

The Role of Relational Information in Contingent Capture

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On the contingent capture account, top-down attentional control settings restrict involuntary attentional capture to items that match the features of the search target. Attention capture is involuntary, but contingent on goals and intentions. The observation that only target-similar items can capture attention has usually been taken to show that the content of the attentional control settings consists of specific feature values. In contrast, the present study demonstrates that the top-down target template can include information about the relationship between the target and nontarget features (e.g., redder, darker, larger). Several spatial cuing experiments show that a singleton cue that is less similar to the target but that shares the same relational property that distinguishes targets from nontargets can capture attention to the same extent as cues that are similar to the target. Moreover, less similar cues can even capture attention more than cues that are identical to the target when they are relationally better than identical cues. The implications for current theories of attentional capture and attentional guidance are discussed.

Keywords: attention, cuing, contingent capture, similarity, linear separability

The visual world is rich in stimulation, far exceeding the computational capacity of the human information processing system. To compensate, mechanisms of visual attention serially select an object or location in the visual scene for processing and filtering out other, presumably irrelevant, information. This means that humans, like all animals, must choose which of a large number of events, objects, or locations to attend to at any given moment. How attention is allocated across time through visual space will largely determine what humans are aware of and, as a result, what will guide their actions. Thus, how humans come to attend to some things and not others has important consequences, as the nature of the choice is often one of whether to attend to those things that further immediate goals (e.g., foraging for food), or to break from goal-directed activity to attend to those unanticipated events that may signal danger (e.g., oddly colored segments of foliage). Given the importance of selective attention for conscious perception and action, much research has been devoted to the factors that can guide attention.

Posner (1980) demonstrated that attention could be moved while the eyes remained fixated and identified two modes of attentional guidance: endogenous and exogenous. In *endogenous orienting*, attention is guided voluntarily toward certain locations in the visual field, under deliberate control (e.g., “I want to look at that red object”; e.g., Posner). In *exogenous orienting* (see also, Posner & Cohen, 1984), attention is presumed to be automatically “captured” by a salient external stimulus regardless of the intent of the observer. Presumably, exogenous guidance protects an organism from danger by interrupting voluntary task-related attending to focus attention on new and potentially important events.

There has been considerable disagreement over the necessary and sufficient conditions for the involuntary capture of attention in exogenous orienting. In particular, the debate has centered on whether and to what extent exogenous orienting of attention is determined by intentions and goals. Historically, there have been two diametrically opposing views: singleton capture and contingent capture. *Singleton capture* accounts propose that attention is always guided in a purely stimulus-driven manner toward a stimulus differing from other stimuli in a critical feature. In some theories, this critical feature is salience, where attention is hypothesized to be drawn to the stimulus that has the largest feature contrast (Theeuwes, 1991, 1992). Other theories deny that feature contrast is sufficient for bottom-up attentional capture and instead propose that attention can be captured only by dynamic properties, for instance, suddenly appearing objects (“onsets”) (e.g., Jonides & Yantis, 1988; Yantis & Egeth, 1999; Yantis & Jonides, 1990; Yantis & Hillstrom, 1994). Although differing in the hypothesized critical feature, stimulus-driven theories share the view that a stimulus that is a singleton in the critical feature will capture attention regardless of task or intent of the observer.

In contrast to these stimulus-driven accounts, the *contingent capture* theory proposes that the deployment of attention ulti-

This article was published Online First October 4, 2010.

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This research was supported by a University of Queensland postdoctoral fellowship grant to Stefanie I. Becker, Air Force Grant FA95550-07-1-0356 to Roger W. Remington, Shy-Chieh Wu, and Harold Pashler, and by Australian Research Council Discovery Grant DP0666772 to Roger W. Remington. We would like to thank Yuhong Jiang, John Hodsoll, and Dominique Lamy for their helpful and insightful comments on drafts of this article.

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mately depends on the goals of the observer (Folk, Remington, & Johnston, 1992, 1993). In this view, attention can be tuned offline to select specific predetermined objects or features of objects matching the content of the attentional control settings. Such features, when present, can then online elicit fast and reactive or “involuntary” attention shifts to their position (involuntary contingent orienting; Folk & Remington, 1998; Folk et al., 1992). However, because of the link to the task, the control still resides in task representations that exert top-down influence on low-level feature and object representations (e.g., attend to red things when looking through a crowd for a friend with a red shirt). It is the emphasis on the task goal, rather than fixed properties of the stimulus per se, that sets the contingent capture theory in direct opposition to stimulus-driven accounts of the control of exogenous attention shifts.

Previous studies investigating attentional capture in a visual search task have shown that attention can be captured by both salient stimuli and stimuli that are similar to the target. Correspondingly, most current models of attentional guidance propose that attention can be guided by both a saliency-based, bottom-up controlled attentional system and a feature-based, top-down controlled attentional system (e.g., Guided Search 2.0; Wolfe, 1994; Navalpakkam & Itti, 2006, 2007).

The Structure and Content of the Attentional Control Settings

Although acknowledging the influence of top-down settings, current accounts disagree about the *nature* of top-down attentional control settings. Some posit a fine-grained set, such that attention is usually tuned toward particular feature values (e.g., a particular shade of gray; e.g., Navalpakkam & Itti, 2006); others posit a coarse-grained set, so that attention is mostly tuned toward rather broad categorical attributes (e.g., redness; Wolfe, 1994).

Spatial cuing studies provide evidence for both broad categorical tuning and fine-grained, feature-specific tuning. For example, Folk, Remington, and Wright (1994) tested the sensitivity of attentional control settings to color, motion, and onset. They found that when the critical target feature was color, neither onset nor motion captured attention. When the critical feature was motion, both motion and onset but not color captured attention. When the critical feature was onset, only onset captured attention. This shows that the ability to filter out certain stimuli can be based on broadly defined feature categories that distinguish between transients and salient stimuli in the color dimension.

However, it has also been shown that attention can be set for a specific color value within the color dimension (e.g., Folk & Remington, 1998). For instance, Folk and Remington (1998) showed that when observers searched for a red target, only red cues, but not green cues, captured attention. This result pattern could also be replicated when the red target was embedded among white nontargets and thus constituted a singleton that could in principle have been found by employing a singleton search strategy (Bacon & Egeth, 1994; Folk & Remington, 1998). Recent work by Adamo, Pun, Pratt, and Ferber (2008) also suggests that the top-down attentional control settings can be quite complex. Adamo et al. found that when the target was defined by a conjunction of location and color value (blue on left, red on right),

then capture occurred only when the cue was consistent both in color value and location (see also Ansorge & Heumann, 2003).

In the color dimension, the most widely endorsed view is perhaps that observers can tune attention in a fine-grained way to particular colors, but that similar distractors can still capture attention by virtue of (partially) matching the mental representation of the target (e.g., Ludwig & Gilchrist, 2002, 2003). According to such a *similarity view*, the attention-driving capacity of irrelevant items critically depends on their similarity to the target-defining feature, so that items that are more similar to the target will capture attention to a higher degree than items that are more dissimilar from the target (Duncan & Humphreys, 1989). In line with this view, Ansorge and Heumann (2003) showed that cues that were featurally similar to the target captured attention (e.g., yellowish-red cue in search for a red target, or bluish-green cues in search for a green target), whereas cues that had a dissimilar color did not capture (e.g., a yellowish-red cue in search for green targets, or a bluish-green cue in search for a red target; Ansorge & Heumann, 2003, 2004; see also Ludwig & Gilchrist, 2002, 2003).

The Relational Account of Guidance

Recently, Becker (2008) proposed that top-down guidance of visual attention operates via a *relational set* (see also Becker, 2010). Rather than a broad or fine-grained tuning around particular feature values, the relational guidance account posits that attention is guided by information about the relational or contextual properties of the target, that is, by information that specifies how the target differs from the surrounding distractors. For example, in a pop-out search task for a size target, eye movement recordings showed that, when the target and nontarget features randomly changed across trials, selection was impaired when the target and nontargets changed such that their relationship reversed (e.g., from smaller to larger or vice versa). In contrast, the target could be selected immediately when the relational properties of the target remained constant, even when all stimuli underwent large physical changes (Becker, 2008). A different study showed that when observers searched for a medium target among small nontargets, a higher proportion of first eye movements went to a large distractor than to a medium distractor, despite the fact that the medium distractor was more similar to the target (Becker, 2010).

These results were taken as evidence for a relational set, that is, as an indicator that observers had tuned attention to the relational properties of the target (i.e., larger) rather than to the particular feature value (i.e., medium). Such a relational setting can be applied successfully whenever the target differs in a single direction from the (majority of) nontargets (e.g., all pop-out search tasks). Hence, it was argued that when observers have to search for a singleton target (e.g., an orange target among yellow distractors), the visual system will not set for the feature value of the target (i.e., orange), but it will assess the relationship of the target to the distractors (i.e., target is “redder”). Attention will then be guided toward stimuli that have the same relational properties as the search target. On the relational account, capture by irrelevant singletons is moreover supposed to occur independently of the featural similarity to the target feature. Thus, the relational account would predict that, in search for an orange (redder) target, a red cue should capture attention to the same extent as an orange cue (provided that both

differ in the correct direction from the competing items), despite the fact that the red item is less similar to the target.

A second interesting prediction that can be derived from the relational account is the following: When the visual scene contains multiple different features, then the item that differs in the correct direction from all other items should capture attention most. Thus, when a red cue is presented together with an orange cue, the red cue but not the orange cue should capture attention when observers are searching for an orange target (among yellow nontargets), because the relational setting is for redder, and the red cue is redder than the orange cue.

Aim of the Present Study

The present study tested both central predictions of the relational account for the first time in a spatial cuing task. Experiment 1 tested whether singleton cues (e.g., orange and red) that differ in the correct direction from other cues would indeed capture attention to the same extent, regardless of their featural similarity to the target (e.g., orange). Experiments 2 and 3 critically tested whether presenting different cues together in the same display (e.g., red, orange, yellow, and green) would lead to capture by the less similar cue (i.e., the red cue in search for an orange target) that differed in the correct direction from all other cues.

