye movements to the relationally better distractor (40% to 50%), which should have rendered selection errors quite noticeable. In line with the latter contention, the results from the mean RT showed that a relationally better distractor substantially delayed responses to the target by about 90 ms compared with the nontarget-similar distractor (see Table 1). Theoretically, these costs could have been avoided by adopting a feature-specific search strategy, indicating that a visual selection bias for feature relationships is adopted even when this is detrimental for search performance. Thus, the present results indicate that previous evidence for a relational selection bias in visual search for a color target was not due to specifics of the spatial cueing paradigm (e.g., Becker et al., 2010, 2013).

Stronger capture by the relationally better distractor is at odds with the often-reported similarity effect (e.g., Folk & Remington, 1998) and feature-based selection views that would predict strongest capture by the target-similar distractor. The results are also inconsistent with pure bottom-up accounts of capture (e.g., Itti & Koch, 2000; Theeuwes, 1992), which would have predicted the most salient items to capture most strongly. In Experiment 1, the red and yellow distractors would always be the most salient items, as they had a unique feature value in all conditions. Yet the red and yellow distractor captured only when it had the same relationship to the other items as the target had to the nontargets, suggesting that the results were due to top-down task demands rather than bottom-up factors. In line with this contention, there were no differences in the time course of shifting the gaze to the target-similar versus the target-dissimilar distractor, indicating that capture was not due to a fast, saliency-based mechanism and a slow, feature-based mechanism (e.g., van Zoest et al., 2004).

Extending on previous work, the present study also assessed possible effects of inhibiting the distractor feature and distractor position. The results of these analyses showed no evidence that observers inhibited the colors of the target-dissimilar distractors. However, there was some evidence for short-lived inhibition of the distractor position: Inhibition of the distractor position was found only for the target-similar and relationally better distractor, indicating that this effect depended on the ability of the distractor to attract attention. Evidence for inhibition of the distractor location was much stronger in the orange target block than the orange target block, indicating that this effect may not be entirely robust across all stimulus conditions. Taken together, the results provide the first evidence that carryover effects of distractor location inhibition can modulate capture by the irrelevant distractor in the present paradigm. However, these effects did not qualitatively change the results pattern and were rather small, indicating that previous results with this paradigm were not unduly influenced by effects of repeating the distractor location (e.g., Becker, 2010a; Ludwig & Gilchrist, 2002, 2003).

Another interesting finding was that distractor selection rates were strongly modulated by the spatial proximity of target and distractors: All distractors captured the gaze more strongly when they were located near to the target than when target and distractor were presented in different hemifields. Hemifield differences modulated distractor selection regardless of whether the distractor matched the target–nontarget relationships or not, which supports the view that interitem distance affects attention independently of the top-down settings in a bottom-up controlled fashion (e.g., Bravo & Nakayama, 1992; Julesz, 1986; Koch & Ullman, 1985; Wolfe, 1994). Interestingly, this effect was apparently independent of the feature contrast of the distractor, as it equally applied to the salient red and yellow distractors, as well as to the nonsalient distractors that had the nontarget color. This result would seem to argue against the notion that interitem distance modulates the feature contrast, which, in turn, determines visual selection (e.g., Bravo & Nakayama, 1992; Julesz, 1986; Koch & Ullman, 1985; Wolfe, 1994). In this case, hemifield effects should have been observed only for the distractors that had a different color, not for the nontarget-similar distractor—contrary to the results. So far, the results seem to be more in line with the biased competition account, which assumes that an additional item placed in the same hemifield as the target competes with the target for selection, regardless of whether it has a larger feature contrast than the target or not (e.g., Beck & Kastner, 2005, 2009; Desimone, 1998; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider 1999; Kastner et al., 2001). More important for the purpose of the present study, the results clearly showed that the relationally better distractor dominated visual selection both when it was near to the target and when it was far away, which supports the relational account over alternative feature-based accounts.

Experiment 2

The results of Experiment 1 were very similar to results obtained in a size search task (Becker, 2010a) and indicate that visual selection is also biased to the relative features of the

target in search for color. Experiment 2 was designed to test whether target–nontarget relationships would also determine visual selection in search for a shape target. As mentioned in the introduction, shapes consist of a conglomerate of several low-level features and can thus be expected to be subject to a feature-specific selection bias that operates independently of the features of the nontargets.

The shapes used in Experiment 2 were star-like stimuli that varied in the number of spikes (see Figure 1, right panel). In one block, the target had 10 spikes and was presented among nontarget stars with 14 spikes (less spiky target). In the other block, the target had 14 spikes and was presented among 10-spike nontarget stars (spikier target). The distractor star had 6, 10, 14, or 18 spikes.

If the target is selected on the basis of its specific feature value, then the target-similar distractor should be selected most frequently. By contrast, if visual selection of the target is based on the target–nontarget relationships, then the relationally better distractors should capture significantly more than the target-similar distractors, namely, in search for the spikier, 14-spike target, the 18-spike distractor should capture most, and in search for the less spiky, 10-spike target, the 6-spike distractor should capture most.

As in Experiment 1, the latencies of first eye movements to the target and distractor were assessed in addition to the proportion of first eye movements. Moreover, short-lived effects of repeating the distractor's shape and its position, as well as possible effects of the target-distractor distance, were evaluated in the same manner as in Experiment 1.

Method

Participants. Eight new participants participated in Experiment 2 and received \$10 in exchange for participating in the experiment. All of the participants had normal or corrected-to-normal vision and were not informed about the purpose of the experiment.

Materials. The materials were the same as in the previous experiment.

Stimuli, design, and procedure. These were the same as in the previous experiment, with the following exceptions: All search displays contained five green star shapes, which consisted of a green disk (diameter = 0.8°) and a variable number of sharply pointed triangles that constituted the spikes of the star shape (0.7° long; base = 0.3). Observers were instructed to make a fast and precise eye movement to the predefined target shape, and to ignore an irrelevant distractor presented to the right or left of the four possible target positions. The distractor had 6, 10, 14, or 18 spikes, and capture by the irrelevant distractors was assessed in two blocked target conditions: a less spiky target condition, in which the target was a 10-spike star among 14-spike nontarget stars, and a spikier target condition, in which the target was a 14-spike star among 10-spike nontarget stars. As in Experiment 1, the conditions were counterbalanced across participants, and participants completed 512 trials, 256 in each condition.

Results

Data. Excluding trials with anticipatory eye movements (<100 ms) and trials in which the eyes had failed to fixate on the target within 3,000 ms from the onset of the search display led to

a loss of 1.72% of data (0.02% because of anticipatory eye movements). Of all first fixations, 93.87% could be assigned to the target, the distractor or the nontarget, using the same criteria as in Experiment 1 (i.e., fixation endpoint within 1° of the center of the search items).

Proportion of distractor fixations.

Repeated versus nonrepeated distractor shape. Separate 2 × 4 ANOVAs were computed first over the 10-spike target block and

then the 14-spike target block to assess possible effects of the different distractor shapes (8- vs. 10- vs. 14- vs. 18-spike distractor) on the first eye movements, when the distractor from the previous trial was repeated versus not repeated (see Figure 3A). In both blocks, capture was significantly modulated by different distractor shapes, with more fixations being made on the relationally better distractor than the remaining distractors (10-spike target, $F[3, 21] = 8.3, p = .001, \eta^2 = .55$; 14-spike target, $F[3, 21]$

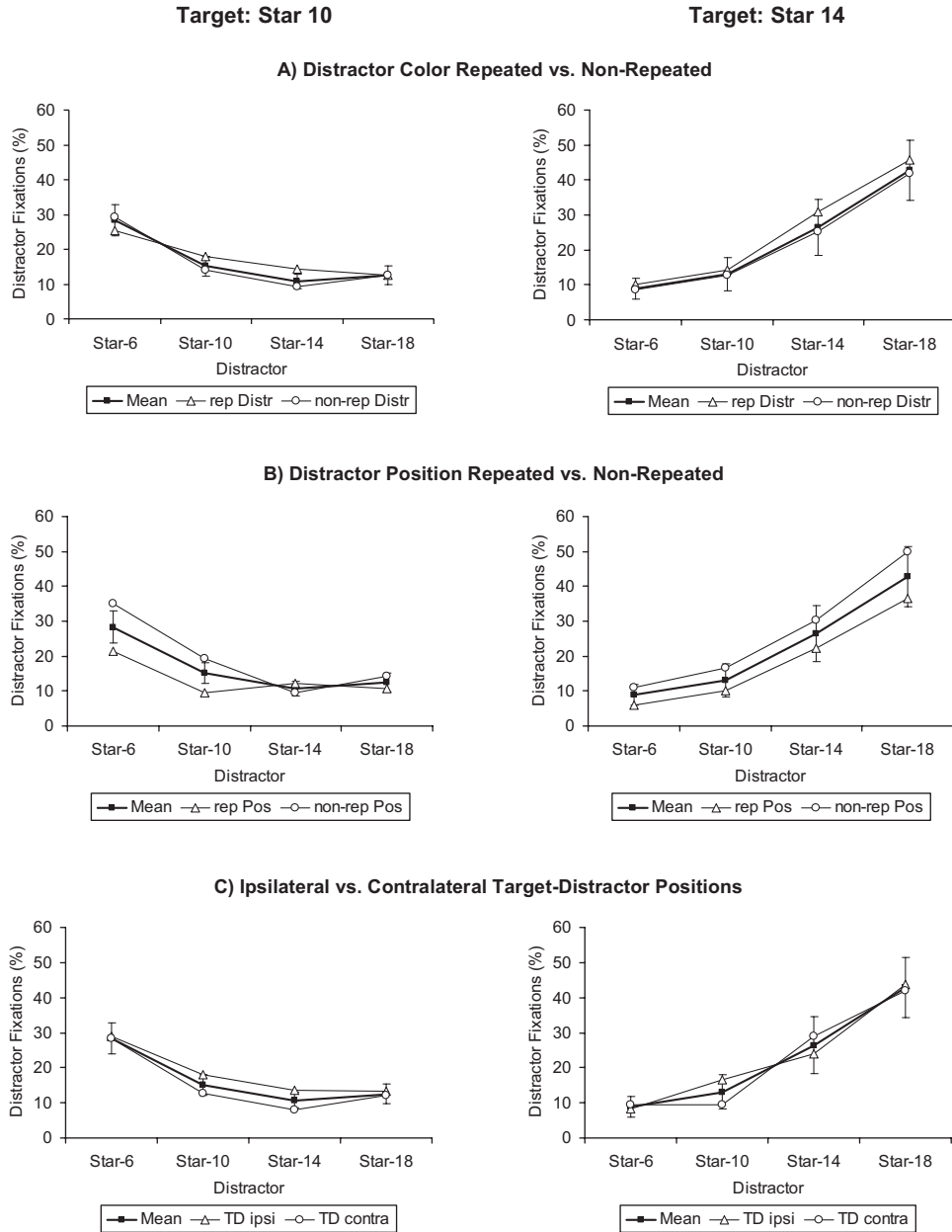


Figure 3. The mean proportion of first distractor fixations in the shape-search task of Experiment 2: Distractor fixations are depicted separately for each of the four distractor conditions, and for the 10-spike, less spiky target (left panel) and the 14-spike target that was spikier than the nontargets (right panel). From top to bottom, the panels additionally depict the results for repeating versus not repeating the distractor shape (A; *rep Distr* vs. *nonrep Distr*), for repeating versus not repeating the distractor position (B; *rep Pos* vs. *nonrep Pos*), and for ipsilateral versus contralateral presentations of the target and distractor (*TD ipsi* vs. *TD contra*). Error bars present ±1 standard error of the mean and are only shown for the mean proportion of distractor fixations.

