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ORIGINAL ARTICLE

Contingent capture in cueing: the role of color search templates and cue-target color relations

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Abstract Visual search studies have shown that attention can be top-down biased to a specific target color, so that only items with this color or a similar color can capture attention. According to some theories of attention, colors from different categories (i.e., red, green, blue, yellow) are represented independently. However, other accounts have proposed that these are related—either because color is filtered through broad overlapping channels (4-channel view), or because colors are represented in one continuous feature space (e.g., CIE space) and search is governed by specific principles (e.g., linear separability between colors, or top-down tuning to relative colors). The present study tested these different views using a cueing experiment in which observers had to select one target color (e.g., red) and ignore two or four differently colored distractors that were presented prior to the target (cues). The results showed clear evidence for top-down contingent capture by colors, as a target-colored cue captured attention more strongly than differently colored cues. However, the results failed to support any of the proposed views that different color categories are related to one another by overlapping channels, linear separability, or relational guidance ($N = 96$).

Introduction

Humans are surprisingly good at attending to information that is relevant to their task and goals. Most theories of attention assume that observers are able to exert top-down control over attention, so that relevant objects are selected and processed faster. Previous research suggests that observers are not only able to attend to particular locations in the visual field, but can also tune attention to specific, elementary feature values (e.g., red, large, tilted). For instance, Folk and Remington (1998) demonstrated that attention could be selectively tuned to a target of a particular color: when the task was to search for a green target, a green but not a red distractor captured attention, whereas the opposite was found when participants searched for red targets. According to the *contingent capture hypothesis* (Folk, Remington, & Johnston, 1992), observers can tune attention off-line towards particular feature values (e.g., particular colors) or dimensions (e.g., all colored stimuli), so that irrelevant stimuli that have the same feature as the target (e.g., red) can involuntarily capture attention, whereas target-dissimilar stimuli can be successfully ignored (e.g., Eimer & Kiss, 2008).

The content and structure of the mental representation that guides attention has not been fully specified. Strikingly, participants seem to be capable of searching for two different colors and ignoring a third color (Worschech & Ansorge 2012), even if the irrelevant color falls in-between the two searched-for and relevant colors in color space (Irons, Folk, & Remington, 2012). Simultaneously, it seems clear that attention is not narrowly tuned to only one particular shade of color (e.g., of red): when participants search for a particular color target (e.g., red), an irrelevant distractor with a different but target-resembling color can still capture attention (e.g., orange if the target is red).

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By contrast, a distractor that differed largely from the target color (e.g., greenish) failed to capture attention. In the corresponding experiment (Ansorge & Heumann, 2003), the distractor was briefly presented prior to the target, as a *cue*: when a target-resembling orange cue was presented randomly either at the same position (SP condition) as the target, or at a different position (DP condition) than the target (Ansorge & Heumann, 2003), search for the red target was faster when the cue validly indicated the target location. This was in contrast to target-different greenish cues. Valid target-resembling cues significantly facilitated search times by 18 ms as compared to valid target-different cues, whereas invalid target-resembling cues non-significantly delayed search times by 5 ms as compared to invalid target-different cues. This stronger cueing effect (reaction time [RT] in DP condition − RT in SP condition) by the target-resembling cues indicates that attention is deployed to the cue as a consequence of the cue-target color resemblance so that attention also needs to be redirected to the target in a time-consuming manner in the target-resembling DP condition. The fact that such cueing effects are regularly found with target-resembling and target-similar colors but not with starkly target-different colors (Anderson & Folk, 2010; Ansorge & Heumann, 2003) suggests that a *broadband feature search principle* applies in search for a color target. In line with this, Grubert and Eimer (2013) observed that the findings of Irons et al. (2012) did not hold up if event-related potentials (ERPs) were used to track the early capture of attention by in-between-target colors. Using an attention-elicited ERP (the so-called N2pc) these authors found that if participants searched for two color targets (i.e., numbers) and reported their identity, an irrelevant target-different distractor stimulus captured attention, and that the lack of evidence for attentional capture by an in-between-target-color cue in the RTs of Irons et al. could thus be misleading. To explain the discrepancy between the N2pc and the behavioral results, Grubert and Eimer explained that the in-between-target-color cue of Irons et al. (2012) might have first captured attention and that thereafter, within the cue-target interval of 200 ms, attention could have been deallocated from the cue and back to the center so that this capture effect was not reflected in the target RTs (cf. Theeuwes, Atchley, & Kramer, 2000).

Thus, the important question exactly how colors from different categories (e.g., red, green, blue, yellow) are used during top-down search for color and how they relate to one another has not been answered conclusively. Naturally, one possibility is that colors from different color categories represent atomic identities that are not related to one another in visual search. For instance, Müller, Geyer, Zehetleitner, and Krummenacher (2009) proposed that colors from different categories such as red and green may constitute their own sub-dimensions that are not related to one another. Indeed, previous research has found that search is faster when the target and irrelevant distractors are from different color categories than when they both fall within the same category (e.g., green), despite the fact that the distances between the colors (e.g., in CIE color space) were equal (Gilbert, Regier, Kay, & Ivry, 2006). This cross-categorical advantage seems to support the view that color categories may constitute special entities whose separation facilitates search (see also Witzel & Gegenfurtner, 2011).