Attentional capture was assessed in two ways. First, attentional capture by singleton cues was inferred when there was a *validity effect*, that is, when response times (RTs) were significantly shorter on valid trials (where the cue was presented at the target position) than on invalid trials (where the cue was presented away from the location of the target). Second, invalid trials were also examined for *response-compatibility effects*, by comparing the RTs when the cued nontarget letter had the same identity as the target (i.e., both Ts or both Ls; response compatible) versus a different identity as the target (i.e., L nontarget letter and T target letter and vice versa; response incompatible). If attention is allocated to the cue, then the identity of the nontarget letter at the cued location will be processed, leading to faster RTs on response-compatible trials. In contrast, if attention is not captured by the cue, then the identity of the nontarget letter at the cue location should not modulate performance.

In all experiments, eye movements were monitored with an eye tracker to ensure that observers maintained fixation during the whole trial and that, correspondingly, effects arising for some cues but not others were due to covert orienting of attention and not, for instance, to variations in the ability of cues to elicit eye movements.

Experiment 1

The search display in Experiment 1, and the following experiments, consisted of four letters (*Ts* or *Ls*). Observers had to search for a target letter with a particular color, and to respond to the identity of the odd-colored target letter. One group of participants searched for an orange target among yellow-orange (henceforth *yorange*) nontargets, and another group searched for a yorange target among orange nontargets.

The search display was preceded by a cue display consisting of four cues that surrounded the four possible target locations. Three of the four cues always had the same color as the nontargets in the

search display. Attentional capture was assessed for the singleton cue that had a different color than the other cues. This cue could have the same color as the target (orange or yorange), or it could be red, green, or yellow. The color of the singleton cue was chosen pseudorandomly across trials, and the location of the singleton cue was uncorrelated with the target location (see Figure 1A for an example of the stimulus display).

This design allowed a critical test of the relational hypothesis and the feature-based as well as saliency-based accounts. First, according to the saliency-based account, cues should capture when they are sufficiently distinct on one or more feature dimensions from all other stimuli. Saliency would then suggest equal capture by the red and green cues, as they are both quite distinct from the other items, with perhaps less capture from the yellow and orange because the latter are more similar to the other cues (i.e., yorange) and, thus, have less feature contrast.

According to feature-based accounts, only cues that share the target feature capture attention. Feature-based accounts would then predict that, in search for an orange target, only the orange cue should capture attention, and in search for a yorange target, only the yorange cue should capture, whereas cues with different colors than the target should not capture. However, feature-based accounts could accommodate broader settings by allowing cues similar to the target in feature value to capture attention. Such similarity accounts would predict that the red and yellow cues might also capture attention because both colors are present in the target color (i.e., orange or yorange). Still, attentional capture should be strongest for the orange cue and markedly weaker for the red and yellow cues.

According to the relational hypothesis, to efficiently locate the target in the two conditions, observers should tune attention to all redder items when the target is orange and redder than the nontargets, and to all yellower items when the target is yorange, and thus yellower than the nontargets. This holds because observers should generally tune attention to the direction in which the target differs from the nontargets, and in the case of an orange target among yorange nontargets, it is the redness of the orange target that discriminates the target from the nontargets. According to the relational view then, in search for an orange (redder) target, both the orange and the red cue should capture attention because they are both redder than the yorange nontargets and nonsingleton cues, and thus both differ in the correct direction from yorange. Yellow and green cues should not capture attention because they do not differ in the correct direction from the yorange cues; however, the yellow cue should capture attention when the target is yellower than the nontargets (whereas the red cue should then cease to capture).

The green cue served as a control cue, and was matched in luminance to the red cue prior to the experiment by a flicker test. This was done to ensure that any evidence of attentional capture by the red cue could be clearly interpreted as being due to the task, and not because the red cue was also the darkest and possibly most salient stimulus in the display. If the red cue captures attention because of its luminance, then the green cue should equally capture attention, resulting in equal validity effects and response-compatibility effects. If, on the other hand, only the red cue captures attention but not the green cue, then we can be sure that capture occurs as a result of the top-down attentional control settings favoring all redder stimuli for selection.

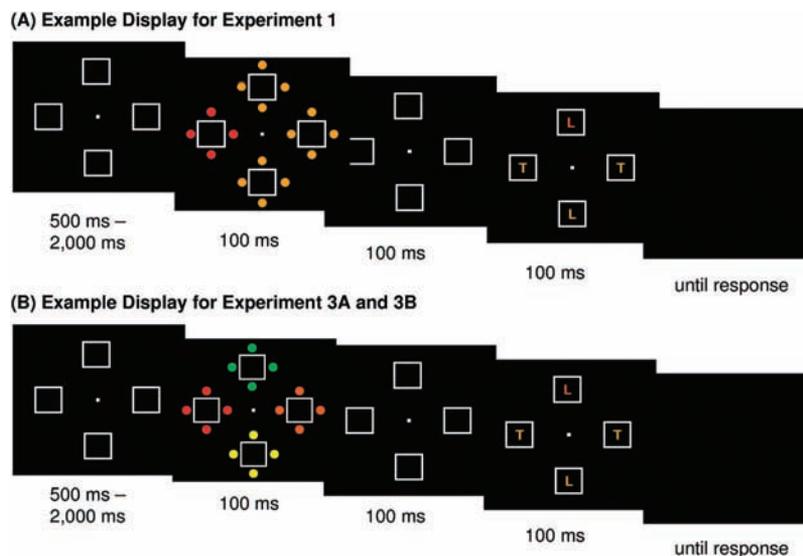


Figure 1. Examples of the stimulus displays used in the cuing tasks. (A) In Experiment 1, observers had to search for an orange target among yellowish-orange nontargets in one block (whereas target and nontargets had the reverse color assignment in the other block). Capture by a target-similar (here: orange) cue was then compared to capture by a red, yellow and green singleton cue. All cues were presented among nonsingleton cues that had the same color as the nontargets. (B) In Experiments 2 and 3, capture was assessed when the target-similar cue had to compete with a red, yellow, and green cue.

Method

Participants. Sixteen volunteers from the University of Queensland, Australia, took part in Experiment 1. Seven were men, nine were women, and their mean age was 28.1 years. All participants had normal or corrected-to-normal vision, gave informed consent prior to the experiment, and were paid \$10 for their participation. Half of the participants searched for an orange target, whereas the other half searched for a yorange target.

Materials. An Intel Duo 2 CPU 2.4 GHz computer with a 17-in. CRT color monitor was used to generate and display the stimuli and to control the experiment. Stimuli were presented with a resolution of $1,024 \times 768$ pixels and a refresh rate of 85 Hz. 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 500 Hz. Participants were seated in a normally lit room, with their head fixated by the eye tracker's chin rest and forehead support, and viewed the screen from a distance of 57 cm. For registration of manual responses, a standard USB keyboard was used. Event scheduling and RT measurement were controlled by Presentation software (Neurobehavioral Systems).

Stimuli. Flicker photometry was used to equate the luminance of the red and green stimuli. The stimulus display in the flicker test consisted of two vertically aligned squares ($3.0^\circ \times 3.0^\circ$) presented in the center of the display against a black background (RGB: 0, 0, 0). When one of the squares was red (1.0, 0.0, 0.0/RGB: 255, 0, 0), the other one was green and the color changed every 24 ms. Participants adjusted the luminance of the green square to match the luminance of the red square by minimizing the flicker.

The spatial cuing task consisted of a series of displays beginning with a fixation display composed of a central white fixation box ($0.3^\circ \times 0.3^\circ$; RGB: 255, 255, 255) and four boxes ($2.0^\circ \times 2.0^\circ$,

of which only the small white outlines were visible (0.05°). The boxes were placed at the 12, 3, 6, and 9 o'clock positions 6.0° from the center of the display (measured to the center of the box). The cuing display consisted of the fixation display with the addition of four cues, each consisting of four circles ($0.4^\circ \times 0.4^\circ$) located around the boxes in a diamond configuration (distance to frame = 0.4°). The target display consisted of the fixation display plus four colored letters that were presented centrally inside the boxes. For one group of participants, the target letter was always colored orange (1.0, 0.333, 0.0/RGB: 255, 85, 0), whereas the three nontarget letters were always colored yorange (i.e., yellowish-orange: 1.0, 0.666, 0.0/RGB: 255, 170, 0), so that the target was consistently redder than the nontargets. For the other group, the target was always yorange and presented among orange nontarget letters (yellow target). Each of the four letters was either a *T* or an *L* (Arial, 13 point; $0.5^\circ \times 0.6^\circ$), and observers had to report the identity of the target letter by pressing a key.

The colors of the cues were chosen such that three of the four cues always had the same color as the nontarget letters (yorange or orange, depending on the condition). One cue had a unique color drawn from four possible colors: It either had the same color as the target (orange or yorange) or it was red (1.0, 0.0, 0.0/RGB: 255, 0, 0), green, or yellow (1.0, 1.0, 0.0/RGB: 255, 255, 0).

Design. Across the experiment, both singleton cue and target occurred equally often at all positions. Thus, the position of the color singleton cue was uncorrelated with the position of the target and provided no information as to the target location. The two target letters, *T* and *L*, were presented equally often at each cue-target pairing. The three nontarget letters were randomly drawn from a set containing two *T*s and two *L*s, with the constraint that for invalid cues there was an equal number of trials in which

the identity of the nontarget letter at the cued location was compatible and incompatible with the identity of the target. The colors of target and nontarget items were varied between subjects. This design yielded 4 (cue colors) $\times 4$ (cue positions) $\times 4$ (target positions) $\times 2$ (target identities) = 128 trials. Each participant completed six blocks, resulting in 768 observations per participant and condition.

Procedure. Before each experiment, participants completed three runs of the flicker test, adjusting the luminance of the green square by pressing the *right arrow* and *left arrow* keys of the keyboard until the flicker (or the oscillations) became minimal. They indicated when flicker was minimized by pressing the spacebar. Those color luminance values were saved, and the next run started with the initial green value chosen randomly (range: 0.0, 0.0, 0.0 to 0.0, 1.0, 0.0). If the three chosen luminance values deviated less than 0.1 (25 RGB units) from one other, they were averaged to form the color value used for the green cues in the experiment. If the difference in settings was greater, another three runs of the flicker test were administered.