= 18.3, $p = .001$, $\eta^2 = .72$). The main effect of repeating the distractor shape failed to reach significance (10-spike target, $F < 0$; 14-spike target, $F[1, 7] = 4.8$, $p = .065$, $\eta^2 = .41$) and did not interact significantly with the distractor type (10-spike target, $F[3, 21] = 1.5$, $p = .25$; 14-spike target, $F < 1$). Therefore, for the follow-up analysis of the distractor effect, data were again pooled over repeated and nonrepeated trials (see Figure 3A).

Paired two-tailed t tests showed that with the less spiky, 10-spike target, the 6-spike distractor captured the gaze more strongly than the target-similar 10-spike distractor, $t(7) = 4.1$, $p = .005$. However, the 10-spike distractor did not capture more strongly than the 14-spike distractor, $t(7) = 2.0$, $p = .08$, and the 14-spike distractor did not differ significantly from the 18-spike distractor, $t(7) = 1.2$, $p = .28$.

In search for the spikier, 14-spike target, the 18-spike distractor captured more frequently than the 14-spike distractor, $t(7) = 5.0$, $p = .002$, which, in turn, captured more strongly than the 10-spike distractor, $t(7) = 3.1$, $p = .018$. The 10-spike distractor did not differ from the 6-spike distractor, $t(7) = 1.7$, $p > .12$.

Repeated versus nonrepeated distractor position. To analyze possible effects of repeating the distractor position, separate 2×4 ANOVAs with the variables position repetition (repeated vs. nonrepeated distractor position) and distractor type (6-, 10-, 14-, 18-spike star) were computed over the proportion of first fixations to the distractor (see Figure 3B). In search for the 10-spike star, the analysis showed significant main effects of the distractor type, $F(3, 21) = 12.7$, $p = .005$, $\eta^2 = .65$, position repetition, $F(1, 7) = 30.1$, $p = .001$, $\eta^2 = .81$, and a significant interaction between both variables, $F(3, 21) = 5.1$, $p = .024$, $\eta^2 = .42$. The interaction was due to the fact that repeating the distractor position attenuated capture by the target-similar distractor, $t(7) = 2.5$, $p = .047$, and the 6-spike distractor, $t(7) = 6.2$, $p < .001$, whereas capture by the remaining distractors was unaffected by position repetition, $ps > .20$.

In search for the 14-spike target, the 2×4 ANOVA showed that capture was significantly modulated by the distractor shape, $F(3, 21) = 19.9$, $p = .001$, $\eta^2 = .74$, and position repetition, $F(1, 7) = 41.2$, $p = .001$, $\eta^2 = .86$, whereas the interaction between the variables was nonsignificant, $p > .20$. Pairwise t tests revealed that repeating the distractor position significantly attenuated capture by the 18-spike distractor, $t(7) = 7.1$, $p < .001$, whereas these differences were only marginally significant or nonsignificant for the other distractors: 14-spike distractor, $t(7) = 2.1$, $p = .068$; 10-spike distractor, $t(7) = 2.3$, $p = .054$; 6-spike distractor, $t(7) = 2.0$, $p = .085$.

Ipsilateral versus contralateral target-distractor displays. The distractor selection rates in the ipsilateral versus contralateral presentation of target and distractor are depicted in Figure 3C. A 2×4 ANOVA comprising the variables distractor shape (6-, 10-, 14- and 18-spike distractor) and hemifield (ipsilateral vs. contralateral target-distractor positions) computed over the distractor selection rates in the 10-spike target condition showed only a significant main effect of the distractor shape, $F(3, 21) = 13.5$, $p = .004$, $\eta^2 = .66$, whereas the main effect of hemifield and its interaction with distractor shape failed to reach significance, $F(1, 7) = 3.7$, $p = .097$, and $F(3, 21) = 1.1$, $p = .47$, respectively. Pairwise two-tailed t tests confirmed that capture did not differ for any distractors between the ipsilateral and contralateral condition, all $ts < 2.1$, $ps > .07$.

In search for the 14-spike target, the ANOVA yielded a significant main effect of the distractor, $F(3, 21) = 20.5$, $p = .001$, $\eta^2 = .75$, no effect of hemifield, $F < 1$, and a marginally significant interaction between both variables, $F(3, 21) = 3.9$, $p = .057$, $\eta^2 = .36$. The interaction was due to the fact that in search for the spikier, 14-spike target, only the 10-spike distractor (that had the same shape as the nontargets) was significantly more frequently selected in the ipsilateral condition than the contralateral condition, $t(7) = 2.9$, $p = .024$ (all other $ts < 1.7$, $ps > .13$).

Mean latencies of the first eye movements to target and distractor. Analyses of fixation latencies were subject to the same limitations as in Experiment 1, allowing analysis of the distractor effect only. One subject selected the target as the first item on less than five trials in one condition and, hence, had to be excluded from these analyses.

Two one-way ANOVAs showed that the target fixation latencies were not modulated by the distractor type, neither in search for the 10-spike target, $F < 1$, nor in search for the 14-spike target, $F < 1$. Hence, interpretation of the data is not complicated by a speed-accuracy trade-off or particularly high rates of covert attention shifts to one of the distractors.

Moreover, comparing the distractor fixation latencies across the effective distractors did not show any evidence for more rapid capture by target-dissimilar distractors than the target-similar distractors. In search for the 10-spike target, gaze shifts to the 10-spike distractor ($M = 256$ ms) did not take longer than to the 6-spike distractor ($M = 265$ ms), $t < 1$. In search for the 14-spike target, latencies for selecting the 14-spike distractor ($M = 249$ ms) were equally not elongated compared with the 18-spike distractor ($M = 260$ ms), $t < 1$.

Discussion

The results of Experiment 2 show that visual attention can be biased to the relative properties of the target also in search for shape (i.e., spikier vs. less spiky). In line with previous results from color and size search tasks, the shape search task showed no similarity effect. Rather, relationally better distractors captured attention and the eyes more strongly than the target-similar distractors (see Figure 3). These results are inconsistent with current feature-based theories of attention and eye movements, and suggest that guidance by feature relationships may be a very general phenomenon that is applied in a variety of search tasks. Of note, observers in Experiment 2 adopted a selection bias for the relative target feature, despite the fact that this rendered them vulnerable to two types of distractors (i.e., the target-similar distractor and the relationally better distractor). Selection of the relationally better distractor also led to large costs of 183 to 186 ms in the manual RT compared with the nontarget-similar distractor—costs that could have been avoided by adopting a feature-specific search strategy (see Table 1). Thus, it seems that relational search is the default search strategy, which is generally preferred in visual search, even when the design favors a feature-specific search strategy (see also Becker, 2010a).

In line with the results of Experiment 1, the results did not show attenuated capture when the distractor feature was repeated: In search for the 14-spike target, corresponding nonsignificant trends were even in the opposite direction, with more frequent selection of repeated distractor shapes than nonrepeated distractor shapes.

As in the previous experiment, there was some evidence for short-lived inhibition of the distractor location, and inhibition of the distractor location again seemed to depend in part on the ability of the distractor to capture attention. In search for the 10-spike target, evidence for short-lived inhibition of the distractor position was limited to the target-similar and the relationally better distractors. In search for the 14-spike target, capture by all distractors was slightly reduced when the distractor position was repeated, but distractor selection rates were significantly reduced only for the relationally better, 18-spike distractor.

Deviating from the results of the color search task, capture by shape distractors was not systematically modulated by the spatial proximity of target and distractors. Capture was not significantly stronger in the ipsilateral condition than the contralateral condition, except for one distractor in the 14-spike target condition, in which the overall results were quite inconsistent, as some distractors showed the opposite trends. In the 10-spike target condition, the hemifield effect failed to reach significance. Taken together, it seems that the competition between the target and the distractor in shape search is largely unaffected by their spatial proximity. Yet there was evidence that the distractors competed with the target for attention: Although target selection rates were reduced overall in the shape search task (especially in search for the 10-spike target; see Table 3), the data still showed the typical trade-off, with the target selection rates decreasing by the same amount as distractor selection rates increased in the different conditions. This trade-off is the hallmark of competition, and indicates that the distractor and target directly competed for attention. Taken together, the findings suggest that competition between the target and the distractor in shape search may reside at higher levels of visual processing, in which neurons have large, bilateral receptive fields (e.g., Desimone, 1998; see also Ahissar & Hochstein, 2004).

Experiment 3

Experiments 1 and 2 showed that a target-dissimilar distractor captured attention and the gaze more strongly than a target-similar distractor. These results were taken to support the relational account—that visual selection is usually not biased to the exact target feature value but to target–nontarget relationships or the relative attributes of the target. However, proponents of a feature-based selection view could argue that attention is tuned to the target in a broad manner (e.g., Wolfe, 1994), so that the feature of the relationally better distractor is activated to the same degree as the target-similar distractor. The relationally better distractor could then capture more than the target-similar distractor because it has a larger bottom-up feature contrast. According to this explanation, observers may have been unable to inhibit the relationally better distractors because (a) these were coactivated by broad top-down tuning to feature categories, and (b) they additionally had a higher bottom-up feature contrast than the target-similar distractor.

This alternative explanation was tested against the relational account by priming a subgroup of observers to use a feature-specific selection bias in a color search task similar to Experiment 1. In Experiment 3, a subgroup of observers had to complete a *feature search task* prior to the pop-out search task. In the feature search task, observers had to make a fast and precise eye movement to an orange target that was either presented among equal numbers of red and yellow nontargets (dissimilar condition) or

among equal numbers of yorange and red-orange nontargets (similar condition; see Figure 4 for an example of the stimuli and conditions). It was reasoned that this feature search task would force observers to bias selection to the specific feature value of the target (orange), as the target was never the reddest or yellowest item in the display. The similar condition with the red-orange and yorange nontargets was primarily included as a manipulation check, to ensure that these colors were sufficiently dissimilar from the target color (orange) that they could not be directly confused with the target color. The set size varied between five and nine items, and all displays contained an equal number of redder and yellower nontargets.