But what forms a color category? It seems desirable to strive for a model where different colors are represented in a feature space and can be related to one another in virtue of their similarity—that is, their position and distance within this feature space. The most well-known feature space is perhaps CIE color space; however, it is at present unclear whether and how CIE color space forms the basis of color-cueing effects. CIE color space is based on similarity judgments; hence, the distance between two colors in this space provides a measure of their similarity or dissimilarity. To be exact, CIE color space is two-dimensional with x- and y-coordinates corresponding to the contributions of red and green, respectively, that would add up to a value of 1.0 by a z coordinate (for the contribution of blue). CIE color space can provide a good framework for early perceptual or attentional processes, in terms of the described similarity relations between colors from different categories. However, depending on the number and type of color channels that are assumed in a search model, categorical color relations can be mimicked with a model based on color wavelengths, too (see Wolfe, 1994, described in more detail below). In contrast to CIE color space, wavelength is a uni-dimensional variable that is not based on similarity judgments. Instead it is an objectively measured physical feature. Perhaps for this reason, multiple different models of inter-category relationships of colors have been proposed, which will be described below in more detail.

In the present study, we tested whether and to what extent colors from different categories are related to one another during attention capture, by asking observers to search for a target of a particular color, and to ignore an irrelevant and unpredictive cue that could be presented either at the same location (valid condition; 50 %) or at a different location (invalid condition; 50 %) than the target. In different blocks, the target was red, green, yellow or blue, and the cue could be similarly red, green, yellow or blue.

This design permits testing several hypotheses of how colors from different categories are related to one another during top-down search for a particular color. First, according to a categorical, *four-channel model*, attention is tuned to stimuli via one of four broad categorical color channels; red, green, blue or yellow. These four channels are ordered according to their wavelengths and overlap with their adjacent color channels to a large extent (cf. Wolfe, 1994). In the model of Wolfe (1994), because of the large overlap with neighboring channels, top-down activation of one channel could lead to capture by other items than the sought-for item. For instance, in search for red, a yellow or blue stimulus activating red-adjacent color channels could still co-activate the red channel and capture attention. By contrast, a green cue could not capture in search for red, because green and red color channels are non-adjacent and there is no overlap between red and green (see Fig. 1). Essentially the same predictions could be derived from *opponent color processing models* that propose that color is encoded via red–green and blue–yellow color-opponent processing mechanisms. These models would predict that search for red should automatically lead to inhibition of green and vice versa, whereas non-opponent colors such as blue or yellow could still capture.

A second view that has been proposed is the *linear-separability view*. According to this account, if the target color is linearly separated by a single line from all irrelevant colors in CIE color space, attention can be directed to relevant colors while the irrelevant colors can all be ignored. However, if it is impossible to separate the target from all distractor colors, at least one of the distractor colors ought to capture attention. Hence, the linear separability view would predict that it should be possible to ignore yellow, green and blue cues in search for red (see Fig. 2). However, in search for a yellow target, it should be impossible to ignore both red and green cues equally well, because the yellow target falls directly in-between the two other colors, so that the relevant and irrelevant colors are not linearly separable. As a consequence, one of the non-separable irrelevant colors should capture attention (Bauer, Jolicoeur, & Cowan, 1998).

According to a third, *relational account* (Becker, 2010a; Becker, Folk, & Remington, 2010), observers can adopt a relational search criterion that allows distinguishing the target from the surrounding, irrelevant items (see Fig. 3). For instance, in search for an orange target among yellow distractors, attention would be set for all redder items, whereas attention would be set for yellower if the orange target is embedded among red distractors. In line with the relational principle, cueing experiments showed that, in search for an orange target that was redder than the simultaneously presented distractors, attentional capture was stronger for a red cue than for an orange cue (Becker et al., 2010)—indicating that attention was indeed tuned towards all redder items and not the feature value of the target (orange).

If we assume that tuning directions are based on CIE color space, the relational account would seem to make the same predictions as the linear separability view (cf. Becker, 2010a; Becker et al., 2010). However, at present it is unclear whether the two-dimensional CIE color space provides the correct framework for the relational account (cf. Becker, 2010a). Another plausible view is that different