In the spatial cuing task, participants were instructed to ignore the irrelevant colored circles in the cuing display and to search for the orange target letter in the display. Participants were instructed to respond as fast and accurately as possible to the orange target by pressing the *right arrow* key of the keyboard when the target was a *T* and the *left arrow* key when it was an *L*. Furthermore, participants were instructed to maintain fixation on the white box in the center of the display.

The eye tracker was calibrated before the start of the experiment. A fixation control was implemented such that the cue display was presented only when the gaze was within a region of 1.5° of the center of the box for at least 500 ms (within a time window of 2,000 ms). Otherwise, participants were calibrated anew. The cue display was presented for 100 ms, followed by the fixation display (for 100 ms) and the target display (for 100 ms). The target display was replaced by a blank black screen. Immediately after responding, participants received written feedback consisting of "Correct!" or "Wrong!" printed in white (Arial Black, 13 point) at the center of the screen. After an intertrial interval of 250 ms, during which a blank black screen was presented, the next trial again started with the fixation control.

On average, it took 60 min to complete the experiment. Participants were encouraged to take a short break after each block (128 trials).

Results

Data. Across all experiments, trials where the eyes had left the central fixation area (distance greater than 1.5° from the center of the display) during the presentation of the cuing or target display were excluded. This led to a loss of 1.59% of all data in Experiment 1. Moreover, RTs shorter than 200 ms or longer than 1,000 ms were excluded from all analyses, which led to a loss of 3.20% of all data.¹

RTs. The mean RTs for valid and invalid cues are shown in Figure 2 (top panels), plotted separately for orange (or yorange), red, green, and yellow color singleton cues when the target was redder (see Figure 2A) or yellower (see Figure 2B) than the nontargets. The bottom panels analogously depict the response-compatibility effect on invalid trials, separately for conditions

where the target was redder than the nontargets (see Figure 2C) and when it was yellower (see Figure 2D).

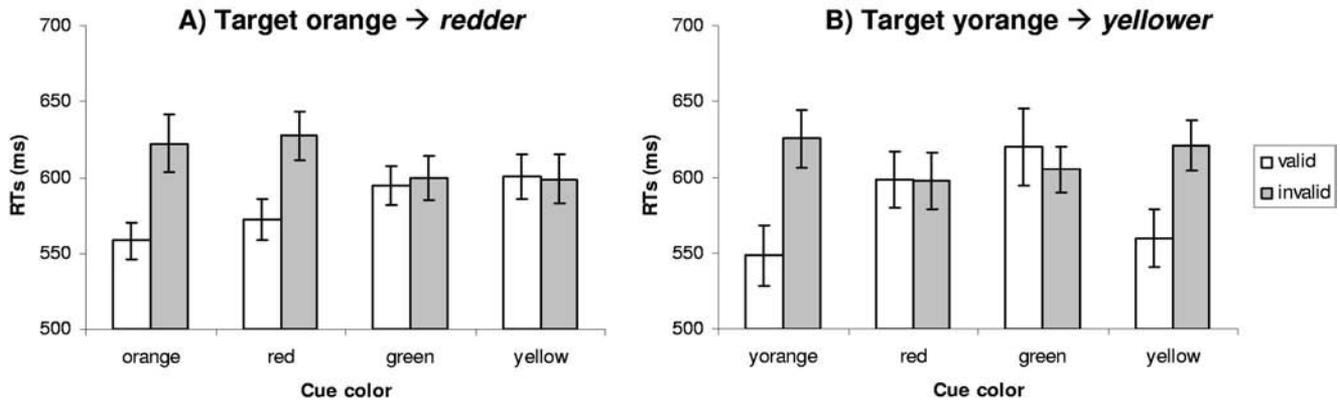
Validity effects. The effects of valid versus invalid cues were first assessed for the condition where the target was orange, and thus redder than the nontargets (see Figure 2A). A 4×2 analysis of variance (ANOVA) with the factors of cue color (red, green, yellow, orange) and cue validity (valid, invalid) showed significant main effects of cue validity, $F(1, 7) = 37.5, p < .001, \eta^2 = .84$, and a significant interaction of color and validity, $F(1, 7) = 22.4, p < .001, \eta^2 = .76$, but no significant effect of cue color, $F(3, 21) = 2.5, p = .10$ (*ps* Greenhouse–Geisser corrected). Pairwise comparisons revealed that only the orange cue and the red cue resulted in significant cue validity effects, with slower responses on invalid trials than on valid trials, $t(7) = 5.8, p = .001$, and $t(7) = 6.0, p = .001$, whereas the green and yellow cues did not show any validity effects ($ts < 1$). Separate 2×2 repeated measures ANOVAs comparing the validity effects between different cue colors showed that the validity effects between the red and orange cues did not differ from each other ($F < 1$), as shown by the nonsignificant Cuing Condition \times Validity Effect interaction. However, the red and orange cues both produced significantly stronger validity effects than the yellow cue, $F(1, 7) = 35.3, p = .001, \eta^2 = .84$, and $F(1, 7) = 33.1, p = .001, \eta^2 = .83$, respectively, and the green cue, $F(1, 7) = 26.7, p = .001, \eta^2 = .79$, and $F(1, 7) = 23.9, p = .002, \eta^2 = .77$, respectively. By contrast, the green and yellow cuing conditions did not differ in terms of their validity effects, $F(1, 9) = 2.6, p = .15$.

The result pattern was mirror-reversed in the condition where the target was yorange, and thus yellower than the nontargets (see Figure 2B): The same 4×2 ANOVA computed over the mean RTs in this condition showed a significant main effect of cue validity, $F(1, 7) = 57.4, p < .001, \eta^2 = .89$, cue color, $F(3, 21) = 6.2, p = .03, \eta^2 = .47$, and a significant interaction between cue color and cue validity, $F(3, 21) = 15.6, p = .001, \eta^2 = .69$. Pairwise comparisons revealed significant validity effects only for yellow and yorange cues, $t(7) = 8.7, p < .001$, and $t(7) = 6.2, p < .001$, respectively; no significant cuing effect was found for red or green cues ($ts < 1$). Separate ANOVAs comparing the validity effects across the different cuing conditions revealed that the yellow cue produced significantly stronger validity effects than the red cue, $F(1, 7) = 154.1, p < .001, \eta^2 = .96$, and the green cue, $F(1, 7) = 22.2, p = .002, \eta^2 = .76$. Similarly, the yorange cue also produced stronger validity effects than the red cue, $F(1, 7) = 25.2, p = .002, \eta^2 = .78$, and the green cue, $F(1, 7) = 14.4, p = .007, \eta^2 = .67$. However, there were no significant differences between the validity effects of the yellow cue and the yorange cue ($F < 1$).

Response-compatibility effects. To test more stringently whether attention was allocated to the location of the cue on invalid trials, we assessed the response-compatibility effects by

¹ The data of Experiments 1–3 were also analyzed using (a) a more liberal cutoff criterion of 2,000 ms and (b) without using any exclusion criteria. This, however, did not change the result pattern. The reasons for choosing the present outlier criterion were, first, that the same criterion has been used by previous studies examining capture by similar cues (e.g., Ansorge & Heumann, 2003, 2004), and second, that RTs longer than 1,000 ms probably reflect uncertainties in decisions that could have arisen from poor attentional control on a given trial.

Exp. 1: Validity effect



Exp. 1: Compatibility Effect

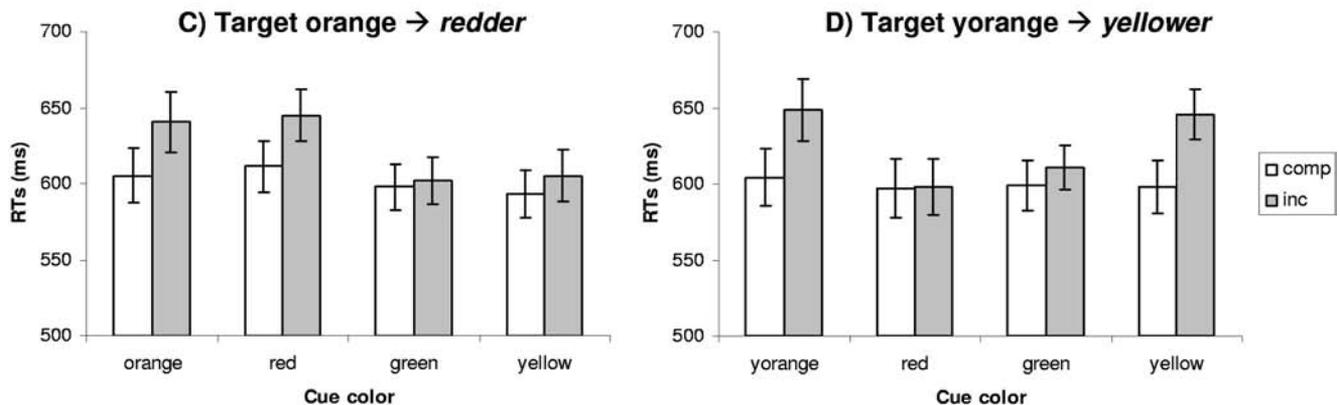


Figure 2. The upper panels depict the mean response times (RTs) on validly and invalidly cued trials in Experiment 1, where the target was either orange (A) or yorange (B), depicted separately for singleton cues of different colors. The bottom panels depict mean RTs on response-compatible and response-incompatible trials, when the target was either redder (C) or yellower than the nontargets (D). White histograms depict mean RTs on response-compatible trials; gray histograms depict mean RTs on response-incompatible trials. Error bars represent ± 1 SEM. The figures show that, depending on the relational properties of the target, either the red or the yellow cue captured attention to the same extent as the orange or yorange cue, which had the same color as the target.

comparing RTs on trials where the cued nontarget letter was identical with the target letter (compatible) versus different from the target letter (incompatible). First, a 4×2 ANOVA with the factors of cue color (red, green, yellow, orange) and response compatibility (compatible vs. incompatible) was computed over the mean RTs of the redder target condition (orange target among yorange nontargets; see Figure 2C). The results showed a significant main effect of response compatibility, $F(1, 7) = 17.1, p = .004, \eta^2 = .71$, and a significant interaction between cue color and response compatibility, $F(3, 21) = 6.2, p = .006, \eta^2 = .47$. Paired t tests yielded significant compatibility effects for the red and orange cues, $t(7) = 3.6, p = .009$, and $t(7) = 5.3, p = .001$, respectively, and a trend for a compatibility effect for the yellow cue, $t(7) = 2.2, p = .067$, but no compatibility effects for the green

cue ($t < 1$). Separate 2×2 ANOVAs comparing the compatibility effects across different cue colors showed that the compatibility effects did not differ significantly between the orange and the red cue ($F < 1$). Both red and orange cues produced stronger compatibility effects than the green cue, $F(1, 7) = 8.3, p = .024, \eta^2 = .54$, and $F(1, 7) = 12.7, p = .009, \eta^2 = .65$, respectively, and significantly or marginally significantly stronger compatibility effects than the yellow cue. $F(1, 7) = 5.1, p = .060, \eta^2 = .41$, for the red cue, and $F(1, 7) = 7.9, p = .026, \eta^2 = .53$, for the orange cue (see Figure 2C).