After completing the feature search task, observers completed the experimental condition, which consisted of two blocks of a pop-out search task with irrelevant distractors (similar to Experiment 1). Another half of the observers were first tested in the pop-out search task and then the feature search task (naïve group). To provide optimal conditions for feature-specific tuning, the target in the pop-out search task was always orange. Across two different blocks, the target–nontarget relationship was varied by presenting the orange target either among three yellow nontargets (redder target condition) or three red nontargets (yellower target condition). To test whether visual selection was biased toward the specific feature value of the target (orange) or the target–nontarget relationships (redder vs. yellower in the different blocks), an irrelevant distractor was presented at a position that was never occupied by the target, namely, a red, red-orange, orange, yorange, or yellow distractor. With this, the conditions of the experimental condition of Experiment 3 were very similar to those tested in Experiment 1, with the exceptions that the target was always orange and that a red-orange distractor was added to the set of distractor colors.

If the results of Experiment 1 can be replicated in the conditions of Experiment 3, we would expect naïve observers to bias visual selection to the target–nontarget relationships in the pop-out search task. This should lead to more capture by the relationally better distractors than by the target-similar distractor, that is, in search for

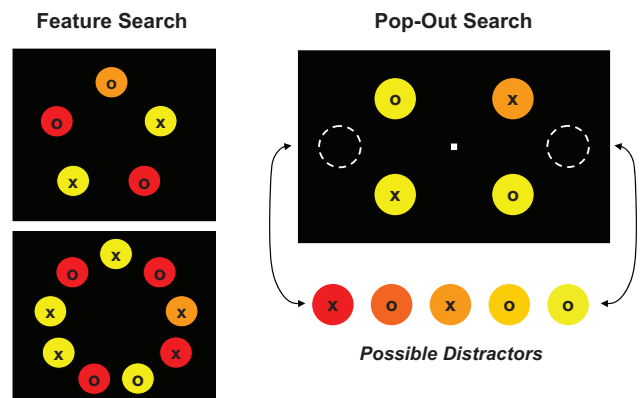


Figure 4. Examples of the search displays used in the color search task of Experiment 3. Left panels depict example search displays for the feature search task, in the Set Size 5 condition (top left) and the Set Size 9 condition (bottom left). The right panel shows the stimuli and design used in the pop-out search task of Experiment 3. Deviating from the figure, the background was light gray in all conditions.

the orange target among yellow nontargets (redder target), the red and red-orange distractors should be selected most frequently, and significantly more frequently than the target-similar orange distractors, whereas in search for orange among the red nontargets (yellow target), the yellow and yorange distractors should be selected more frequently than the orange distractor.

For the group of observers who first completed the feature search task (henceforth, “feature first group”), it was expected that they would maintain the feature-specific setting in the experimental condition, as the target had the same color in both tasks. If this is correct, then the feature first group should show a feature-based selection bias in the pop-out search task, which should result in a true similarity effect, that is, more capture by the target-similar orange distractor than any of the target-dissimilar distractors. Corresponding results would demonstrate that attention can be tuned narrowly to the target feature value of orange, and that the failure to observe feature-specific tuning in Experiment 1 was not due to an inability to reject relationally better distractors (e.g., because of a high bottom-up feature contrast).

Method

Participants. Sixteen new participants took part in the experiment and were compensated with \$10.

Materials. The materials were the same as in Experiment 1.

Stimuli, design, and procedure. The procedure was the same as in Experiment 1, with the following exceptions: The disks were colored either red ($Lu'v'$: 20.1 cd/m², 0.352, 0.543), red-orange ($Lu'v'$: 24.0 cd/m², 0.310, 0.547), orange ($Lu'v'$: 29.3 cd/m², 0.266, 0.551), yorange ($Lu'v'$: 38.4 cd/m², 0.227, 0.555), or yellow ($Lu'v'$: 52.9 cd/m², 0.198, 0.558). In the feature search task, all stimuli were positioned on the circumference of an imaginary circle with a diameter of 6.1°, whereas for the pop-out search task, the same rectangular configuration was used as in Experiment 1.

The target was always orange in all conditions and search tasks, to provide optimal conditions to apply a constant feature-specific setting. In the feature search task, the target was embedded among four or eight nontargets. In the similar block, half of the nontargets were always red-orange, whereas the other half was yorange. In the dissimilar block, half of the nontargets were red and the other half was yellow. Stimuli were equally spaced in both set size conditions, so that the distance between neighboring stimuli was 9.1° in the Set Size 5 condition and 5.1° in the Set Size 9 condition. The target position was chosen randomly on each trial, and observers completed 160 trials in each condition (in counterbalanced order).

The pop-out search task was identical to Experiment 1, with the following exceptions: In the redder and yellower target condition, an orange target was presented either among three yellow nontargets (redder target condition) or three red nontargets (yellower target condition). The irrelevant distractor could be either red, red-orange, orange, yorange, or yellow. Participants completed 640 trials, 320 trials in each block with the red and yellow nontargets, respectively. The order of blocks was counterbalanced across participants, such that participants either completed the two blocks of the feature search task first (similar/dissimilar, in counterbalanced order) or the two blocks of the pop-out search task first (red/yellow nontargets, in counterbalanced order).

Results

Data. Removing trials with anticipatory eye movements (<100 ms) and trials in which observers failed to select the target within 3,000 ms from the onset of the search display led to a loss of 2.4% of all data in the pop-out search task (0.02% because of anticipatory eye movements). Moreover, 96.79% of first eye movements fell within the boundaries of one of the search items (target, nontarget, or distractor).

Results I: Feature search task. Analysis of the mean RT and error scores of the feature search task showed that the orange target could be distinguished from the target-similar red-orange and yorange nontargets, whereby search was more difficult in this condition than in the dissimilar condition with the red and yellow nontargets. In the dissimilar feature search condition, observers committed on average 5.9% errors, and had a mean RT of 825 ms. In the similar feature search condition, mean errors were higher, 8.7%, $t(15) = 2.1$, $p = .051$, and mean RTs were 1,269 ms, significantly elevated compared with the dissimilar condition, $t(15) = 6.1$, $p < .001$. These results indicate that yorange and red-orange were more similar to the target colour than yellow and red, while still being sufficiently dissimilar from the target colour to allow target discrimination.

Results II: Pop-out search task.

Proportion of distractor fixations.

Feature first versus pop-out first group. Figure 5 depicts the distractor effect in the naïve group that first completed the pop-out search task and the feature first group that had completed the feature search task first. As shown in the figure, the naïve group that started with the pop-out search task showed the typical relational effect, with more frequent selection of the relationally better distractors than the target-similar orange distractor. By contrast, the group that started with the feature search task selected the target-similar orange distractor most frequently, reflecting that attention was indeed biased to the feature value of the target.

Two 2×5 mixed AVOVAs with the between-subjects variable group (feature search task first vs. pop-out search task first) and the within-subjects variable distractor color (red, red-orange, orange, yorange and yellow) were computed over the proportion of distractor fixations in the redder target condition and the yellower target condition. The analyses yielded no significant differences between the groups (redder target condition, $F < 1$; yellower target condition, $F[1, 14] = 2.1$, $p = .17$), but showed a significant main effect of the distractor color (redder target condition, $F[4, 56] = 41.4$, $p < .001$, $\eta^2 = .75$; yellower target condition, $F[4, 56] = 27.2$, $p < .001$, $\eta^2 = .66$), as well as a significant Group \times Distractor Color interaction (redder target condition, $F[4, 56] = 9.4$, $p < .001$, $\eta^2 = .40$; yellower target condition, $F[4, 56] = 4.4$, $p = .024$, $\eta^2 = .24$).

Differences between groups. Independent samples t tests comparing distractor fixations for each distractor color across the two groups showed that the group starting with the feature search tasks showed significantly higher levels of capture by the orange distractor than the group starting with the pop-out search task, both in search for the redder target, $t(14) = 2.5$, $p = .024$, and in search for the yellower target, $t(14) = 2.5$, $p = .027$. In the redder target block, participants starting with the feature search task also showed elevated levels of capture by the yorange distractor, $t(14) = 2.1$, $p = .050$, whereas distractor selection rates did not

differ between the two groups for the remaining distractors, $ps > .15$.

Distractor effects. To assess effects of the different distractors in more detail, pairwise t tests were computed over the distractor selection rates within each group. In the target redder condition, the results showed stronger capture by the red than the red-orange distractor in the pop-out first group, $t(7) = 3.2, p = .016$, whereas the feature first group showed a nonsignificant reduction in capture by the red distractor, $t < 1$. Similarly, in the pop-out first group, the red-orange distractor captured more strongly than the orange distractor, $t(7) = 4.5, p = .003$, whereas capture for the red-orange distractor was nonsignificantly attenuated in the feature first group, $t(7) = 1.7, p = .11$. The orange distractor captured more than the yorange distractor in the feature first group, $t(7) = 4.3, p = .004$, as well as in the pop-out first group, $t(7) = 4.6, p = .002$. In addition, the yorange distractor was selected more frequently than the yellow distractor in feature first group, $t(7) = 4.6, p = .002$, but not in the pop-out first group, $t(7) = 2.2, p = .068$.

In search for the yellower target, the yellow distractor captured significantly less than the yorange distractor in the feature first group, $t(7) = 10.3, p < .001$, whereas the reverse effect in the pop-out search group remained nonsignificant, $t < 1$. Capture by the yorange distractor was marginally significantly stronger than capture by the orange distractor in the pop-out first group, $t(7) = 2.3, p = .054$, and nonsignificantly attenuated for the feature first group, $t < 1$. Moreover, the orange distractor captured more strongly than the red-orange distractor, both for the feature first group, $t(7) = 5.7, p = .001$, and the pop-out first search group, $t(7) = 4.4, p = .003$, whereas capture by the red and red-orange distractors did not differ from one another in either group ($ps > .23$).

Repeated versus nonrepeated distractor colors. To assess whether capture was attenuated when the distractor color was repeated, separate $2 \times 5 \times 2$ mixed ANOVAs with the variables group (feature first vs. pop-out first), distractor color (red, red-orange, orange, yorange, yellow), and repetition (distractor color repeated vs. nonrepeated) were computed over the redder target and yellower target blocks.

For the redder target blocks, the ANOVA showed a significant main effect of distractor color, $F(4, 56) = 36.6, p < .001, \eta^2 = .72$, and a significant Distractor Color \times Group interaction, $F(4, 56) = 10.3, p < .001, \eta^2 = .42$. The remaining effects and interactions were all nonsignificant, $Fs < 3.4, ps > .086$. Two-tailed t tests showed less capture by the red distractor on repeat than nonrepeat trials in the feature first group, $t(7) = 3.4, p = .011$, and a similar nonsignificant trend for the yellow distractor, $t(7) = 1.9, p = .099$ (all other $ts < .1.2, ps > .29$). In the pop-out first group, capture did not differ between repeated and nonrepeated distractor colors, all $ts < 1.6, ps > .15$.