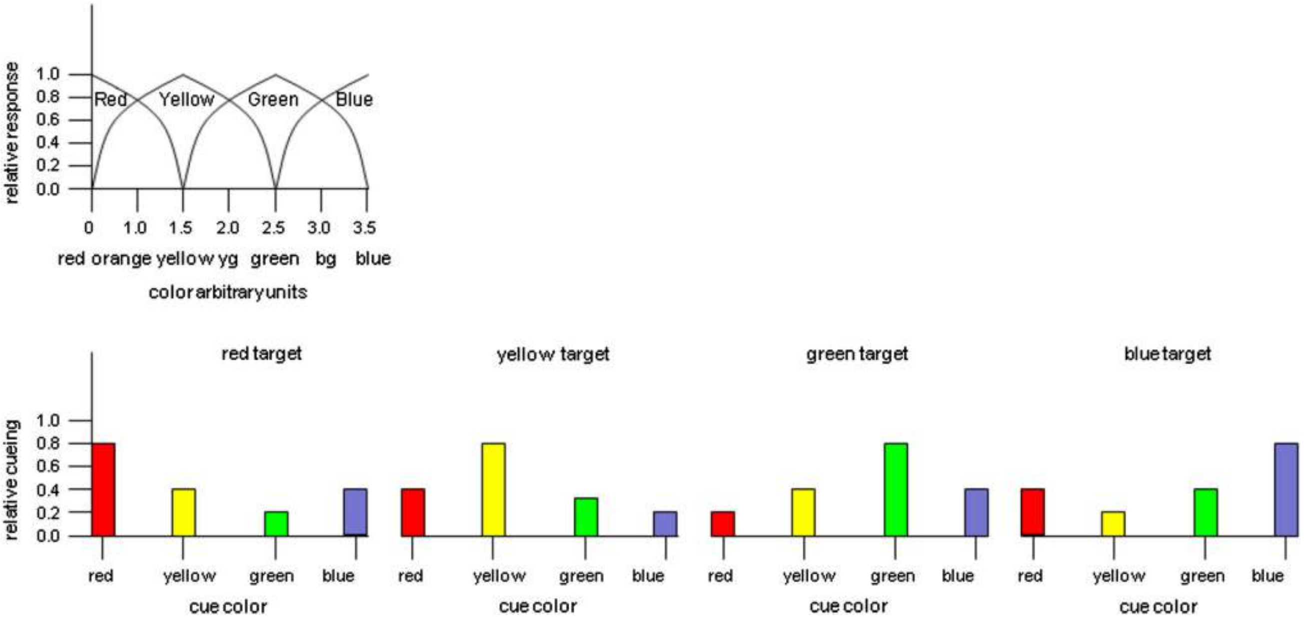

Fig. 1 The four-channel model and its predictions. *On the top* activation of color-specific channels on the *y*-axis as a function of perceived color on the *x*-axis (in arbitrary units of color adjacency between color channels). *On the bottom from left to right* predictions of cueing effects (RT in DP conditions − RT in SP conditions) for different color cues and different color targets based on the four-channel model. In essence, each cue color contributes according to an adjacency rule. *yg* yellow-green, *bg* blue-green (color figure online)

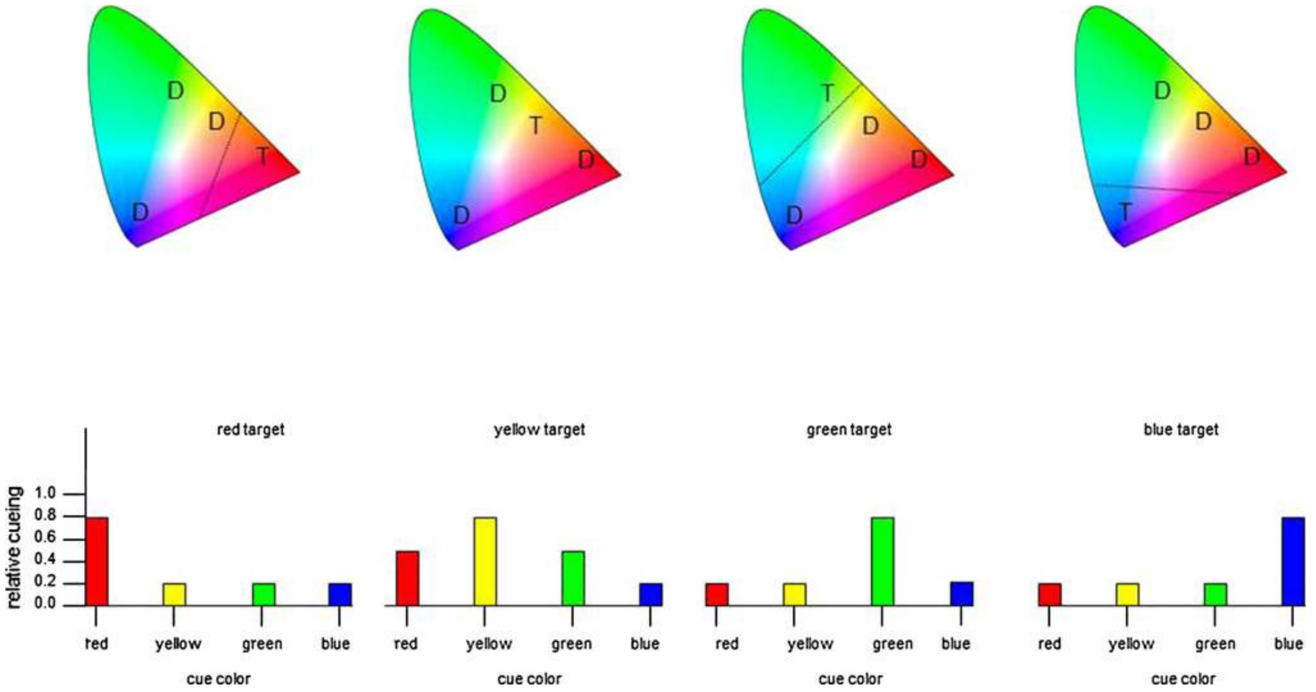

Fig. 2 The linear-separability principle. *On the top* the locations of the used cue and target colors in CIE color space. (CIE color space expresses colors by two color values [for red on the *x*-axis and green on the *y*-axis] out of a three-color triplet for contributions by green, red, and blue that add to 1.0.) *In the middle* for different target colors of decreasing wavelength (*from left to right*), the CIE color space is depicted with the positions of target (*T*) and distractors (*D*), and a line of linear separability between the relevant target color and irrelevant distractor colors where such a line existed. This was the case in all conditions but in the yellow-target conditions. *On the bottom from left to right* the predicted cueing effects (RT in DP conditions − RT in SP conditions) for different cue and target colors based on the linear-separability principle. As can be seen, dissimilar color cues could all be ignored with the different target colors, but in green-target conditions (color figure online)