As can be seen in Figure 2D, this result pattern was reversed in the condition where the target was yorange, and thus yellower than the nontargets. The ANOVA showed significant main effects of response compatibility, $F(1, 7) = 15.6, p = .006$, cue color, $F(3,$

trials for the yorange, yellow, and green cue. However, these differences proved to be significant only for the yorange cue ($t(8) = 2.7$, $p = .031$, and not for the other cues ($ts < 1.8$, $ps > .11$). Taken together, the analysis of the errors indicates that the results were not due to a speed–accuracy trade-off.

Comparing effects of the same cue for different target conditions. To examine whether the effects of red and yellow cues indeed depended on the way in which the target differed from the nontargets (redder vs. yellower), we also analyzed validity and response-compatibility effects of each cue (red, yellow, orange, or yorange and green) across the different conditions where the target was either yellower or redder than the nontargets. Separate 2×2 between-subjects ANOVAs comprising the variables validity (valid vs. invalid trials) and condition (target redder vs. yellower) showed that the red cue produced stronger validity effects when the target was redder than when it was yellower, $F(1, 14) = 31.4$, $p < .001$, $\eta^2 = .69$. Analogously the yellow cue produced stronger validity effects in search for a yorange and yellower target than in search for an orange and redder target $F(1, 14) = 60.3$, $p < .001$, $\eta^2 = .81$. In contrast, capture by the remaining cues did not differ between the target conditions, $F < 1$ for the orange and yorange cue, $F(1, 14) = 1.5$, $p = .24$, for the green control cue.

The same pattern of results could be observed with regard to response-compatibility effects: The response compatibility of the red cue was significantly stronger when the target was the redder item than when the target was the yellower item, $F(1, 14) = 8.3$, $p = .012$, $\eta^2 = .37$. Conversely, the yellow cue produced significantly stronger compatibility effect when the target was the yellower item than when it was redder than the nontargets, $F(1, 14) = 10.9$, $p = .005$, $\eta^2 = .44$. In contrast, the orange (or yorange) cues and the green cues showed similar compatibility effects across both target conditions ($Fs < 1$). This shows that red and yellow captured attention to different degrees, depending on the properties of the target and nontargets.

Discussion

The results of Experiment 1 are consistent with predictions of the relational account of the guidance of attention: When the target was orange and redder than the nontargets, both orange and red captured attention, whereas green and yellow did not. When the target was yorange and yellower than the nontargets, both yorange and yellow captured, whereas red and green did not. According to the relational account, this result pattern emerges as a consequence of tuning attention to the direction in which the target differs from the nontargets.

By contrast, there was no evidence for the feature-based or saliency-based accounts of attentional capture. According to feature-based selection accounts, cues that had the same color as the target should have captured attention to a much larger extent than the other-color cues. This is contrary to the finding that red or yellow cues were able to capture attention to the same extent as cues that had the same color as the target. Apparently, attention was not tuned toward the specific feature value of the target (e.g., orange or yorange), but to the relational properties of the target, which helped distinguish the target from the nontargets (e.g., redder or yellower).

Similarly, there was no evidence for the saliency-based accounts of attentional capture. First, green cues failed to capture attention

even though they were just as salient as red and more salient than orange. Second, red cues captured attention (i.e., produced significant validity and response compatibility effects) only when the target was redder than the nontargets but not when the target was yellower. Analogously, yellow cues captured attention only when the target was yellower than the nontargets, whereas the yellow singleton cue was ignored when the target was redder. These effects could not have arisen as a result of a stimulus-driven process: The cues were exactly the same in both conditions. From this it follows that capture by the orange or yorange and the red or yellow cues, respectively, was due to the task demands, which indicates that attention is tuned in a top-down controlled fashion to the relational properties of the target.

Experiment 2

The results of the previous experiment are consistent with the predictions of the relational account, while failing to provide any support for either a feature- or saliency-based account of attentional capture. However, in Experiment 1, the red cue was actually more similar to the orange target and more dissimilar from the yellow-orange (yorange) nontargets than the yellow cue. Thus, the yellow cue might have failed to capture attention because it was more similar to the yorange nontargets than to the target. Moreover, red cues might have captured attention to the same degree as orange cues because attention is always captured in an all-or-none fashion. Although it seems more intuitive to construe the similarity view such that it predicts graded differences in capture, it is still possible to reshape the predictions such that cues that are sufficiently similar to the target (and sufficiently dissimilar from the nontargets) capture attention in an all-or-none fashion, whereas cues that fail to meet these similarity criteria or boundaries do not capture attention.

Experiment 2 was designed to control for the possibility that similarity may have played a role in the previous experiments. One of the corollaries of the relational account is that when the display contains several items, then the item that differs most strongly from all other items in the correct direction will foremost capture attention. Experiment 1 did not test this explicitly as each cue frame contained only one color singleton (that differed either in the correct or wrong direction from the other cues). Experiment 2 was designed as a critical test of this corollary by having all cue displays consist of all four colors. In the redder target condition of the present experiment, observers looked for an orange target among yorange nontarget stimuli, and each cue display contained an orange, red, yellow, and green cue. In the yellower target condition of Experiment 2, the target and nontarget colors were again reversed, so that now observers searched for a yorange target among orange nontargets. The cuing displays analogously contained one cue with the same color as the target (yorange), and a red, yellow, and green cue (see Figure 1B for an example of the cuing display).

According to feature-based accounts, the similarity between cue and target color is important, predicting that the orange and yorange cues should capture attention most strongly when the target is orange or yorange, respectively. Weaker capture would be expected for the red and yellow cues and no capture for the green cue.

A salience account would predict that whichever of the colors captures attention most should do so in both target conditions, as it would have proven itself the most salient. Plausible candidates for the most salient cues would again be the red and green cues.

By contrast, the relational account predicts that the red cue should capture attention most when the target is orange and, thus, redder than the nontargets. Moreover, when the target is yorange and, thus, yellower than the nontargets, the yellow cue should capture attention most and significantly more than the yorange cue that has the same color as the target. This holds because, in Experiment 2, only the red and yellow cues differed from all other cues in one direction, whereas the orange and yorange cues were sandwiched between the more extreme feature values of red and yellow, and thus differed in one direction from one cue (e.g., the yellow cue), but in an opposite direction from another cue (e.g., the red cue). Thus, if search for an orange target is accomplished by tuning attention to all redder items, the red cue should capture attention most because the red cue is redder than the orange cue. Similarly, if search for a yorange target is accomplished by tuning attention to all yellower items, then the yellow cue should capture attention most strongly because it is yellower than the yorange cue.

Experiment 2 also controlled for other aspects of saliency. The heterogeneity of the cue display reduces the likelihood that salience differences between the cue colors and the nontarget color would play a role in capture. It is possible, although unlikely, that in the previous experiments there was a set for the specific color of the target but that the target color made a less effective cue because it was more difficult to discriminate from the nontarget colors than the more extreme values on the color dimension. For example, red and orange cues in Experiment 1 might have captured attention because they were easier to distinguish from the yorange nonsingleton cues that had the same color as the nontargets (red more so than orange), and yet still similar to the target. In Experiment 2, it was no longer the case that the nontarget colors were included in the cue frame, obviating the need to discriminate cues from nontarget colors. Thus, Experiment 2 allowed a more straightforward test of the feature-based hypothesis.

Because the cuing displays always contained all four colors, the ability of a specific color to capture attention was revealed by the RT on valid trials of that color: To the extent that a given color captures attention better than the other colors, mean RT should be shorter when the target occurs at that location (valid trial). In addition, we analyzed response-compatibility effects on invalid trials to assess whether attention was captured more strongly by red and yellow cues than cues that were identical to the target feature when the target was presented at a different location from the cue.

Method

Participants. Eighteen paid volunteers from the University of Queensland, Australia, participated in Experiment 2. Four were men, 14 were women, and their mean age was 24.8 years. Half of them participated in the redder target condition, where observers searched for an orange target among yorange nontargets, and the other half of the participants completed the yellower target condition, where a yorange target was presented among orange items. All participants had normal or corrected-to-normal vision and were paid \$10 for their participation.

Materials. These were the same as those in Experiment 1.

Stimuli, design, and procedure. The stimuli, design, and procedure were the same as those in Experiment 1, with the exception that the cue displays in Experiment 2 consisted of four different-color cues whereby each cue surrounded one of the four locations. In the redder target condition, an orange target was embedded among three yorange nontargets, and the cuing display consisted of one orange, red, green, and yellow cue. In the yellower target condition, a yorange target was embedded among three orange nontargets, and the cuing display consisted of one yorange (target-similar), red, green, and yellow cue.

As in the previous experiment, red and green were matched for luminance by a flicker test. The position of all differently colored cues was counterbalanced with the target position and target identity (*T* or *L*), so that all $4! = 24$ possible cue color and cue position combinations (1234, 1243, . . . , 4321) were paired with the four possible target positions and the two possible target letters, yielding 192 trials per search condition. Participants completed three blocks, yielding 576 observations per participant.

Results

Data. Removing all data where an eye movement had occurred led to a loss of 1.87% of all data in Experiment 2. Removing the RT outliers accounted for a further loss of 4.89% of the trials.

RTs.