In the yellower target block, the same analysis showed a significant main effect of distractor color, $F(4, 56) = 21.5, p < .001, \eta^2 = .61$, that interacted significantly with repetition, $F(4, 56) = 3.0, p = .044, \eta^2 = .18$ (all other $Fs < 2.4, ps > .061$). Two-tailed t tests revealed no significant differences between repeat and nonrepeat trials in the feature first group, $ts < 1.7, ps > .13$, and significantly less capture on repeat trials than nonrepeat trials for the yellow distractor in the pop-out first group, $t(7) = 4.7, p = .002$ (all other $ts < 1.7, ps > .11$).

Repeated versus nonrepeated distractor position. To analyze possible effects of repeating the distractor position, $2 \times 5 \times 2$ mixed ANOVAs comprising the variables group (feature first vs. pop-out first), distractor color (red, red-orange, orange, yorange, yellow), and distractor position repetition (distractor position repeated vs. nonrepeated) were computed over the data from the target redder and the target yellower block.

For the redder target condition, the results showed a significant main effect of the distractor color, $F(4, 56) = 42.5, p < .001, \eta^2 = .75$, repetition of the distractor position, $F(1, 14) = 25.4, p < .001, \eta^2 = .64$, a marginally significant interaction between repeated distractor position and distractor color, $F(4, 56) = 2.9, p = .054, \eta^2 = .17$ and a significant Distractor Color \times Group interaction, $F(4, 56) = 10.9, p < .001, \eta^2 = .42$. Two-tailed t tests showed that, in the pop-out first group, repeating the distractor position significantly attenuated capture for the red distractor, $t(7) = 3.4, p = .011$, the red-orange distractor, $t(7) = 4.6, p = .003$, and the orange distractor, $t(7) = 2.8, p = .027$ (other $ps > .17$). In the feature first group, capture was on average reduced when the distractor position was repeated, but the respective pairwise comparisons all failed to reach significance (all $ps > .05$).

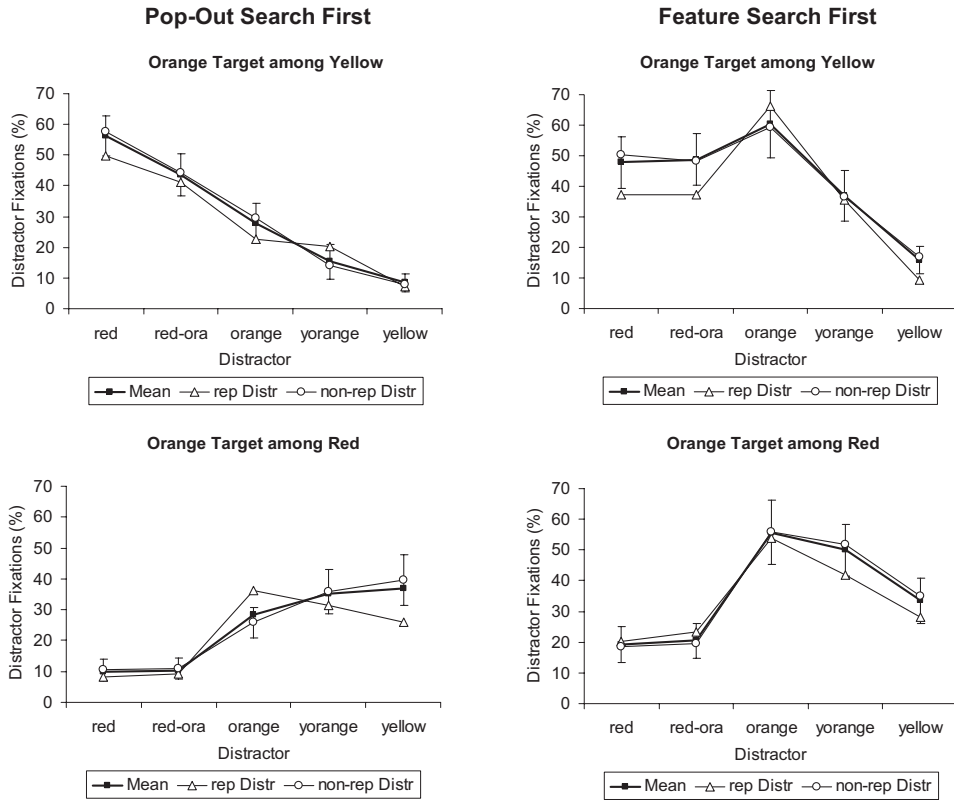
In the target yellower block, the same $2 \times 5 \times 2$ ANOVA showed a significant main effect of the distractor color, $F(4, 56) = 22.6, p < .001, \eta^2 = .61$, and of repeating the distractor position, $F(1, 14) = 18.3, p = .001, \eta^2 = .56$, as well as a significant Distractor Color \times Group interaction, $F(4, 56) = 3.2, p = .019, \eta^2 = .19$ (all other $ps > .24$). Pairwise comparisons showed that repeating the distractor position attenuated capture by the yellow distractor, $t(7) = 2.6, p = .034$, and the orange distractor, $t(7) = 3.0, p = .020$, in the feature first group, whereas the same trends remained nonsignificant in the pop-out first group, all $ps > .066$.

Ipsilateral versus contralateral target-distractor displays. Two mixed $2 \times 5 \times 2$ ANOVAs with the variables group (feature search first vs. pop-out search first) distractor color, and hemifield (target and distractor presented in same vs. different hemifield) were computed over the mean distractor selection rates of the redder and yellower target conditions, respectively.

In the redder target condition, the ANOVA showed a significant main effect of hemifield, $F(1, 14) = 35.2, p < .001, \eta^2 = .71$, and of the distractor color, $F(4, 56) = 75.7, p < .001, \eta^2 = .84$.

Figure 5 (opposite). The mean proportion of first distractor fixations in the color-search task of Experiment 3, depicted separately for the two search conditions (orange target among yellow nontargets vs. orange target among red nontargets). Panels on the left depict the results for the naïve group that first completed the pop-out search task. Panels on the right depict the results for the pretrained group that first completed the feature search task. From top to bottom, each four-panel figure additionally depicts the results for (a) repeating versus not repeating the distractor shape (A; *rep Distr* vs. *nonrep Distr*), (b) for repeating versus not repeating the distractor position (B; *rep Pos* vs. *nonrep Pos*), (c) for ipsilateral versus contralateral presentations of the target and distractor (*TD ipsi* vs. *TD contra*), and (d) for data obtained in the first half versus the second half of trials in each pop-out search block. Error bars present ± 1 standard error of the mean and are only shown for the mean proportion of distractor fixations.

A) Distractor Color Repeated vs. Non-Repeated



B) Distractor Position Repeated vs. Non-Repeated

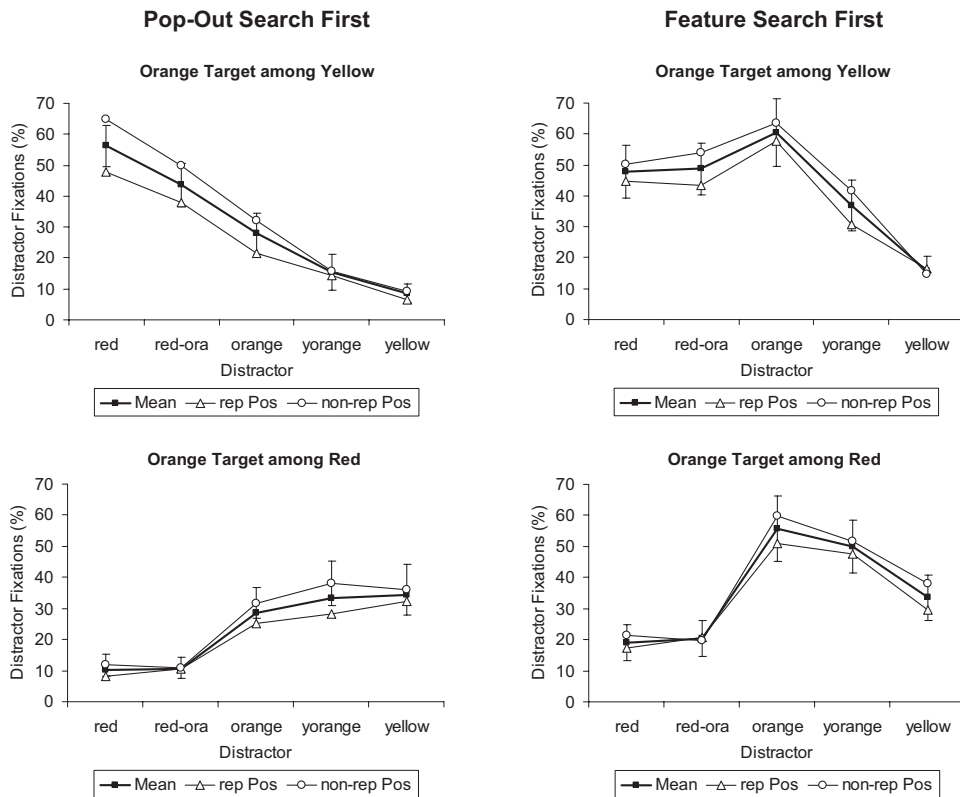
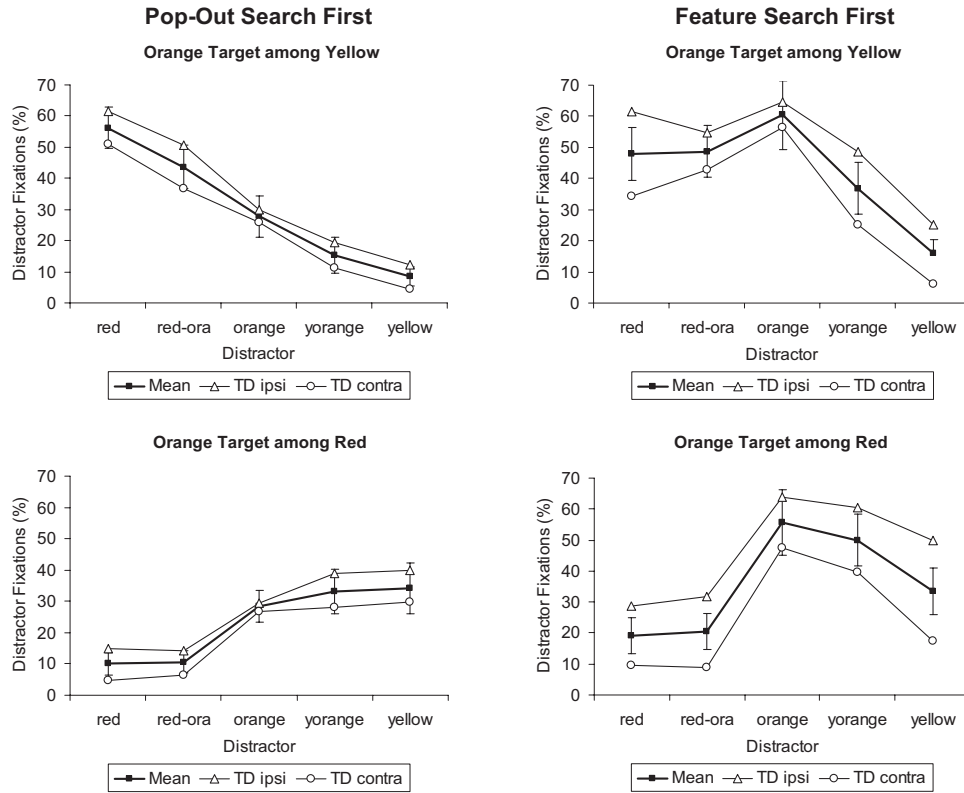