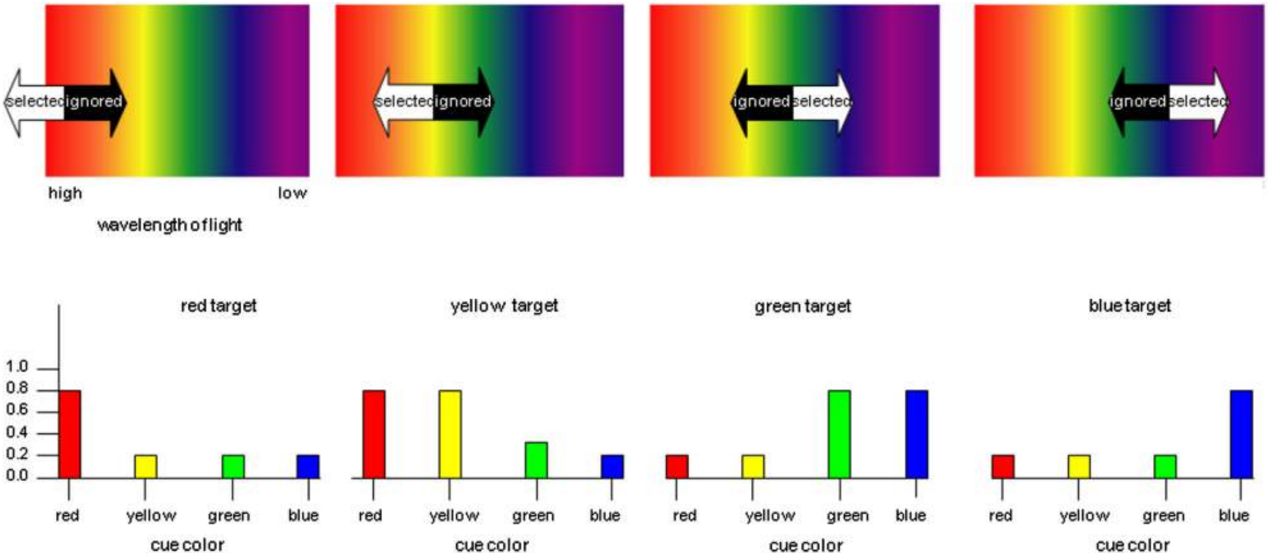

Fig. 3 The relational search model (for wavelength) and its predictions. *On the top* color spectra, with decreasing wavelength in each spectrum from left to right. Each spectrum shows a relational search criterion for a different target color, red, yellow, green, and blue, from left to right spectrum. The relational search criterion is depicted as a *directed double arrow*. As it can be seen, it marks one reference wavelength above (or below) of which the relevant target color could be selected (*white arrow*), and a majority of the irrelevant cue colors could be ignored (*black arrow*). A single relational search criterion would thus predict capture by colors exceeding the reference wavelength. This is shown for different color targets in the *lower panels from left to right* for decreasing target wavelength (color figure online)

wavelengths of colors account for relational search. If we assume that the tuning of directions is based on an ordering of colors according to their position on a single dimension of wavelengths rather than on the color coordinates in two-dimensional CIE space, we would arrive at a new prediction: in this case, observers would only be able to ignore all target-different colors when the target color is located at one of the extreme ends of the wavelength bands (i.e., search for the longest wavelength red or the shortest wavelength blue). By contrast, in search for colors of intermediate wavelength between the more extreme colors (i.e., search for yellow or green), observers could only ignore colors that are all below or all above the wavelength of the sought-for color, but not both. In search for yellow, observers should be able to ignore green and blue—because both wavelengths are above yellow—or they should be able to ignore red—because this wavelength is below yellow. Therefore, in search for yellow targets, capture by red should be negatively correlated with capture by green and blue, whereas capture by green and blue should be positively correlated (because green and blue both differ in the same direction on the wavelength dimension from yellow, whereas red differs in the opposite direction). In search for green, it should be possible to ignore red and yellow, or to ignore blue, and therefore, capture by red should correlate with capture by yellow, and both should be inversely related to capture by blue.

The different principles mentioned above have so far been tested only in visual search (e.g., Becker, 2010a), where the target or the cue is presented synchronously with irrelevant distractors. However, simultaneous presentation of target and distractor(s) is not ideal for testing the contents of top-down search settings, as adding similar versus dissimilar distractors to the display will also dramatically alter the local feature contrasts in the display—a factor that demonstrably affects search performance in a stimulus-driven manner (e.g., Itti & Koch, 2001). Thus, it is notoriously difficult to distinguish between top-down and bottom-up influences in the visual search paradigm (see Bauer et al., 1998 and Hodsoll & Humphreys, 2005, for a discussion of this point).

The aim of the present study was to test the hypotheses mentioned above under the better controlled conditions of a spatial cueing paradigm: this paradigm allows probing the contents of the attentional control settings in a more exact manner, if a single cue is presented in isolation, prior to the target display and cannot affect the feature contrast of the target, allowing more direct insights into the top-down set that guides attention. Yet, to prevent that quick deallocation after capture disguises (or minimizes) the differences in the cueing effects, the cue-target interval was kept well below 100 ms (here: 68 ms; cf. Ansorge & Heumann, 2003, 2004), an interval too short to allow for deallocation (e.g., Kim & Cave, 1999; Theeuwes et al., 2000).