Mean RTs on valid trials. Figures 3A and 3B depict the mean RTs on valid trials, separately for each target condition and cue color. A one-way ANOVA computed over the mean valid RT showed significant differences between the different cue colors, $F(3, 24) = 13.1, p = .001, \eta^2 = .62$. In search for an orange target, mean RT was fastest when the target occurred at the location of the red cue, and significantly faster than when the target occurred at any other cue location (as shown by pairwise comparisons): In particular, mean valid RTs were 36 ms faster for the red cue than for the orange cue, $t(8) = 4.0, p = .004$; 27 ms than for the green cue, $t(8) = 3.6, p = .006$; and 39 ms faster than for the yellow cue, $t(8) = 4.5, p = .002$. In contrast, mean valid RT for the orange cue was not significantly different from either the green, $t(8) = 1.6, p = .15$, or the yellow cue ($t < 1$). Mean valid RT for the green cue was faster than for the yellow cue, $t(8) = 4.0, p = .004$.

In the yellower target condition, cue color similarly had a significant main effect on valid mean RT, $F(3, 24) = 10.4, p = .001, \eta^2 = .56$, but the result pattern was mirror-reversed. Mean RTs were shortest for the yellow cue and significantly shorter on valid yellow cue trials than when the target appeared at the location of the red cue, $t(8) = 4.1, p = .003$, the green cue, $t(8) = 4.0, p = .004$, and the yorange cue, $t(8) = 2.6, p = .032$. Moreover, mean valid RT for valid yorange cues was marginally faster than for valid red cues, $t(8) = 2.1, p = .066$, and green cues, $t(8) = 2.6, p = .054$.

Response-compatibility effects. Figures 3C and 3D depict the mean RTs on compatible and incompatible trials when cues of different colors were presented away from the target location. A 4×2 ANOVA with factors of cue color (orange, red, green, yellow) and compatibility (compatible vs. incompatible) was first computed over the mean RT of the orange target condition where

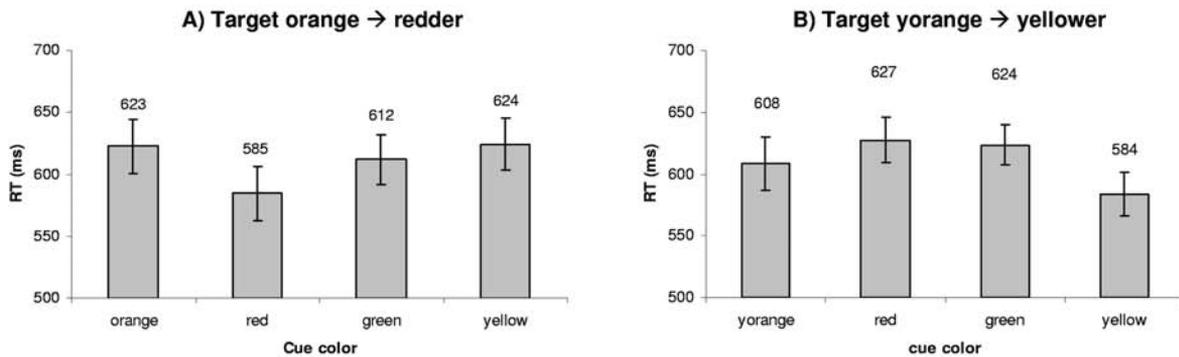
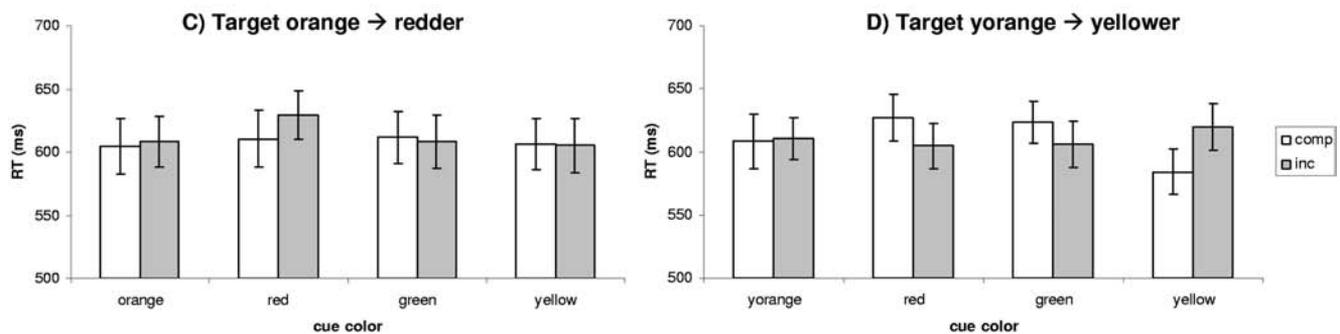
Exp. 2: Valid trials**Exp. 2: Compatibility Effect (invalid trials)**

Figure 3. Results of Experiment 2: The upper panels depict mean response times (RTs) on validly cued trials when the target was either redder than the nontargets (A) or yellower (B). The lower panels depict mean RTs on response-compatible versus response-incompatible trials, in blocks where the target was redder than the nontargets (C) or yellower (D). Error bars represent ± 1 SEM. The results show that, depending on the search condition, only the red or yellow cue captured, whereas the orange or yorange, target-similar cue failed to capture when it had to compete with yellower and redder cues.

the target was redder than the nontargets. The analysis showed significant main effects of response compatibility, $F(1, 8) = 8.2$, $p = .021$, $\eta^2 = .51$, and of cue color, $F(3, 24) = 13.4$, $p = .001$, $\eta^2 = .63$, as well as a (marginally) significant interaction between the two variables, $F(3, 24) = 3.5$, $p = .051$, $\eta^2 = .30$. Significant compatibility effects of 19 ms were observed only for the red cue, $t(8) = 2.7$, $p = .027$. No response-compatibility effects were found for the orange, green, or yellow cues (-3 to 4 ms difference; $t_s < 2.5$, $p_s > .17$).

In the yorange target condition, where the target was yellower than the nontargets, the 4×2 ANOVA showed a significant main effect of cue color, $F(3, 24) = 10.1$, $p = .001$, $\eta^2 = .56$. The interaction between cue color and compatibility was also significant, $F(1, 8) = 6.6$, $p = .006$, $\eta^2 = .45$, reflecting a significant compatibility effect for the yellow cue only, $t(8) = 6.8$, $p < .001$.

Errors.

Mean errors on valid trials. The same one-way ANOVA computed over the mean error scores of the redder target condition showed significant effect of cue color, $F(3, 24) = 4.5$, $p = .012$, $\eta^2 = .36$. Errors were lower on valid trials for the red cue ($M = 3.4\%$) than for the orange cue ($M = 7.0\%$), $t(8) = 3.3$, $p = .010$,

or for the green cue ($M = 6.6\%$), $t(8) = 2.6$, $p = .031$. However, there were no differences in errors between red and yellow cues ($M = 5.2\%$), $t(8) = 1.3$, $p = .23$.

When the target was yorange and yellower than the nontargets, the mean error scores on valid cue trials did not show any significant differences between the different cue colors, $F(3, 24) = 1.8$, $p = .20$. Mean errors were lowest for yellow valid trials ($M = 4.4\%$) and significantly lower than errors on green valid trials ($M = 6.8\%$), $t(8) = 2.7$, $p = .026$, whereas the remaining differences between valid trials were all nonsignificant ($t_s < 1.8$, $p_s > .10$).

Response-compatibility effects. A 4×2 ANOVA computed over the errors in the orange target condition showed only a significant main effect of the cue color, $F(3, 24) = 4.2$, $p = .027$, $\eta^2 = .34$. Pairwise comparisons showed that compatibility effects were not significant for any of the cue colors. However, the red cue produced 2.4% more errors when it was response incompatible than when it was response compatible, indicating that the results were not due to a speed-accuracy trade-off.

In the yellower target condition, response compatibility affected the mean errors, $F(1, 8) = 21.8$, $p = .002$, $\eta^2 = .73$, but did not interact with the cue color. Errors were significantly lower on

response-compatible trials for the yellow cue, $t(8) = 2.6, p = .033$, but not for any other cues ($ts < 1$).

Discussion

Experiment 2 examined attentional capture by irrelevant cues in search for an orange or yorange target when the target-similar cue (orange or yorange) was always presented together with a red, green, and yellow cue. The results showed that, in search for an orange target (among yorange nontargets), a red cue captures attention more than an orange cue, whereas in search for a yorange target (among orange nontargets), a yellow cue captures attention more than a cue that has the same color as the target. These results again provide strong support for the relational account while effectively ruling out the alternative similarity explanation: In the similarity view, the cue that is most similar to the target should have captured attention most (i.e., the orange or yorange cue), contrary to the findings. In contrast, the relational hypothesis correctly predicted that observers would tune attention toward redder or yellower items, and would therefore be captured most by red and yellow cues, because only these cues differ from all other cues in the correct direction.

Experiment 3

Although the results of the previous experiments are consistent with the relational account, one might argue that the results are also consistent with a *linear separability* account (e.g., Bauer, Jolicoeur, & Cowan, 1995; D'Zmura, 1991). According to this view, the orange cue in Experiment 2 may have failed to capture attention because it was sandwiched between the red and yellow cues in color feature space. Features that are sandwiched between other features (e.g., medium items among small and large items, or orange items among red and yellow) are labeled "nonlinearly separable" because they cannot be separated from the other features by drawing a single straight line through color feature space, but need nonlinear either-or or neither-nor operators to be singled out from the other items (XOR problem; Minsky & Papert, 1969).

Previous studies have shown that features that are directly sandwiched between other features do not pop out (Bauer et al., 1995; D'Zmura, 1991; Hodsoll & Humphreys, 2001; Navalpakkam & Itti, 2006). This linear separability effect has usually been interpreted as a purely bottom-up effect, which modulates capture in a similar manner as feature contrast (e.g., D'Zmura, 1991). Hence, it is possible that, in the previous experiment, the orange cue failed to capture attention because it did not pop out from the display and, thus, was not preattentively available. By contrast, the red and yellow cues were linearly separable from the other cues, and thus may have captured over the orange cue because they popped out from the cuing display and were sufficiently similar to the target in the respective conditions (orange and yorange target condition, respectively) to instigate a shift of attention to their position (e.g., Hodsoll & Humphreys, 2001; Hodsoll, Humphreys, & Braithwaite, 2006).