Figure 5 (opposite)

C) Ipsilateral vs. Contralateral Target-Distractor Positions



D) First Half vs. Second Half of the Experiment

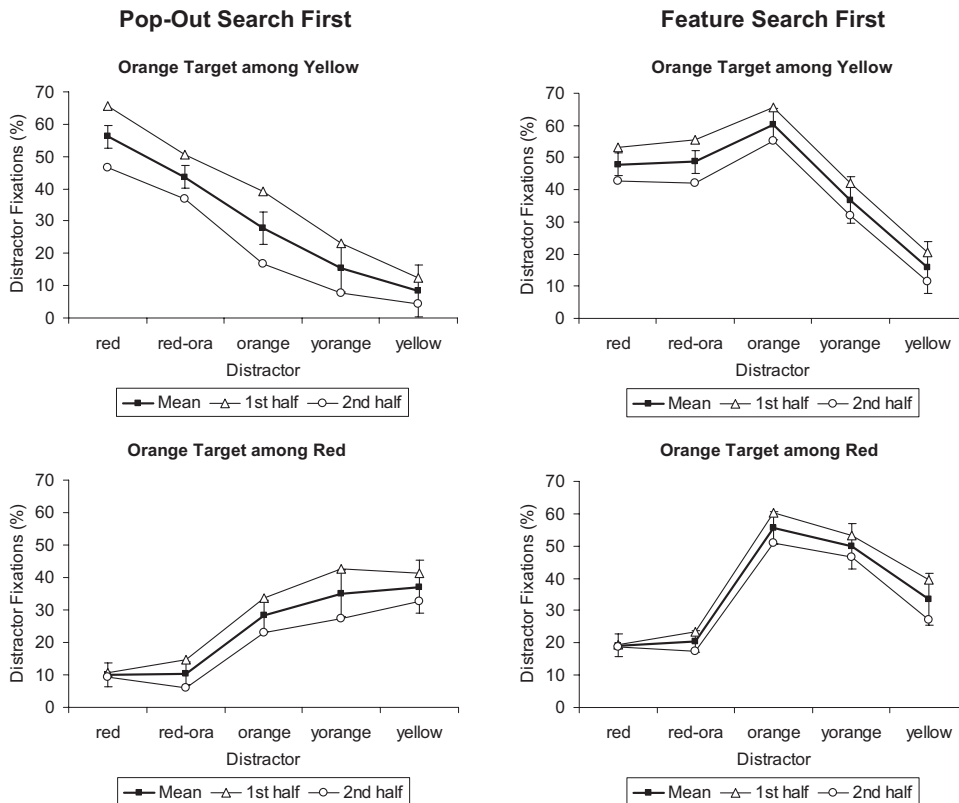


Figure 5. (continued).

Distractor color interacted significantly with group, $F(4, 56) = 9.4, p < .001, \eta^2 = .40$, and with hemifield, $F(4, 56) = 4.6, p = .008, \eta^2 = .25$, and the three-way interaction between all variables was also significant, $F(4, 56) = 3.2, p = .032, \eta^2 = .19$. The Hemifield \times Distractor Color interaction was due to the fact that capture was significantly stronger on ipsilateral trials than contralateral trials for all distractors (all $t_s > 2.6, p_s < .037$), except the target-similar distractor ($t_s < 1.7, p_s > .13$). The three-way interaction was due to the fact that the difference between ipsilateral and contralateral conditions was stronger in the feature first group than in the pop-out first group, but these differences were significant only for the red distractor, $t(14) = 2.6, p = .003$ and the yorange distractor, $t(14) = 2.3, p = .046$.

The target yellower condition showed similar results, with the $2 \times 5 \times 2$ ANOVA showing significant main effects of the distractor color, $F(4, 56) = 23.1, p < .001, \eta^2 = .62$, and hemifield, $F(1, 14) = 80.1, p = .001, \eta^2 = .85$. Of the interactions, the Distractor Color \times Group interaction was significant, $F(4, 56) = 3.5, p = .049, \eta^2 = .20$, as well as the Hemifield \times Group interaction, $F(1, 14) = 16.9, p = .001, \eta^2 = .55$. The Hemifield \times Distractor Color interaction also approached significance, $F(4, 56) = 2.7, p = .082, \eta^2 = .16$, whereas the three-way interaction was nonsignificant, $F(4, 56) = 1.1, p = .38$. The Hemifield \times Group interaction was due to the fact that hemifield effects were stronger in the group that had started with the feature search task (mean difference = 22.4%) than the group that had started with the pop-out search task (mean difference = 8.3%). However, capture was significantly stronger in the ipsilateral than the contralateral condition for all target-dissimilar distractors, both in the feature first group and the pop-out first group,

all $t_s > 2.8, p_s < .024$. In the feature first group, capture by the target-similar distractor was also stronger in the ipsilateral condition than the contralateral condition, $t(7) = 2.6, p = .032$, whereas this difference was nonsignificant in the pop-out first group, $t < 1$.

Mean latencies of the first eye movements to target and distractor. The target and distractor fixation latencies could only be analyzed with respect to the differences between the two groups and the main effect of distractor color. In the target redder condition, two subjects from the feature first group had to be excluded, and in the target yellower condition, two subjects from the feature first group and one subject from the pop-out first group, had to be excluded, because they had less than 5 first fixations on the target.

In the target redder condition, a 5×2 mixed ANOVA comprising the variables distractor color (red, red-orange, orange, yorange, and yellow) and group (feature group vs. pop-out group) showed that target fixation latencies were significantly modulated by the different distractor colors, $F(4, 48) = 5.9, p = .007, \eta^2 = .33$, whereas they did not differ between the groups, all other $p_s > .33$. In the pop-out first group, target fixation latencies were longest for the red-orange distractor, followed by the red, orange, yorange, and yellow distractor (see Table 4). Of the corresponding pairwise comparisons, only the difference between the red-orange and orange distractor reached significance, $t(7) = 2.6, p = .027$ (all other $p_s > .11$). In the feature search group, target fixation latencies were longest when the red distractor was present, followed by the same target fixation latencies for the red-orange and orange distractor, and the yorange and yellow distractor. However, none of the corresponding pairwise comparisons reached significance, all $p_s > .11$.

Table 4
Mean Proportion and Latencies for First Fixations on the Target and Distractor in Experiment 3

	Distractor				
	Red	Red-Ora	Orange	Yorange	Yellow
Prop. target fix (%)					
Target redder					
Feature first	42.3% [8.3]	42.9% [9.5]	30.1% [10.4]	53.2% [9.0]	63.3% [6.4]
Pop-out first	36.9% [7.3]	45.8% [9.0]	60.0% [9.4]	73.3% [8.4]	81.8% [7.5]
Target yellower					
Feature first	63.8% [7.3]	59.6% [7.3]	28.1% [8.5]	32.3% [7.2]	47.8% [7.1]
Pop-out first	74.1% [7.4]	76.5% [8.0]	54.2% [9.0]	47.3% [7.5]	45.3% [7.8]
Target latency (ms)					
Target redder					
Feature first	286 [11.4]	280 [13.9]	280 [18.2]	267 [7.4]	262 [7.0]
Pop-out first	265 [11.0]	271 [11.9]	259 [8.0]	256 [7.8]	253 [6.0]
Target yellower					
Feature first	286 [14.3]	279 [13.2]	307 [25.6]	293 [19.9]	295 [14.5]
Pop-out first	265 [11.3]	266 [12.7]	276 [13.9]	279 [14.9]	282 [14.3]
Distr. latency (ms)					
Target redder					
Feature first	247 [6.1]	251 [7.9]	268 [8.3]	274 [10.4]	254 [5.8]
Pop-out first	238 [4.6]	241 [5.3]	252 [7.0]	242 [6.1]	237 [8.0]
Target yellower					
Feature first	243 [8.4]	249 [4.9]	264 [9.7]	261 [7.6]	254 [6.3]
Pop-out first	207 [37.2]	242 [11.8]	260 [14.8]	249 [9.4]	246 [11.4]

Note. The results of Experiment 3 are depicted as a function of the search task (target redder vs. target yellower condition) and pretraining (feature first vs. pop-out first group), separately for each distractor condition (red, red-orange, orange, yorange, and yellow distractor). Numbers in brackets describe the standard error of the mean. Numbers in italics indicate that averages were based on few trials per cell or that individual data were missing. Distr. latency = latency of first eye movements to the distractor; Prop. target fix = mean proportion of first fixations on the target; Target latency = latency of first eye movements to the target.

In the target yellower condition, the same 5×2 mixed ANOVA similarly showed a significant main effect of the distractor color only, $F(4, 44) = 6.0, p = .007, \eta^2 = .35$ (all other $ps > .36$). In the pop-out first group, target fixation latencies were longest with the yellow distractor, followed by the yorange, orange, red-orange, and red distractor (see Table 4). Target fixation latencies with the yellow, yorange, and orange distractor were all significantly longer than target fixation latencies in the presence of a red or red-orange distractor, all $ts > 2.5, ps < .036$ (all other $ps > .37$). In the feature first group, target fixation latencies were longest with an orange distractor, followed by the yellow, yorange, red-orange, and red distractor. However, none of the corresponding contrasts was significant, all $ps > .080$. In sum, the effects observed in the target fixation latencies are in line with the results observed in the first eye movements to the distractors.

Latencies of distractor fixations. Regarding the fixation latencies to the distractor, there were only sufficient trials for analyzing the fixation latencies of eye movements to the target-similar distractor and the two relationally better distractors. In the target redder condition, data from two subjects were removed, and in the target yellower condition, data from one subject were removed, because one of these distractors was selected less than five times.