Experiment

In order to test how the different color categories are related to one another in contingent capture, we presented a single target with a fixed color on every trial. Balanced across participants, the target was always blue, green, yellow, or red within a block, and was always preceded by an irrelevant color cue. The cue-target positions were equally often SP and DP conditions; participants were instructed to ignore the cue and were informed that it did not predict the target location.

The experiment consisted of two separate conditions; in the 2-cue-color (2CC) blocks, only two color cues were used, one of which was always a target-similar cue (e.g., a red cue with a red target), and the other a dissimilar cue (e.g., a green cue with a red target). In the 4-cue-color (4CC) blocks, the cue had one out of four colors (blue, green, yellow, or red), which changed randomly from trial to trial so that participants did not know the color of the next to-be-ignored cue.

If colors from different categories show no interdependencies, then we would expect capture to occur for the target-similar cues (across all cue colors), but not for any of the target-different cues. However, if colors from different categories are related to one another, then we would expect that some of the target-different cues can also capture attention. Specifically, according to the four-channel view, cues activating channels next to the target channel could show significant capture effects (see Fig. 1). If colors are related to one another by their positions in CIE color space, and the linear separability principle (or relational principle) holds, then it should be possible to ignore the target-different cues perfectly in search for red, blue, or green, whereas in search for yellow, either the green or the red cue should capture attention. If colors are instead related to one another by their wavelengths, and the relational-guidance principle holds, then it should be possible to ignore all target-different cues in search for the extreme wavelengths of red (~700 nm) and blue (~470 nm). However, in search for yellow (~580 nm), either the red cue or the blue and green cues (~510 nm) should capture. Similarly, in search for green, either the blue cue or the red and yellow cue should capture, because these cues differ in two opposing directions from the target and hence, cannot both be ignored with equal efficiency.

According to the linear separability account and the relational account, we would moreover expect differences when only a single target-dissimilar cue is presented (2CC) versus when multiple different cues are present (4CC). In search for yellow, it should be impossible to tune attention both against green and red, but tuning attention against only one of these colors should be unproblematic. Hence, the linear separability view and the relational account would predict no capture for target-different cues when only a single target-different cue is present (2CC). However, when two or more target-different cues are presented within a block (4CC), one of the target-different cues should capture attention. In other words, the 2CC conditions provided a baseline against which to compare whether indeed any of the expected effects based on the use of multiple color cues that are predicted for relational search and linear separability views are indeed restricted to the conditions with more cue colors (4CC).

Method

Participants

Ninety-six paid volunteers (75 female), 24 per target color, with a mean age of 27 years participated. All had normal or corrected-to-normal vision, including color vision (verified by Ishihara color plates). Two participants were excluded because of more than 20 % errors.

Stimuli and procedure

Figure 4 shows the essentials of the setup. A fixation display with a cross in the screen center was presented for 800 ms. Next one colored disk was shown as a cue for 34 ms. It was equally often left or right of the screen center, at an eccentricity of 4.0°. The cue subtended 1.0°. The subsequent display contained one ‘pacman-style’ target disk, also of 1.0° size and of 34 ms duration, with its top or bottom quarter missing. The target was at the same position as the cue (SP condition) in 50 % of the trials and opposite to the cue (DP condition) in the other 50 %. The stimulus onset asynchrony (SOA) between cue and target displays was 68 ms.

The participants searched for the predefined color target and ignored the irrelevant cue. They had to press the left key if the upper target segment was missing and the right key if the lower segment was missing, or vice versa (balanced across participants). Balanced across participants, target color (CIE chromaticity *x*/*y* coordinates in brackets) was red (.619/.333), green (.295/.579), yellow (.449/.455), or blue (.151/.107). All colors were approximately equated for luminance (~28 cd/m^2).

There were two blocks. In the 2CC block, the cue either had the same color as the target (50 %) or it had a different color, which was fixed and balanced across participants to be equally likely one of the non-target colors. Every target-different cue color in the 2CC blocks was also equally likely used with every target color (balanced across participants). In the 4CC block, the cue was equally likely of each of the four colors.

The 2CC block consisted of 5 repetitions of 2 cue colors × 2 cue positions × 2 target locations × 2 target shapes (80 trials in sum). The 4CC block consisted of 5 repetitions of 4 cue colors × 2 cue positions × 2 target locations × 2 target shapes (160 trials in sum). Within blocks, different conditions were randomized. Half of the participants started with the 2CC block and half with the 4CC block. Prior to every block, participants practiced the upcoming task for 32 trials (not analyzed).

Results

Figures 5 and 6 show capture effects in RTs of target-similar colors and target-different color cues, separately for 2CC blocks (Fig. 5) vs. 4CC blocks (Fig. 6), and for different target and cue colors. In the figures, it can be seen that contingent capture was found, with the smallest differences between relevant red and green colors: participants struggled especially when searching for green targets, as was evident from strong capture by the target-different cues, particularly of red and yellow cues in the 2CC block. By contrast, clear-cut evidence for any of the other color search principles was absent. The analyses confirmed this impression.

Contingent capture

Out of all trials, 5.2 % were discarded because RTs were more than 2 SDs away from the mean correct RTs (computed separately by condition). Correct RTs were subjected to a mixed-model analysis of variance (ANOVA), with the within-participant repeated-measures variables cue-target positions (SP vs. DP), block (2CC vs. 4CC) and cue-target color similarity (target-similar vs. target-different), and the between-participants variables target color (red, yellow, green, or blue) and dissimilar cue color in the 2CC block (red, yellow, green, or blue).