In Experiment 3, we addressed this possible confound by assessing capture in cuing displays where the orange (target-similar) cue was linearly separable (LS condition) versus nonlinearly separable (NLS condition) from the remaining cues.² In Experiment 3, the target was always orange and presented among yorange non-

targets (redder target). To create LS and NLS cuing displays, the chromaticity of the colors was measured with a colorimeter, and colors were chosen on the basis of their position in CIE color space. In the LS condition, the orange cue was embedded among purple, red, and blue cues (whereby blue substituted the green cue to allow construing linearly separable displays). In the NLS condition, the orange cue was presented together with red, yellow, and blue cues, so that orange was sandwiched between red and yellow.

To ensure that our manipulation of separability worked as intended, we also tested the same stimuli in a visual search task. Linearly separable stimuli can also fail to pop out when they are too similar to the nontargets (e.g., Bauer et al., 1995). Therefore, we tested whether orange cues would pop out from the other cue colors by asking observers to search for an orange target among six or 12 nontargets that either rendered the target nonlinearly separable (nontargets yellow, red, and blue) or linearly separable (nontargets purple, red, and blue). The hallmark of pop out is that the target can be found efficiently, that is, independent of the number of nontargets. If the linearly separable target pops out whereas the nonlinearly separable target fails to pop out, search should be independent of the number of nontargets in the LS condition, whereas in the NLS condition, search should be slower with 12 nontargets (set size 13 condition) than with six nontargets (set size 7 condition).

Furthermore, if the previous failure of the orange cue to capture attention was due to the fact that it was nonlinearly separable, then the orange cue should capture in the spatial cuing task when it is linearly separable, whereas it should fail to capture when it is nonlinearly separable from the other cues. By contrast, according to the relational account, we should observe capture by red (not orange) even when orange is linearly separable because the target is always redder than the nontargets, prompting observers to tune attention to all redder items.

Method

Participants. Eight new paid participants took part in Experiment 3. Five were men, three were women, and their mean age was 21.3 years.

Materials. These were the same as those in the previous experiments.

Stimuli, design, and procedure. For the cuing task, the stimuli, design, and procedure were very similar to those in the previous experiments, with the following exceptions. First, green cues were omitted from all cuing displays because green is located directly behind yellow in CIE space so that the green cue would have rendered the orange cue nonlinearly separable even when orange was not sandwiched between red and yellow. To avoid this complication, we replaced green cues with blue cues. Second, the flicker task was omitted from Experiment 3 because the stimuli were controlled by measuring their chromaticity and luminance,

² Note that the orange, target-similar cue was only linearly separable or nonlinearly separable from the other cues, not from all other cues (e.g., red) plus the target and nontarget features (e.g., orange, yorange). It also makes sense to assess the linear separability of a cue only within the cue frame because linear separability is assumed to be a bottom-up factor, analogous to feature contrast, and the feature contrast of a cue also depends solely on the colors of the other cues and not on the colors present in the target frame.

and pilot tests showed that the flicker between blue and red could not be eliminated for any luminance of blue.

In Experiment 3, the target was orange (1.0, 0.4, 0.0; CIE: $u' = 0.32$; $v' = 0.538$) and presented among yorange nontargets (1.0, 0.596, 0.0; CIE: $u' = 0.246$; $v' = 0.547$). The NLS cue frame contained four differently colored cues one each of red (1.0, 0.0, 0.0; CIE: $u' = 0.394$; $v' = 0.529$), orange, yellow (1.0, 0.765, 0.0; CIE: $u' = 0.204$; $v' = 0.553$), and blue (0.0, 0.336, 1.0; CIE: $u' = 0.16$; $v' = 0.226$). The LS cue frame was the same except that yellow was replaced by purple (0.77, 0.20, 0.77; CIE: $u' = 0.243$; $v' = 0.314$), so that the four cues were red, orange, purple, and blue. The position of all stimuli in CIE color space is depicted in Figure 4A. The colors were not equiluminant as this would have required using highly desaturated colors, which would have hampered the comparability of Experiment 3 to the previous results. However, the luminance of the saturated colors varied such that, in the LS cue frame, orange was brighter than the other cues, and thus, was linearly separable in luminance, whereas this was not the case in the NLS cue frame, where the yellow cue was brightest (red: 10.4 cd/m², orange: 14.8 cd/m², yorange: 23.6 cd/m², yellow: 36.3 cd/m², blue: 9.4 cd/m², purple: 9.2 cd/m²).

In the visual search task, observers searched for an orange *T* or *L* among six or 12 distractor *T*s and *L*s (Arial Black 23 point; 0.7° × 0.8°), which were presented on the outlines of an imaginary circle around the fixation point (distance to fixation: 4.5°). The number of nontargets was varied to assess search efficiency. In the NLS search condition, the nontargets were red, yellow, and blue so that the orange target was nonlinearly separable from the red and yellow nontargets; in the LS condition, the nontargets were red, blue, and purple, which rendered the orange target linearly separable. Observers were instructed to maintain fixation and report the identity of the orange target (*T* or *L*) by a key press. The target display was presented until response, and eye movements were monitored. The position of the target and distractor *T*s and *L*s and the set size were varied randomly, with the restriction that each display contained an equal number of nontarget colors and *T*s and *L*s (exempting the target). Linear separability was varied across different blocks, and the order of the four blocks was counterbalanced across participants such that participants completed both blocks of the cuing task before doing the visual search task or vice versa (resulting in eight sequences). Participants completed altogether 876 trials: 150 trials in each of the conditions in the visual search task, and 288 trials in the respective conditions of the cuing task.

Results

Data. The RT outlier criterion for Experiment 3 was increased to 1,200 ms to avoid excessive data loss in the visual search task. Excluding trials with RTs under 200 ms and above 1,200 ms led to a loss of 3.0% of the data in the cuing task and to 3.7% of all data in the visual search task. Excluding all trials where participants had moved their gaze away from fixation led to a further loss of 0.78% of the data in the cuing task and 21.6% in the visual search task. Because of the prohibitively high exclusion rate, we report the results for the visual search task with and without applying the fixation criterion.

RTs.

Visual search. Figure 4B depicts the mean RTs in the visual search task, separately for the LS and NLS conditions and the

different set size conditions. In the NLS condition, RTs significantly increased with increasing the number of nontargets in the display, $t(7) = 5.5$, $p = .001$. RTs in the LS condition were shorter and did not differ between the set size 7 and set size 13 conditions, $t(7) = 1.7$, $p = .14$. The differences between the LS and NLS conditions were also significant, $t(7) = 3.9$, $p = .006$, indicating that search in the NLS condition was more inefficient than search in the LS condition.³ This pattern of results remained the same when trials with eye movements were included in the analysis, $t(7) = 3.9$, $p = .006$.

Mean RTs on valid trials. The results from the cuing task are depicted in Figure 5, separately for the NLS cues (see Figure 5A) and the LS cues (see Figure 5B). Comparing, first, the mean valid RTs for each cue color across the LS and NLS conditions with a 2 × 4 ANOVA showed a significant main effect of cue color, $F(3, 21) = 14.0$, $p < .001$, $\eta^2 = .67$, and a trend for an interaction between cue color and linear separability, $F(3, 21) = 2.7$, $p = .070$, $\eta^2 = .28$, whereas the differences between the LS and NLS conditions were not significant ($F < 1$). Mean valid RTs were significantly faster for the red cue than for the orange cue in the LS condition, $t(7) = 6.6$, $p < .001$, and the NLS condition, $t(7) = 3.0$, $p = .019$, and contrary to the linear separability view, this difference was more pronounced in the LS condition (mean difference = 48 ms) than in the NLS condition (mean difference = 25 ms), $F(1, 7) = 11.8$, $p = .011$, $\eta^2 = .63$ (compare Figures 5A and 5B).

Mean valid RTs for the red cue were also faster than for all other cues (i.e., blue, yellow, purple) in the LS and NLS conditions ($t_s > 2.3$, $p_s < .05$). Moreover, in the NLS condition, valid RTs for the blue cue were significantly faster than for the yellow cue, $t(7) = 2.9$, $p = .023$, whereas the remaining differences were all nonsignificant ($t_s < 1.5$, $p_s > .15$).

Response-compatibility effect. A 2 × 4 × 2 ANOVA computed over the RTs to analyze compatibility effects on invalid trials showed significant main effects of cue color, $F(3, 21) = 17.0$, $p < .001$, $\eta^2 = .71$, and of response compatibility, $F(1, 7) = 47.9$, $p < .001$, $\eta^2 = .87$, and a significant interaction between the two variables, $F(3, 21) = 16.4$, $p < .001$, $\eta^2 = .70$, whereas linear separability remained nonsignificant and did not interact with any of the variables ($F_s < 1.6$, $p_s > .24$; compare Figures 5C and 5D). In the NLS and LS conditions, there were significant compatibility effects for the red cues only: NLS, 37 ms, $t(7) = 4.3$, $p = .004$; LS,

³ Computation of the search slopes was complicated by using blue colors in the search displays. Blue nontargets were included in order to mimic the conditions in the spatial cuing task, but these were probably completely ineffective in the visual search task. Hence, it is unclear whether the computation of search slopes should be based only on yellow and red nontargets (or purple and red nontargets), or whether they should include the blue nontargets. However, in both cases, search performance for the linearly separable target was in the range of search slopes reflecting efficient search, whereas search for the nonlinearly separable target was in the range of slopes reflecting inefficient search (slope > 10 ms/item; Wolfe, 1998): When blue was included, search slopes were 2 ms/item for the linearly separable target and 11 ms/item for the nonlinearly separable target (when trials with eye movements were included, slopes were 3 ms/item and 12 ms/item, respectively). When the blue nontargets were excluded, slopes were 4 ms/item and 17 ms/item (5 ms/item and 17 ms/item when trials with eye movements were included).