For the target redder condition, a 2×3 mixed ANOVA with the variables group (feature search first vs. pop-out search first) and distractor color (orange, red-orange, red) showed only a significant main effect of the distractor color, $F(2, 24) = 17.5, p < .001, \eta^2 = .59$ (all other $ps > .21$). In the feature first group, distractor fixation latencies were longest for the orange distractor ($M = 268$ ms), and differed significantly from fixations on the red-orange distractor ($M = 250$ ms), $t(6) = 3.8, p = .009$, and the red distractor ($M = 247$ ms), $t(5) = 3.1, p = .022$, whereas the latter two did not differ significantly from one another, $t < 1$. Similarly, the pop-out first group showed longer latencies for fixations on the orange distractor ($M = 268$ ms) than the red-orange distractor ($M = 241$ ms), $t(5) = 4.4, p = .005$, and the red distractor ($M = 238$ ms), $t(5) = 3.4, p = .014$, whereas latencies for fixations on the red and red-orange distractor did not differ, $t(5) = 1.2, p > .28$.

In the target yellower condition, the 2×3 mixed ANOVA comparing latencies of fixations on the orange, yorange, and yellow distractor across the two groups showed that distractor fixation latencies were modulated by the distractor color only, $F(2, 26) = 4.1, p = .028, \eta^2 = .24$ (all other $ps > .55$). However, two-tailed t tests failed to show any significant differences in the latencies between fixations on the orange, yorange, and yellow distractor in the feature first group, $ts < 2.0, ps > .087$, as well as in the pop-out first group, $ts < 1.9, ps > .107$.

Discussion

Experiment 3 showed qualitatively different results in color search, depending on whether observers were naïve or whether they were pretrained to select the target by virtue of its exact color. Observers primed to use a feature-specific search strategy in a feature search task continued to use the feature-specific selection bias in two blocks of a pop-out search task with yellow and red nontargets, as shown by the fact that the target-similar orange distractor captured the gaze most strongly. By contrast, a naïve group of observers showed more capture by the relationally better

distractors than the target-similar orange distractor, in line with the results of Experiment 1. Of note, qualitatively different results between a pretrained and naïve group were obtained despite the fact that both groups were tested in exactly the same stimulus conditions. As observers are evidently able to ignore the relationally better distractors when primed to use a feature-specific selection bias, more capture by the relationally better distractors in Experiment 1 cannot be attributed solely to bottom-up, stimulus-driven factors. Instead, the results suggest that capture by target-dissimilar distractors strongly depends on strategic factors, namely, whether observers adopt a relational search setting in search for a pop-out target or a feature-specific bias.

In the pretrained group, capture by the relationally better distractor was only attenuated but not completely eliminated, which resulted in asymmetries in the distractor selection rates (see Figure 5a–c). The asymmetrical results pattern could be due to the fact that (some) observers in the feature first group changed their search strategy in the course of the experiment, from an initial feature-specific selection bias to a relational selection bias. In this case, more capture by the relationally better distractors would be mostly due to the observers' gaze behavior in the latter part of the pop-out search task. To address this possibility, we plotted the proportion of first distractor fixations in the first versus the second half of the pop-out search block. As shown in Figure 5d, there was no indication that observers changed their search strategy during the course of the experiment. In particular, the results showed the same asymmetries in distractor selection rates across the first and second half of the block. These results rule out that the feature first group initially adopted a feature-specific search strategy and later switched to a relational search mode, and instead suggest that the feature first group maintained a feature-specific setting for the entire duration of the pop-out search task.

Figure 5c shows that the observed asymmetries in the distractor selection rates in the pretrained group were stronger in the ipsilateral condition, in which the target was located near to the distractor. By contrast, distractor selection rates approached a more symmetrical results pattern when the target and distractor were located in different hemifields. This suggests that the asymmetrical results pattern (of more capture by the relationally better distractors) than the nontarget-similar distractors was in part driven by the hemifield effect. Interestingly, the hemifield effect itself was significantly stronger in the feature first group than the pop-out first group, indicating that a feature-specific search strategy may render observers more vulnerable to capture by irrelevant distractors that are in close proximity to the target.

Despite the fact that the pop-out first group in Experiment 3 clearly showed relational search for the target, some of the results deviated from the findings of Experiment 1. First, in the redder target condition of Experiment 3, latencies for selecting the target-similar distractor were longer than latencies for selecting the target-dissimilar (relationally better) distractor. It is possible that this effect reflects fast, bottom-up driven selection of the more salient target-dissimilar distractors and slow, top-down controlled selection of the target-similar distractor (e.g., Theeuwes, 1992; van Zoest & Donk, 2005; van Zoest et al., 2004). A second possible explanation is that latencies for selecting the orange distractor were longer because it was more difficult to distinguish from the target than the target-dissimilar distractors after covert attention had been shifted to the distractor location. Hence, distractor fixa-

tions to the dissimilar distractors were all shorter, because saccades to these distractors could be aborted quickly after attention had been shifted to the distractor. By contrast, discriminating the target-similar distractor from the target required more in-depth processing (e.g., of the distractor location), so that saccades to this distractor were executed after a point in time in which a saccade to a dissimilar distractor would have been aborted. The present experiments cannot distinguish which of the two explanations accounts for the findings. However, it is interesting that the distractor fixation latencies were quite long in Experiment 3, around 260 ms. This indicates that observers adopted a rather conservative criterion for executing saccades in Experiment 3 (e.g., compared with the color search task of Experiment 1, in which distractor fixation latencies were around 220 ms). The rather long distractor fixation latencies of Experiment 3 would seem to argue against the notion that the target-dissimilar distractors elicited very fast, reflexive saccades.

The results of Experiment 3 also provided some evidence that observers inhibited the color of the previous distractor, as capture for the relationally better distractor was reduced on repeat trials, especially in the feature first group. This indicates that a feature-specific setting may in part be achieved by inhibiting relationally better distractors. However, the naïve group also showed some evidence for inhibition of the yellow distractor in the yellow target condition that carried over to the next trial and reduced capture when the yellow distractor was repeated. These results indicate that short-lived inhibition of the distractor color can occur independently of whether attention is biased to the target feature value or the target–nontarget relationships.

Interestingly, Experiment 3 showed significant effects of repeating the distractor position and the distractor color; however, in each instance, only one of these effects reached significance. For instance, in the pop-out first group, repeating the distractor position but not the distractor color modulated capture in the target redder condition, whereas in the target yellower condition, the opposite was the case (i.e., repeating the distractor color, but not the distractor position, modulated capture). The same pattern of results could be observed in the feature first group, and suggests that there could be a trade-off between inhibition of the distractor feature and the distractor position: Depending on the stimulus conditions, observers may be more inclined to inhibit either the distractor position or the distractor color, but not both.

General Discussion

The present study yielded several interesting results. In Experiment 1, capture by irrelevant distractors was tested using the same colors as in a previous spatial cueing study (Becker et al., 2010). Extending on previous work, capture was tested in the ecologically more valid conditions of a visual search task, in which the distractors were presented for the entire duration of search, they directly competed with attention for the target (which was always present), and selection errors were clearly noticeable (by erroneous eye movements to the distractor). Despite these differences in the methods, capture in Experiment 1 closely followed the results pattern observed in spatial cueing tasks, with a target-dissimilar (relationally better) distractor attracting attention and the gaze more strongly than a target-similar distractor. This demonstrates that previous results were not due to specifics of the spatial cueing

paradigm. Rather, the results support the relational theory and indicate that capture is generally not determined by target-distractor similarity, but by whether the distractor matches the relative attributes of the search target.

Experiment 2 further showed that the same principles that guide attention and eye movements in search for color and size also determine capture in search for a star shape. In particular, Experiment 2 showed that attention is not tuned to the particular shape of the target, but that the visual system apparently assesses how the target differs from the nontargets and biases attention to the relative properties of the target (spikier vs. less spiky). This was an interesting result, as shape is a complex property of objects that can plausibly be expected to be encoded independently of other shapes in the display.

Naturally, it is possible that visual selection was biased toward a different (relative) property of the target. Of note, the star shapes also differed in the size of the surface area, so that it is possible that attention was biased to the relative size of the colored area rather than the relative shape of the target. Admittedly, this possibility cannot be ruled out: As it is impossible to vary the shape of different objects without also altering some other attributes of the object, it is always possible to explain experimental results by variations in some other low-level property (e.g., Arguin & Saumier, 2000; Becker, 2013a). It is still noteworthy that, in Experiment 2, the target was clearly defined by a particular shape, and yet, attention was not biased to the specific shape of the target but to the shape (or some other property) that the target had relative to the nontargets.

In addition, it is noteworthy that, in Experiments 1 and 2, attention was biased to a relative attribute of the target, despite the fact that this led to more frequent erroneous selection of an irrelevant distractor. Intuitively, it is implausible that observers would choose a search strategy that impairs target selection. Hence, in previous studies, it has been suggested that observers may be unable to tune attention to the exact feature value of the target (e.g., Becker, 2010a). Contrary to this view, Experiment 3 showed that attention can be biased to the feature value of the target, demonstrating that observers are able to encode and select the target feature independently of the features of the surround. With this, the results reject a strong version of the relational account, according to which all instances of a feature-specific selection bias are due to a selection bias for feature relationships (e.g., Becker, 2010a). However, the results also do not unequivocally support a feature-based theory, as evidence for a feature-specific selection bias could only be observed when observers had been pretrained to use a feature-specific bias in a previous feature search task.

Importantly, once observers had adopted a feature-specific selection bias in Experiment 3, they rigidly maintained this setting across two blocks of a pop-out search task. These results are at odds with the view that observers continuously adjust their top-down settings to achieve and maintain an optimal level of performance, as has been suggested by optimal tuning accounts and statistical learning models (e.g., Lee et al., 1999; Mozer & Baldwin, 2008; Navalpakkam & Itti, 2006). Instead, the results are in line with models of executive control (e.g., Norman & Shallice, 1986) that assume that behaviors are largely driven by learnt routines, which are carried out automatically—at least for as long as the visual input remains approximately the same and the be-

havior is sufficient to accomplish the task goals (see also Bargh, 1992; Reason, 1979). These findings have two important implications for current theories of visual search, (a) in that attentional settings are not completely determined by the instructions and stimulus conditions, but are influenced by past learning experience; and (b) in that the visual system does not constantly evaluate the efficiency of the current attentional set, but rather applies a previously successful or possible strategy until the stimulus input changes (see also Bacon & Egeth, 1991; Krummenacher, Grubert, & Mueller, 2010, Exp. 2; Leber & Egeth, 2006). In the following, we will discuss possible reasons why observers apparently preferentially biased visual selection to feature relationships rather than the exact feature value, and why pretraining was vital for observers to adopt a feature-specific search strategy.