A highly significant main effect of cue-target positions, $F(1, 82) = 74.23$, $p < .01$, partial $\eta^2 = .48$, reflected attentional capture, with faster responses in SP than DP trials (543 vs. 571 ms). An equally marked significant interaction between cue-target positions and color similarity, $F(1, 82) = 16.21$, $p < .01$, partial $\eta^2 = .17$, indicated that cueing effects were larger for the target-similar cues (cueing effect = 39 ms; $t[93] = 8.05$, $p < .01$) than for the target-different cues, where cueing effects were however still significant (cueing effect = 17 ms; $t[93] = 5.55$, $p < .01$). In separate ANOVAs for different target colors, however, stronger capture by target-similar colors could only be confirmed for red, yellow, and blue target-similar cues, but not for the green cue (cue-target positions × similarity interactions: all significant

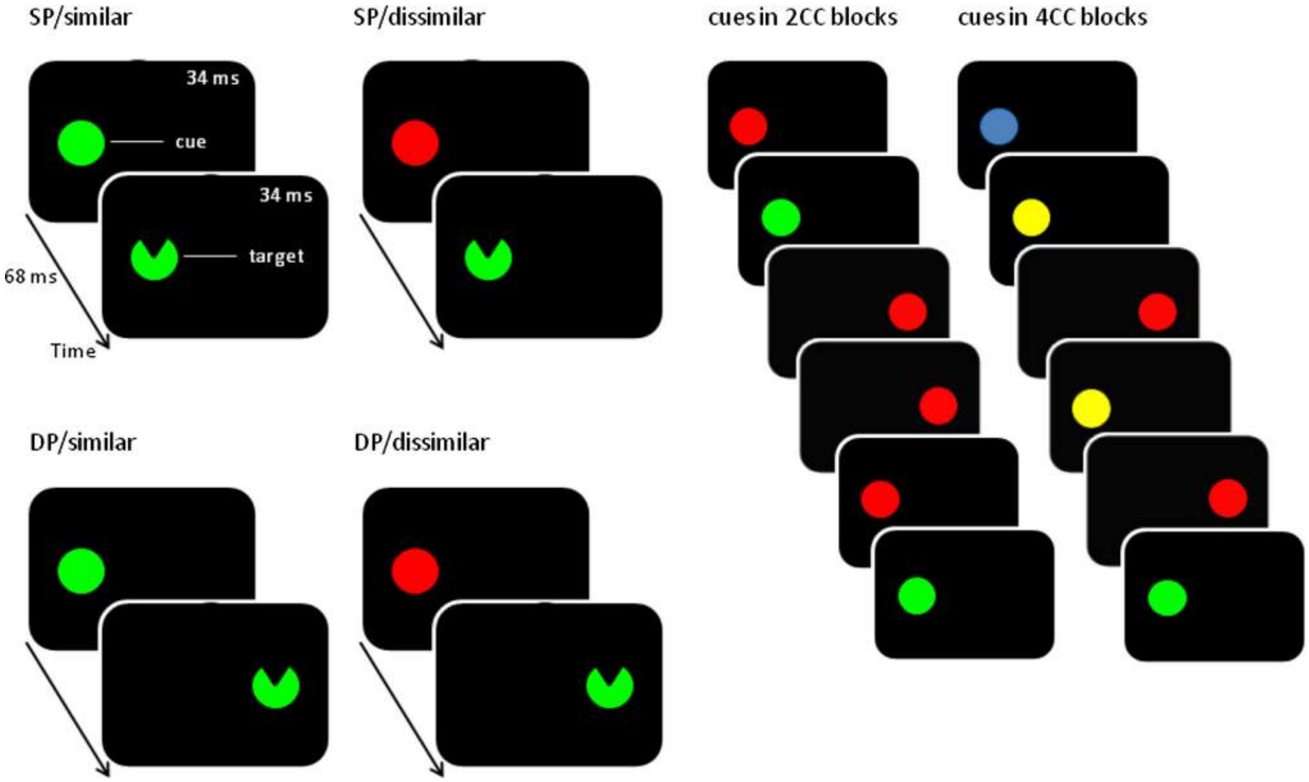

Fig. 4 Examples of trials with cue and target at the same position (*upper left* SP) and cue and target at different positions (*lower left* DP) with target-similar cue (*1st column from left*) and target-dissimilar cue (*2nd column from left*), and cue sequences (intermittent target displays not depicted) in blocks with two cue colors (*3rd column from left* 2CC) and in blocks with four cue colors (*right column* 4CC). Stimuli are not drawn to scale. Mean cueing effects in correct reaction times (RT [DP] − SP [RT]) for matching cues (*in black*) and non-matching cues (*in white*), as a function of the number of cue colors (*upper panel* two cue colors [2CC] or four cue colors [4CC]), of the target color (*lower left panel*), and of the cue color (*lower right panel*) (color figure online)

*F*s > 6.00, all *p*s < .05; vs. $F < 1.00$ for green cues). None of the remaining effects or interactions reached significance, all *F*s < 1.90, all *p*s > .14 (see also "Appendix").

A corresponding ANOVA computed over the mean error rates (ERs) yielded only very few weak effects that were not indicative of a speed–accuracy trade-off (see "Appendix").