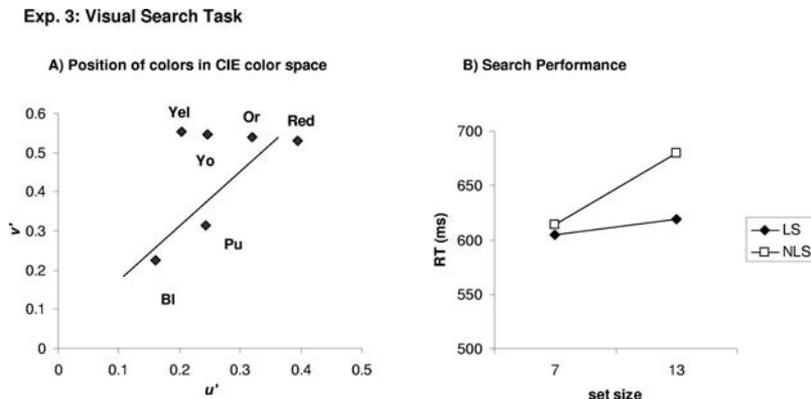


Figure 4. (A) The left panel depicts the positions of the cue, target, and nontarget colors in CIE color space. The orange cue was nonlinearly separable from yellow, red, and blue cues, but was linearly separable from the red, purple, and blue cues, as indicated by the line. (B) The right panel depicts the mean response times (RTs) and slopes of the search functions for the visual search task: Search for a nonlinearly separable orange target was inefficient, whereas search for a linearly separable orange target was efficient. Error bars represent ± 1 SEM. Yel = yellow; Yo = yorange; Or = orange; Pu = purple; Bl = blue; LS = linearly separable condition; NLS = nonlinearly separable condition.

27 ms, $t(7) = 3.7$, $p = .008$, whereas the nonsignificant trends for the other cues were all in the opposite direction ($t_s < 1.2$, $p_s > .26$). Although the compatibility effect for the red cue was numerically larger in the NLS condition than in the LS condition, these differences were not significant ($F < 1$).

Errors.

Visual search. In the visual search task, observers committed 8.0% and 10.2% errors on set size 7 and 13 trials in the LS condition, respectively, and 12.1% and 13.0% errors on set size 7 and 13 trials in the NLS condition, respectively. A 2×4 ANOVA showed that there was a trend for more errors in the NLS condition (12.5%) than in the LS condition (9.2%), $F(1, 7) = 4.8$, $p = .065$, whereas the set size effect and the Set Size \times Linear Separability interaction remained nonsignificant ($F_s < 1$).

Mean errors on valid trials. A 2×4 ANOVA computed over the valid trials of the cuing task showed a marginally significant main effect of cue color, $F(3, 21) = 3.4$, $p = .052$, $\eta^2 = .33$, reflecting that, on average, fewer errors were committed on red valid cue trials (6.1%) than on other trials (range: 9.4–12.4%). In the NLS condition, only the differences between a valid red cue and the valid blue cue approached significance $t(7) = 2.3$, $p = .056$ (all other $t_s < 1.6$, $p_s > .15$). In the LS condition, there were significantly fewer errors with a valid red cue than with a valid orange and purple cue, $t_s(7) = 2.6$, $p_s = .033$, and a trend for fewer errors with a valid red cue than with a valid blue cue, $t(7) = 1.9$, $p = .099$.

Response-compatibility effects. A $2 \times 4 \times 2$ ANOVA on compatibility showed marginally significant effects of cue color, $F(3, 21) = 3.3$, $p = .059$, $\eta^2 = .32$, and of compatibility, $F(1, 7) = 5.3$, $p = .055$, $\eta^2 = .43$, and a significant interaction between the two variables, $F(3, 21) = 6.1$, $p = .018$, $\eta^2 = .47$. Pairwise comparisons showed significant compatibility effects for the red and orange cues in the LS condition, $t(7) = 2.4$, $p = .042$, and $t(7) = 3.0$, $p = .019$, respectively, indicating that the results were not due to a speed-accuracy trade-off.

Discussion

The present results clearly rule out a linear separability explanation. In the cuing task of Experiment 3, the red cue reliably captured attention stronger than the orange cue, and it is important to note, this occurred independently of whether the orange cue was linearly separable or nonlinearly separable from the other cues.

The failure of the orange cue to capture attention cannot be explained by a failure to achieve a linearly separable orange stimulus: The results of the visual search experiment showed that the orange target could be found efficiently among the linearly separable nontarget colors (i.e., among red, blue, and purple), whereas search was inefficient in the NLS condition (i.e., among red, yellow, and blue), consistent with previous demonstrations of linear separability in visual search (e.g., Bauer et al., 1995; D'Zmura, 1991). Moreover, efficient search for the orange target in the LS condition demonstrated that attention could be guided successfully to the orange target so that the failure of the orange cue to capture could not be attributed to the fact that it was not preattentively available.

However, the finding that a linearly separable orange cue did not capture attention despite supporting efficient search should not be taken to mean that there is a dissociation between visual search and contingent capture in cuing. In both cases, the outcome can be seen to reflect the demands of the two different tasks. On each frame in the visual search task, observers had to search for an orange target among multicolored nontargets. Only in the LS condition was there a clear direction within feature space for which attention could find a control setting (a relational setting, or a linearly discriminant function) that would efficiently find orange. In the cuing task, observers were searching for a target that differed in a single direction from all nontargets (i.e., redder). As they were told to ignore the cue frame, they were not attempting to adjust control settings for that. Instead, the relational set from the target frame was applied to the cue frame, leading to capture by the redder stimulus.

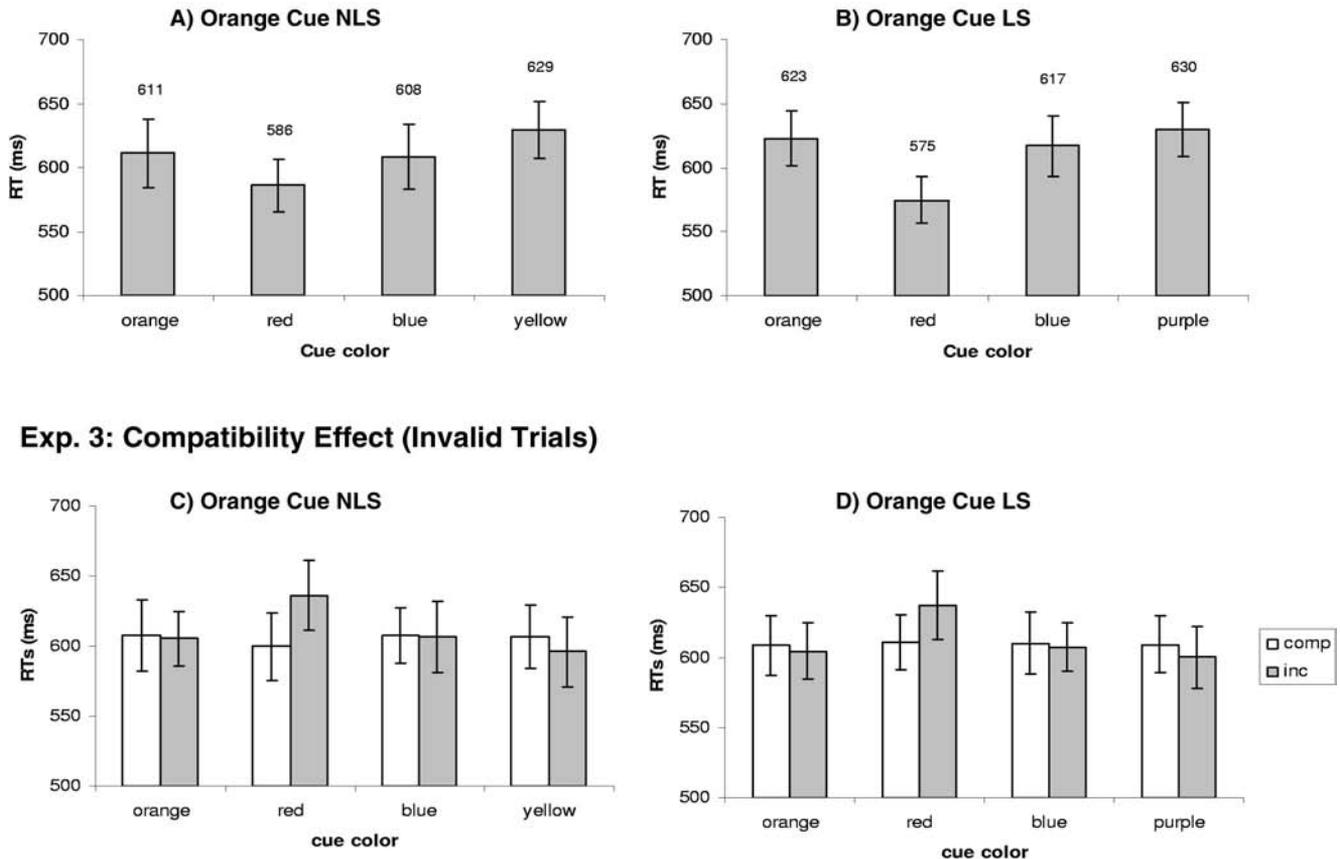
Exp. 3: Cueing Task With Orange, Redder Target, Mean Valid RT

Figure 5. Results from the spatial cuing task of Experiment 3, where the orange, target-similar cue was either nonlinearly separable (NLS; left panels) or linearly separable (LS; right panels) from the other cues in the cuing display. Top panels depict mean response times (RTs) on validly cued trials, separately for the different cue colors when the orange cue was NLS versus LS (A, B). The bottom panels depict mean RTs on response-compatible versus response-incompatible trials, depicted separately for the NLS condition (C) versus the LS condition (D). Error bars represent ± 1 SEM. As can be seen in the figure, capture for the red cue was always stronger than for the orange cue, regardless of whether the orange cue was linearly separable or not.

The present results demonstrate that visual search performance for a particular cue among the other cues cannot validly predict whether or not the corresponding cue will capture. According to contingent capture, this is not surprising; capture depends on the contents of the top-down attentional settings, which are adapted to the properties of the target, not to the properties of elements in the cue display. Contingent capture requires that the target-finding property be available preattentively from the cue frame if it is to capture attention. Whether or not this depends on the cue being linearly separable remains to be seen. What is clear is that the current results show, once again, that capture by elements in the cue frame is not a product simply of bottom-up factors, such as salience or linear separability. Instead, when the target and nontarget features remain constant, attention can be tuned very effectively to the properties that allow efficient discrimination of the target from the nontargets, overriding these stimulus-driven, bottom-up effects.