Causes and Effects of Feature-Specific Tuning

An important question is why observers did not spontaneously tune attention to the target feature in the pop-out search task, but only after completing the feature search task. There were two main differences between the feature search task and the pop-out search task that can potentially answer this question. First, in the feature search task, all displays contained an equal number of yellower and redder nontargets, whereas the pop-out search displays were asymmetrical in that they always contained three nontargets that differed in one direction from the target (e.g., yellower) and only a single distractor that differed in the other direction. Previous studies have shown that differences in the relative ratios of different nontarget features can change top-down search strategies. For example, Shen, Reingold, and Pomplun (2000) found that when observers had to search for a red "O" among red "X" and green "O" characters, visual selection was biased toward red items when there were only few red distractors present, but biased to the target shape when there were many red distractors (see also Egeth, Virzi, & Garbart, 1984; Friedman-Hill & Wolfe, 1995; Kaptein, Theeuwes, & van der Heijden, 1995; Treisman & Sato, 1990; Zohary & Hochstein, 1989). In the present pop-out search task, it is accordingly possible that visual selection was biased to redder or yellower rather than orange, because visual selection was optimized for discriminating the target from the nontargets rather than the (single) distractor.

A second difference between the feature search task and the pop-out search task was that the relationally better distractor was not always present in the pop-out search task, whereas the stimulus displays in the feature search task always contained nontargets that were redder and yellower than the target. Given that a relationally better distractor was present only on 25% to 40% of all trials (in Experiments 1 and 3, respectively), there was perhaps no strong incentive to adopt a feature-specific search strategy or to inhibit relationally better distractors. Geyer and colleagues (2008) found that a target-dissimilar distractor was only effectively ignored when it was presented on 50% or 80% of all trials, whereas it captured when it was presented on 20% of all trials. Hence, observers may have failed to adopt a feature-specific selection bias in the present study because the distractor was not presented frequently enough to provide a strong incentive to inhibit the target-dissimilar distractors and/or adopt a more fine-grained, feature-specific selection strategy (e.g., Geyer et al., 2008).

In addition, it is possible that the relationally better distractor was not strongly inhibited in the present pop-out search task because selection of a target-dissimilar distractor generally does not incur high costs at level of overall search time or RT: For example, Theeuwes et al. (2000) proposed that attention can be more quickly deallocated from target-dissimilar distractors than target-similar distractors, so that capture by target-dissimilar distractors does not produce costs at the same level as capture by target-similar distractors. In line with this view, some eye movement studies showed that dwell times on target-similar distractors were longer than on target-dissimilar distractors (e.g., Becker, 2011; Becker et al., 2009; Shen et al., 2000). Hence, it is possible that a relational search strategy is preferred over feature-specific search, because a feature-specific selection bias increases selection of target-similar distractors, which disproportionately inflate costs at later levels of processing.

To evaluate this possibility, we compared the dwell times and mean RT between the feature first group and pop-out first group. As shown in Figure 6, dwell times were indeed significantly longer on the target-similar distractors than the target-dissimilar distractors, but only for the feature first group, whereas the pop-out first group did not show any pronounced dwell time differences between the different distractors.³

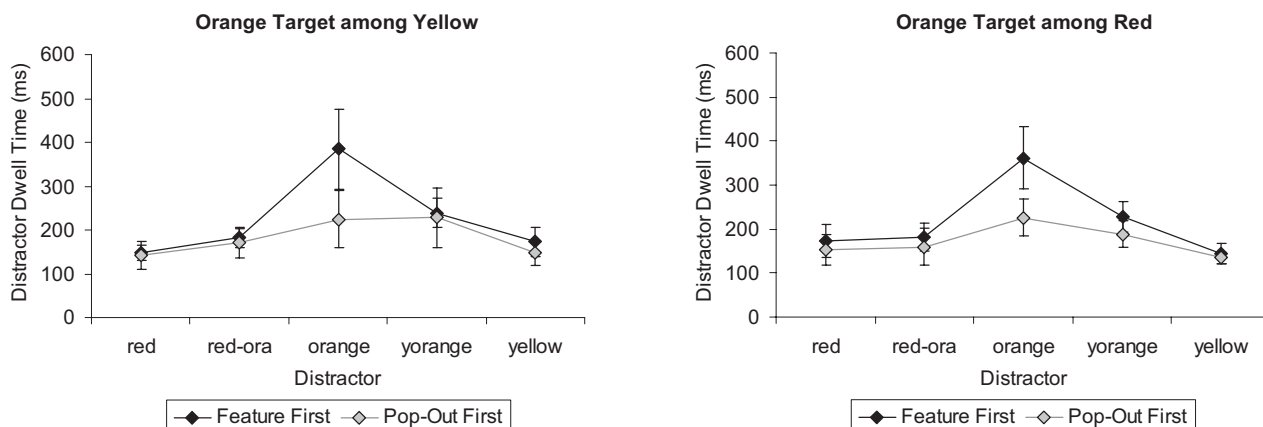
This indicates that the time needed to reject a distractor and to reallocate attention to the target depends on target similarity but also on the search strategy: If attention is biased to a specific feature value, and a corresponding distractor is selected, it is indeed more difficult to recover from the selection error and reorient attention to the target. If visual selection is however biased to the relative attributes of the target, recovery is fast and largely independent of target-distractor similarity.

Essentially the same results pattern was observed in the mean RT, with RT being elevated specifically in the feature first group when the target-similar distractor was present (see Figure 6).⁴ This is an interesting result, because it suggests that the way in which attention is biased to the target affects not only the first eye movement but also later processes that commence after a distractor has been selected. More importantly, the results indicate that capture by relationally better distractors indeed hardly produced

³ Two-tailed *t* tests computed over the dwell times showed that, in the target redder conditions, the feature first group had significantly longer dwell times on the orange distractor than the red-orange or red distractor, $ps < .031$, whereas the pop-out first group showed no significant differences, $ps < .09$. In the target yellower condition, the feature first group similarly showed longer dwell times on the orange distractor than the relationally better distractors, $ps < .012$, whereas the pop-out first group showed only longer dwell times on the orange than the yellow distractor, $p < .032$; other $p > .61$.

⁴ Comparing mean RT in the target redder condition by a 2×5 mixed ANOVA showed a significant main effect of distractor, $F(4, 56) = 8.1, p = .006, \eta^2 = .37$, and a significant Group \times Distractor Color interaction, $F(4, 56) = 8.1, p = .046, \eta^2 = .23$. The same effects were also obtained in the target yellower condition, which showed a significant main effect of distractor, $F(4, 56) = 11.8, p = .001, \eta^2 = .46$, and a significant Group \times Distractor Color interaction, $F(4, 56) = 6.7, p = .012, \eta^2 = .33$. Pairwise *t* tests showed that, both in the target redder and target yellower conditions, RTs were significantly or marginally significantly longer with the orange distractor than all other distractors in the feature first group, $ps < .055$. In the pop-out search group, RTs were longer with the two relationally better distractors and the target-similar distractor than with the nontarget-similar distractors, both in the target redder and the target yellower condition, all $ps < .045$.

A) Distractor Dwell Times



B) Mean Response Time (RT)

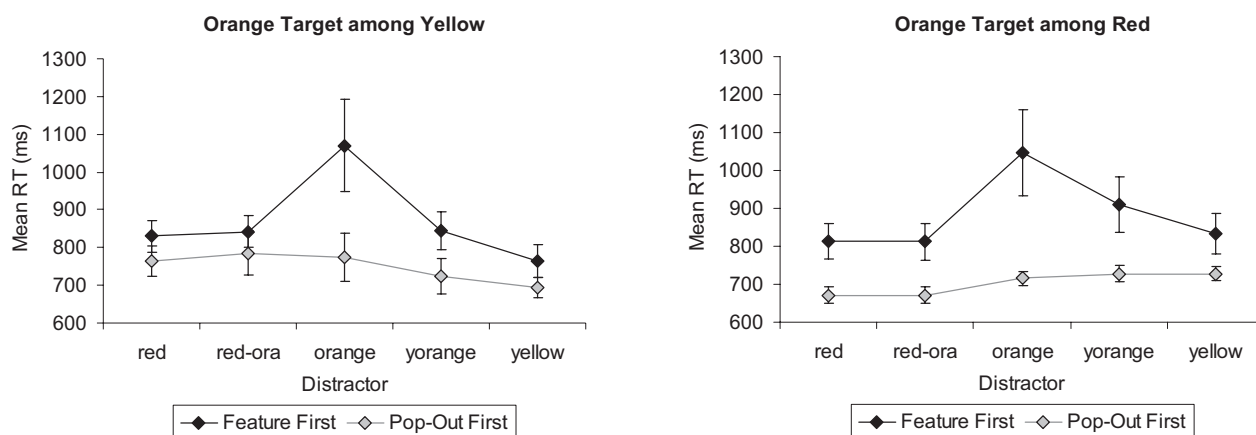


Figure 6. The mean distractor dwell times (A) and manual response times (B) in the color search task of Experiment 3, depicted separately for condition in which the orange target was redder than the yellow nontargets (left) and the block in which the orange target was yellower than the red nontargets (right). Gray line-graphs depict the results for the naïve group that started with the pop-out search task (*Pop-Out First*), black line-graphs the results for the group that first completed the feature search task (*Feature First*). Error bars present ± 1 standard error of the mean.

any noticeable costs at the level of overall search time. As shown in Figures 5 and 6, the pop-out first group selected the relationally better distractors on almost 50% of all trials as the first item; yet overall search times were increased only moderately, with the fastest and slowest RT differing only by about 100 ms. By comparison, in the feature first group, a target-similar distractor slowed RT by 234 ms to 305 ms, compared with the fastest RT, which is more than a threefold increase in RT compared with the pop-out first group.

These results raise the intriguing possibility that a selection bias for feature relationships may be preferred over a selection bias for exact feature values because relational search allows more flexibility in reorienting attention and the gaze. It is also not difficult to understand why reorienting was slowed for the target-similar distractor. A target-dissimilar distractor can pre-

sumably be rejected more quickly because its nonmatching color provides an immediate cue that it is not the target. Rejection of a target-similar distractor, however, takes longer because it can only be identified by another additional feature (i.e., its occupying a nontarget position in Experiment 3; e.g., Becker, 2011; Becker et al., 2009).

When observers adopt a relational selection bias, recovery may be speeded because the target-similar distractor does not exactly match a relative target template. Of note, the orange distractor was not the reddest item in the visual field and hence did not perfectly match the target template (i.e., the description of the sought-after item; Duncan & Humphreys, 1989), which may have facilitated recovery.

According to this explanation, dwell times on an erroneously selected stimulus would be determined by (a) the physical simi-

larity of this stimulus to the target stimulus, and (b) the extent to which the stimulus matches the target template. Top-down tuning to the exact target feature value may incur costs at the level of deallocating attention from the selected stimulus, because an erroneously selected stimulus will very often match both the target feature value and the feature value of the target template, which slows recovery. By contrast, a relational search strategy may be more adaptive, because an erroneously selected stimulus will rarely produce the best match to the relational target template and the physical attributes of the target. This could explain why the visual system usually favors a relational selection bias over a feature-specific one (see also Becker, 2010a, 2013b).