Four-channel model

Figure 5 (lower left panel) shows that there was only little evidence for the four-channel principle. Although we observed more capture for the target-different cues activating the green target's adjacent yellow and red color channels than for the more remote blue channel in 2CC blocks, these results were not replicated in any of the other search conditions. To formally test the model, an ANOVA with the between-participant variables target color, and the within-participant variables cue-target positions, and adjacency (adjacent vs. remote) between the dissimilar cue's color channel and the relevant target color channel was computed over the 4CC trials. Adjacency and remoteness were coded as follows: with red targets blue and yellow cues counted as adjacent (green cues as remote); with yellow targets, red and green cues counted as adjacent (blue cues as remote); with green targets, yellow and blue cues counted as adjacent (red cues as remote); and with blue targets, red and green cues counted as adjacent (yellow cues as remote). The ANOVA led to a significant capture effect, $F(1, 90) = 37.00$, $p < .01$, partial $\eta^2 = .29$, with lower RTs in SP (RT = 546 ms) than DP conditions (RT = 568 ms). In addition, there was an almost significant interaction of adjacency and cue-target positions, $F(1, 90) = 3.18$, $p = .08$, which reflected a trend opposite to the predictions of the four-channel model—that is, more capture in remote (cueing effect = 27 ms) than in adjacent conditions (cueing effect = 17 ms). All other main effects and interactions were not significant, all *F*s < 1.70, all *p*s > .18.

An ANOVA of the 2CC blocks, with the within-participant variable cue-target positions, and the between-participant variables cue-target color adjacency (coded as above), and target color, also led to a significant capture effect, $F(1, 86) = 31.29$, $p < .01$, partial $\eta^2 = .27$, with

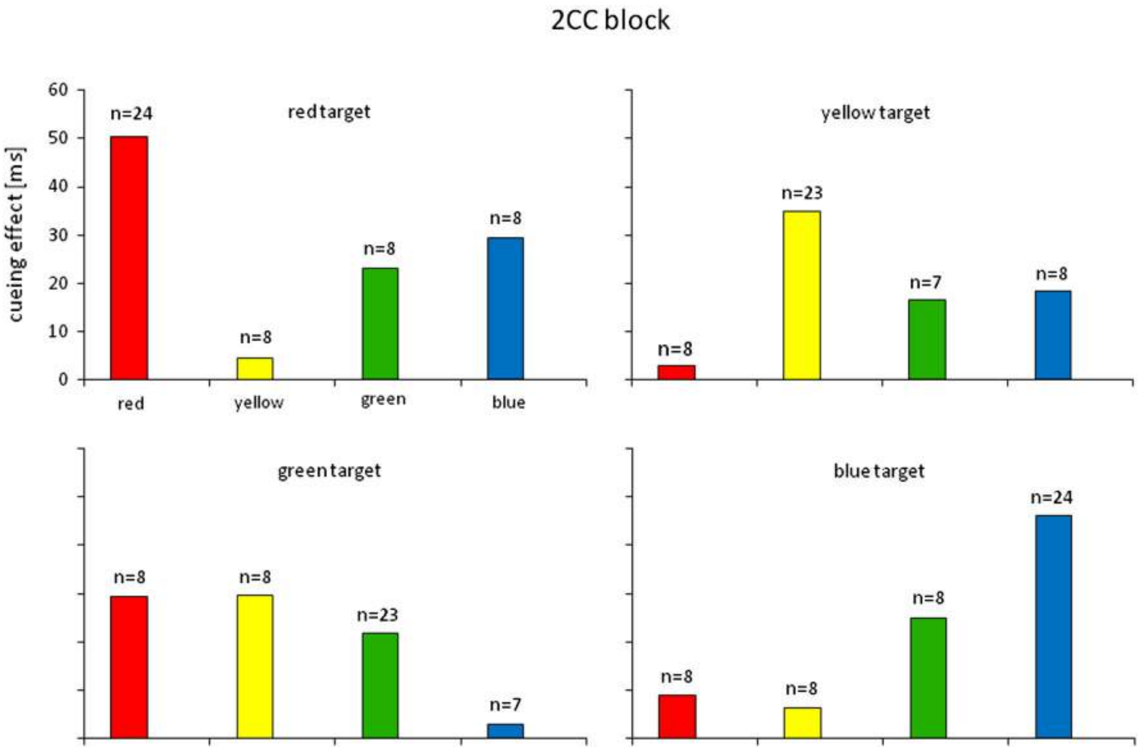

Fig. 5 Mean cueing effects in correct reaction times (RT [DP] − RT [SP]) of the 2CC (one target color, two cue colors) blocks on the *y*-axis, as a function of the cue color (red, yellow, green, and blue) on the *x*-axis, and of target color (*different panels* with decreasing target wavelength from *upper right* to *lower left*). *N* gives the number of participants contributing to a particular cueing effect. (Note that dissimilar cue colors were realized as a between-participant variable in the 2CC blocks.) As can be seen, cueing effects were strongest for the target-similar cues, with the exception of the green-target conditions (color figure online)

lower RTs in SP (RT = 546 ms) than DP (RT = 572 ms) conditions. The remaining main effects and interactions were non-significant, all other *F*s < 2.00, all *p*s > .12.