General Discussion

Folk and Remington (1998) showed that in spatial cuing, attention is not captured by salient stimuli, but by stimuli that match the attentional control settings, that is, stimuli that share similar or identical feature values to the sought-for target. Typically, this has been taken as supporting a feature-based account of contingent capture (e.g., Ansorge & Horstmann, 2007). However, such a feature-based view cannot account for the results of the spatial cuing experiments of the present study: Contrary to the predictions of a feature-based account of contingent capture, attention was not captured most by cues that were most similar to the target. Instead, we found that attentional capture critically depended on the relational properties of the target and cues. The results are thus in line with the relational account, which proposes that attention can be guided by relational information about the target.

It is important to note that the relational account retains the principal assumption of contingent capture, that task demands determine whether a stimulus will capture attention (Folk & Remington, 1998; Folk et al., 1992). However, it departs from conventional accounts in emphasizing the features that distinguish the target from its background and other irrelevant items rather than features of the target per se. In the present study, we tested and confirmed the view that attentional capture by irrelevant items can be determined by information about the relational properties of the target.

This focus on the relational properties of the target has implications for how we view the mechanisms of attention in visual search and spatial cuing. Previous accounts explaining capture by irrelevant items or our ability to ignore them have usually drawn on the feature contrast (i.e., saliency) of the items or feature-specific target activation or nontarget inhibition (i.e., activation and inhibition of separate features; e.g., Duncan & Humphreys, 1989; Navalpakkam & Itti, 2006, 2007; Wolfe, 1994). In this respect, it is interesting to note that relational information plays a role intermediate between feature-specific information and feature contrast information: Relational information characterizes how the target differs from the nontargets and, thus, is more specific than feature contrast information (that specifies merely that the target differs from the nontargets). At the same time, relational information (e.g., “redder”) is more abstract and flexible than feature-specific information (e.g., “red”).

As is argued below in more detail, guidance by relational information can thus potentially account for capture by similar items and for capture by salient items (i.e., items with a high feature contrast), which have previously been attributed to a feature-based or saliency-based selection mechanism.

The Relational Vector Account of Attention

The view that relational properties can guide attention cannot be conceptualized within the framework of different feature-specific maps (e.g., coding for red and green, respectively; e.g., Navalpakkam & Itti, 2006; Wolfe, 1994), but require that all features of a dimension are represented within a continuous feature space. The relationship between two items can then be described by the *direction* of a *vector* in feature space pointing from one item to the other (e.g., “redder” can be represented by vectors pointing from left to right in color feature space). The *length* of the vector can be taken as a “similarity” or “saliency index,” which indicates how much the two features differ from one another.

Within this framework, current models of attentional guidance (e.g., Guided Search 2.0; Wolfe, 1994) would claim that attention is guided toward the stimulus whose vectors have the greatest length (i.e., are most salient) and whose absolute position in feature space has been preactivated by top-down controlled processes, whereas they would dismiss the direction of vectors as unimportant. In contrast to this, the relational account would propose that the vector direction is more important in guiding attention than the vector length (i.e., the feature contrast between items). To capture attention, it will be necessary for the features of the cue and its background to have a reasonably large vector difference (so that the relationship between the items can be assessed), but vector length is not sufficient for capture in and of itself. Rather, selection can be limited to those features whose

vectors point into a predefined direction so that only items that have the same relational properties as the target capture attention (e.g., redder, larger, darker).

How can the relational guidance account handle the many previous findings suggesting that both the feature value and the feature contrast or saliency of the target play a role in capture? Previous studies investigating capture naturally did not systematically vary the relational properties of the target or singleton distractor (or cues). Thus, items that were similar to the target accidentally also differed in the correct direction from the competing items (i.e., in the same direction as the target differed from the nontargets). Thus, it is possible that results that were previously attributed to similarity and a feature-based selection mechanism were in fact due to guidance by relational information. In other words, it is possible that the similarity effect was not due to the featural similarity between the items (e.g., Ansorge & Heumann, 2003, 2004; Ansorge & Horstmann, 2007; Folk & Remington, 1998; Folk et al., 1992; Ludwig & Gilchrist, 2002, 2003), but rather to the fact that similar cues or distractors usually differed in the same direction from the nontargets (or other cues) as the target (differed from the nontargets).

Second, when different features compete with one another, the relational account predicts that capture will be strongest for the stimulus that differs in the correct direction from all other stimuli. Because such an item will always be located at one extreme end of the continuum, this will also be one of the most salient items in the visual field (i.e., the item will have a large feature contrast from the other items). Thus, the relational account is also consistent with previous studies reporting capture by salient stimuli, but again offers an alternative interpretation for this observation (Becker, 2010; see also Folk & Remington, 1998). Taken together, the relational account holds promise for synthesizing a range of visual search and spatial cuing results that were previously attributed to a feature-based or a saliency-based selection mechanism.

Alternative Explanations

It could be asked whether the results of the present study necessitate an explanation in terms of relational information, or whether they can also be explained by other accounts. Experiment 3 already ruled out a linear separability explanation of the findings by showing that stronger capture by red cues occurred regardless of whether the orange cue was linearly separable or nonlinearly separable from the other cues. However, the results may still be consistent with feature-based or categorical accounts.

For instance, Huang and Pashler (2005) proposed that target discrimination can be accomplished by a “feature divider” that divides feature space into a to-be-attended region and a to-be-ignored region, so that the to-be-attended region contains all possible target features, whereas the to-be-ignored region contains only the nontarget features. On this view, selectivity is achieved by tuning attention toward these broad categories or regions in feature space. Such a feature divider account would be consistent with the finding of Experiment 1, that in search for an orange target among orange nontargets, red singleton cues can capture attention to the same extent as orange singleton cues. However, it is difficult to see how a feature divider account could account for the outcome of Experiments 2 and 3, which showed that more dissimilar cues (e.g., red cue) reliably capture attention much stronger than more

similar cues (e.g., orange cue) when both cues are included in the same display and compete for attention. This result cannot be explained by a feature divider view or a categorical account, because the feature divider has to be positioned such as to include the target color (i.e., orange). With this, capture by red cues should not be stronger than capture by orange cues, but red and orange should capture attention equally strongly, contrary to the present findings (see also Becker, 2010).

Second, one might be tempted to model guidance by relational information with a feature-based search engine. For instance, in the Guided Search 2.0 model, there are four categorical channels involved in color search (red, green, blue, yellow; Wolfe, 1994). Search for an orange target among yellow nontargets need not require separate tuning of attention toward both red and yellow channels; it would be sufficient to tune attention to the red channel, using the location with the largest activation as the “redder.” In turn, tuning attention toward the yellow channel would only allow discriminating the target from the nontargets by way of detecting lesser activation for yellow, a suboptimal strategy that would suffer from a decreased signal-to-noise ratio. Thus, it is possible to implement the relational idea into categorical selection accounts by assuming that the relational properties of the target determine the channel that will be monitored during search.

However, it is difficult to see how the relationally best channel can be computed on the basis of separate feature-specific maps coding, for instance, for red and yellow. As these feature maps bear no obvious relation to one another, it is unclear how the visual system could obtain knowledge about different relationships. Current theories of visual search thus seem to lack a mechanism that could plausibly mediate guidance by relational information (e.g., in terms of a causal chain). In addition, the Guided Search model assumes that attention can only be guided by the output of a single channel; for example, see Wolfe (1994): “. . . in GS2, top-down activation is accomplished by selecting the output of the one broadly tuned channel per feature (e.g., ‘red’ for color and ‘steep’ for orientation) . . .” (p. 207). This limitation appears to be critical to correctly model the limitations of search efficiency (e.g., Mozer & Baldwin, 2008). However, if attention could be tuned to only one feature category, then it should not be possible to set for values such as orange, which are combinations of features. This, however, seems to be at odds with results showing that attention can be tuned genuinely toward orange (e.g., Bauer et al., 1995; D’Zmura, 1991). Overall, it seems possible but not necessarily advisable to explain guidance by relational information within the theoretical framework of a categorical or feature-specific search mechanism.

Top-Down Search Heuristics and the Role of Experience

Here, we have shown that attention can be tuned to the relational properties of targets that enable efficient discrimination. The fact that attention was tuned to the relational properties of the target highlights the importance of experience in adapting the contents of the attentional control settings, because knowledge about the relational properties of the target is presumably not conveyed by the instructions, but develops after the first trial, by experience with the task and the visual displays (see also Becker, 2007; Becker, Ansorge, & Horstmann, 2009). The view that experience with the task can alter the contents of the attentional control settings is

consistent with the contingent capture view (e.g., Folk & Remington, 1998; Folk et al., 1994), but contrasts with the view of other researchers, who have defined top-down controlled processes more narrowly with respect to the verbal instructions. For instance, Hodsoll and Humphreys (2001) remarked, “[b]y top-down processes we mean that the perceptual system can be set by instruction, so that the target-distractor differentiation is facilitated” (p. 919).

The present study can be viewed as supporting the more liberal definition of top-down controlled settings: Despite the fact that the relational search setting presumably required some minimal exposure to the stimuli and the task, attention was clearly set in a top-down controlled manner to the relational properties of the target: First, Experiments 1 and 2 tested identical cues when only the target frames differed, and showed that the attention-driving capacity of a cue critically depends on the task and on the relational properties of the target. Second, Experiment 3 clearly demonstrated that the discrimination demands of the target frame, and not the cue frame, determine the contents of the attentional control settings: The linear separability of orange in the cue frame made no difference.

Taken together, these results clearly show that capture is not determined by the saliency or linear separability of the cues, but by the task demands and the specific properties of the target (and nontargets). Hence, the fact that the attentional control settings are adapted to information conveyed by the stimulus display cannot be taken to infer that attention is controlled by stimulus-driven processes. Rather, experience-guided search should be viewed as an element of top-down controlled processes that use information about the stimulus displays and other task parameters to tune attention in a more fine-grained manner to the most informative features. This provides strong support for the claim that the deployment of attention is generally fine-tuned to fit the required action (i.e., to the target), and is not completely determined by salient differences in displays that require no action (i.e., cue frame).

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Received April 29, 2009

Revision received March 1, 2010

Accepted March 29, 2010 ■