In addition, it is possible that relational search is more efficient in a complex and unpredictable environment, because it does not require detailed preknowledge about the target and can be flexibly applied to a large number of different situations and stimuli (e.g., variable lighting conditions; see Becker, 2013b). However, this is certainly speculative and would warrant further research.

How Do We Achieve a Feature-Based Setting?

In the beginning, it was hypothesized that a fine-grained feature-specific selection bias may be achieved by inhibiting (neurons that respond to) relationally better distractors, which constitutes a possible reason for why previous spatial cueing studies failed to show evidence for feature-specific search. However, the results failed to support this hypothesis. First, rendering the distractors clearly visible in the present visual search task did not prompt observers to inhibit target-dissimilar distractors, despite the fact that the relationally better distractors clearly competed for attention with the target and often captured attention and the observers' gaze. Second, previous studies showed that inhibition of a color distractor automatically carries over to the next trial and reduces capture if the distractor has the same color as the distractor on the previous trial (e.g., Becker, 2007, 2010b; Geyer et al., 2008). In the present study, there was some evidence for distractor inhibition in the color search tasks. However, effects of distractor inhibition and automatic intertrial carryover effects were too weak to explain the ability of observers to ignore target-dissimilar distractors. Inhibition of the relationally better distractor was also not limited to observers who engaged in feature search mode, but was found in the naïve group that showed overall more capture by relationally better distractors than the target-similar distractor. These results indicate that the ability to limit search to a specific feature value (i.e., orange) did not depend on inhibiting the colors of relationally better distractors.

In sum, it seems that visual selection was limited to the target feature by selectively enhancing the attention-driving capacity of the target color value, which led to reduced capture by target-dissimilar distractors, because they did not match the top-down control setting. Such a feature-specific selection mechanism, as has been proposed in many feature-based accounts of attention (e.g., Koch & Ullman, 1985; Ludwig & Gilchrist, 2002; Martinez-Trujillo & Treue, 2004; Maunsell & Treue, 2006; Wolfe, 1994), and seems more consistent with the present results (a) that target-similar distractors captured the gaze on a large proportion of trials, and (b) that selection of the orange distractor selectively elevated dwell times and RT in the group that was primed to use a feature-

specific search strategy. As will be discussed next, these results present a problem for the relational account.

Theoretical Implications of Relational Versus Feature-Specific Search

In the first theoretical article on the relational account, it was argued that the relational account is consistent with all effects that have previously been interpreted in support of a feature-based selection account, and that it could provide an alternative interpretation for these effects (Becker, 2010a). Subsequent studies supported this view by showing that feature priming effects and the often-reported similarity effect were not due to a feature-specific selection bias but to top-down tuning to the relative attributes of the target (e.g., Becker, 2010a, 2013a; Becker et al., 2010, 2013).

Contrary to this contention, however, Experiment 3 showed that pretrained observers were able to adopt a feature-specific selection bias that cannot be explained by a context-dependent setting. These results suggest that visual selection can be genuinely biased to a specific feature value, independently of the context. With this, this is the first visual search study to demonstrate that attention can be biased to the target feature value independently of the context—a finding that is consistent with current feature-based accounts of visual selection, but not with an exclusively relational selection bias. Hence, the results reject a strong version of the relational account, according to which all instances of feature-based selection result from tuning attention in a context-dependent manner to the target.

Can the results be explained by a feature-specific account of selection? According to optimal tuning accounts (e.g., Navalpakam & Itti, 2007; Scolari & Serences, 2010), attention can be biased to an exaggerated target feature value, to reduce the overlap between the target and nontarget feature value distributions and increase the signal-to-noise ratio. Tuning attention to an exaggerated feature would lead to more capture by distractor features shifted away from nontarget features and thus can provide an alternative explanation for capture by relationally better distractors (which is the main reason why previous studies on the relational account did not use the visual search paradigm; see Becker, 2010a; Becker et al., 2010).

Still, these accounts have difficulty explaining why attention was tuned to different feature values when observers were given exactly the same task and instructions. According to optimal tuning accounts, observers continuously adjust their top-down settings to yield the optimal signal-to-noise ratio. From this it follows that observers from the naïve group and pretrained group should have biased visual selection to the same (optimal) feature value, contrary to the observed results. Theories that attempt to explain the results pattern of the naïve group and pretrained group by the same underlying process also face difficulties in explaining the pronounced differences observed in the dwell times and RT between the groups. These results suggest that relational search and feature-specific search constitute two distinct and separable search modes that cannot be explained by a purely relational account or a purely feature-based account alone.

Implications for Other Theories of Visual Search

Experiment 3 showed that attention can be tuned to colors that are intermediate between more extreme colors (e.g., orange among red and yellow). This finding can present a problem for a subclass of feature-based selection accounts. For instance, according to the Guided Search 2.0 model, attention can be tuned to broad categorical attributes of the target such as red, yellow, green, and blue, but not to mixed colors such as orange, when an orange target is presented among red and yellow distractors (Wolfe, 1994). The finding that it is evidently possible to bias visual selection to orange is more in line with fine-grained feature-specific selection accounts (e.g., Lee et al., 1999; Navalpakkam & Itti, 2006) rather than broad categorical accounts (e.g., Wolfe, 1994).

Visual selection of intermediate feature values also seems to contradict other feature-specific models, including the linear separability account (e.g., Bauer, Jolicoeur & Cowan, 1996; D'Zmura, 1991) and the feature divider account (e.g., Huang & Pashler, 2005). According to these models, successful visual selection of the target feature depends on the ability to draw a single straight line through feature space such that the target feature occupies one region and the distractor features all occupy another region. From these accounts it follows that it should be impossible to limit selection to items with intermediate features (e.g., orange), when these are surrounded by distractors that have more extreme features (e.g., red and yellow), because this configuration renders a segmentation of feature space into a to-be-attended region and a to-be-ignored region impossible. Contrary to these theories, the results of Experiment 3 demonstrated that visual selection can be biased to a target that is sandwiched between more extreme features.

It should be noted that the relational account is quite similar to the linear separability account and the feature divider model, and can account for the linear separability effect—that is, the finding that search for nonlinearly separable targets is typically more inefficient than for linearly separable targets (e.g., Bauer et al., 1996; D'Zmura, 1991). According to the relational account, search for linearly separable targets may be easier because they can be found by biasing attention to a single feature relation (e.g., redder), whereas search for an intermediate feature requires a different—relational or feature-specific—search strategy (Becker et al., 2013). The present results suggest that less efficient search for nonlinearly separable targets could be due to the fact that observers have to adopt a genuinely feature-specific selection bias in search for such targets (see Experiment 3, feature-first group), which slows rejection of target-similar distractors (see Experiments 1 to 3; see also Harris et al., 2013).

Although further research is required to examine the costs and benefits of relational versus feature-specific selection strategies in more detail, it is clear that the results of the present study require modifications in all major theories of visual attention: Feature-specific accounts have to be modified to account for the possibility of relational search. The relational account, categorical accounts, and other accounts (e.g., linear separability view and feature divider account) have to be modified to accommodate the finding that attention can also be biased to specific, nonlinearly separable feature values.

Theoretical Implications of Short-Lived Inhibition and Hemifield Effects

Apart from these major findings, the study also yielded some intricate other findings that suggest the need to modify extant theories of visual attention. For instance, the results of Experiment 3 showed that capture was modulated by inhibition of the distractor feature as well as by inhibition of the distractor position. Experiments 1 and 2 also showed evidence that the distractor position was inhibited, and in all instances, inhibition of the distractor location was only observed for distractors that were capable of attracting the observer's attention. These results are consistent with inhibition of the distractor location that automatically carries over to the next trial and modulates how attention is allocated to the search items (e.g., Geyer et al., 2007). It is likely that similar carryover effects of distractor inhibition have also played a role in other experiments; yet, to the best of our knowledge, these effects are not accounted for by the major visual search theories (e.g., Lee et al., 1999; Treisman & Sato, 1990; Wolfe, 1994), indicating the need to further examine the factors and mechanisms underlying these effects.

In addition, the results from the hemifield effects showed that the competition between a color target and an irrelevant distractor was modulated by spatial proximity, in line with the biased competition account (e.g., Desimone, 1998; Desimone & Duncan, 1995; Duncan, 1996) and previous results (e.g., Kruminacher, Mueller, & Heller, 2002; Zehetleitner et al., 2009). However, spatial proximity did not modulate attention in search for shape, perhaps indicating that shape is indeed a more complex and higher order property (e.g., Wolfe, 1998). According to the biased competition account (e.g., Desimone, 1998), interitem distance can only modulate competition when attributes are represented by lower level neurons with limited receptive fields, and this is probably true for color but not shape (see also Ahissar & Hochstein, 2004; Nakayama & Martini, 2011).

Importantly, in color search, the competition between target and distractor was not modulated by the feature contrast of the distractor, as differences between the ipsilateral and contralateral presentation conditions were equally large for nonsalient distractors (i.e., distractors with the nontarget color) and highly salient distractors (i.e., distractors with a unique color). These results seem to be at odds with the prevalent view that interitem distance modulates selection by affecting the computations of bottom-up feature contrasts (e.g., Beck & Kastner, 2005; Julesz, 1986; Koch & Ullman, 1985; Lee et al., 1999; Wolfe, 1994; but see Becker & Ansorge, 2013). Specifically, the results are inconsistent with the assumption that interitem distance can affect selection only within feature maps (i.e., neurons that respond to the same feature value; e.g., Bravo & Nakayama, 1992; Julesz, 1986; Koch & Ullman, 1985) and indicate that competition arises also between objects with different feature values (e.g., Desimone, 1998).

Taken together, these results indicate that capture by an irrelevant distractor is modulated by factors that are not accounted for in current theories of visual search. These effects (i.e., carryover effects of inhibition of the distractor feature and position, hemifield effects) will have to be considered in more detail in future studies to gain a complete understanding of the factors and mechanisms that modulate attention and eye movements.

Conclusions

The present results showed, for the first time, that a relational selection bias dominates eye movements in a visual search task for a color or shape target, even when relational search renders observers more vulnerable to distraction, and the design favors a feature-specific selection bias. Second, this is also the first visual search study to demonstrate that observers are able to bias visual selection to the exact color of the target and not its relative color. However, such a feature-specific selection bias was only observed when observers were pre-trained to bias attention to the target feature value in a feature search task. The finding that observers can apply a feature-specific selection bias as well as a relational selection bias in the same task and stimulus conditions challenges current theories of visual search, including feature-based models, optimal tuning models, linear separability accounts, and the relational account. Moreover, the finding that feature-specific search was maintained across two blocks of a pop-out search task highlights the importance of past experience and learning in determining the actual search strategy, and shows that the visual system does not constantly monitor the efficiency of the current attentional settings to ensure optimal performance. Rather, the visual system apparently applies a previously successful or possible strategy until this produces a mismatch or error signal that leads to a reset of the attentional control settings—whereby the contingencies of this error signal and its effects still need to be investigated in future studies.

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