CIE color space: linear separability principle

Figure 5 shows that the findings also did not support the linear separability principle. According to this view, it should have been especially difficult to ignore target-different cues that are not linearly separable from the target color. Hence, the target-different cues should have shown overall more capture in search for the yellow target, which was not linearly separable from all cue colors, than in search for the red, green, or blue target, which were all linearly separable from the other cue colors. Instead, the results indicate that participants had difficulties ignoring target-different cues in search for green targets (see Fig. 6). A second prediction of the linear separability view is that, in search for the yellow target, the non-linearly separable red and green cues should capture more strongly than the blue cue, which was linearly separable from the target color. This prediction was formally tested by an additional ANOVA of the RTs in the yellow-target 4CC block, with the within-participant variables cue-target positions, and target-different cue color (blue, green, and red). This ANOVA again led to significant attentional capture, $F(1, 22) = 10.11$, $p < .01$, partial $\eta^2 = .24$, with faster responses in SP (RT = 545 ms) than DP conditions (RT = 569 ms). However, this cueing effect was not modulated by the cue's color (interaction of cue color × cue-target positions: $F < 1.00$). It was as strong for blue cues (cueing effect = 25 ms, $t[22] = 1.87$, $p < .05$, one sided) as for green (cueing effect = 23 ms, $t[22] = 3.12$, $p < .05$) and yellow cues (cueing effect = 23 ms, $t[22] = 1.93$, $p < .05$, one sided), although linear separability should have allowed to ignore the blue cues better than the green or yellow cues.

However, the size of the capture effect could be misleading: if some participants showed higher individual sensitivities for blue and red than green (or for blue and green than red), such differences could have camouflaged stronger capture by dissimilar green (or red) cues. To address this possibility, individual cueing effects by target-different red and green cues were correlated with cueing effects by target-same yellow cues. If participants searched for yellow by tuning attention away from green and towards redd(er), then capture by yellow cues should be negatively correlated with capture by target-different green

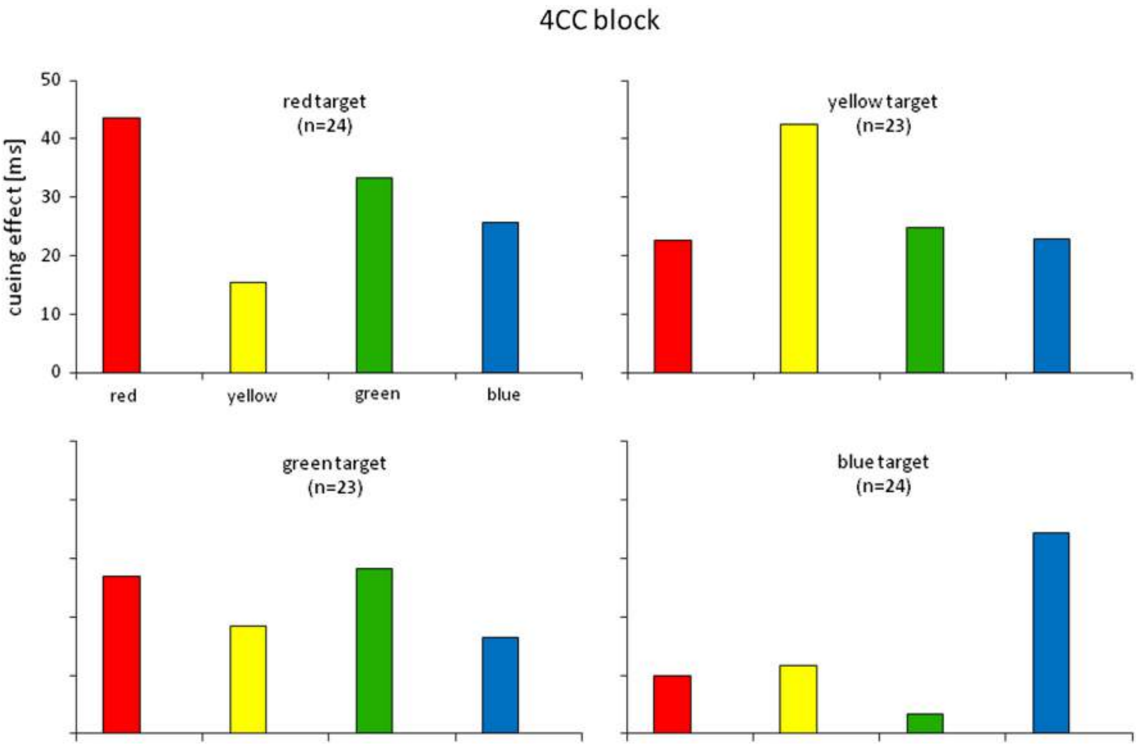

Fig. 6 Mean cueing effects in correct reaction times (RT [DP] − SP [RT]) of the 4CC (one target color, four cue colors) blocks on the *y*-axis, as a function of the cue color (red, yellow, green, and blue) on the *x*-axis, and of target color (*different panels* with decreasing target wavelength from *upper right* to *lower left*). *N* gives the number of participants contributing to a particular cueing effect. As can be seen, cueing effects were strongest for the target-similar cues, but again the similar and dissimilar cueing effect differences were mitigated in the green-target conditions (color figure online)

cues but positively correlated with capture by target-different red cues. In turn, if the yellow target was found by tuning attention away from red and towards green(er), the opposite was expected: capture by yellow and red should be negatively correlated, and capture by yellow and green should be positively correlated.

The results from the correlation analyses were in line with the former possibility: capture by yellow and green cues was (non-significantly) negatively correlated, $r(23) = -.13$, $p = .55$, while capture by yellow and red cues was at the same time significantly positively correlated, $r(23) = .44$, $p < .05$. (The correlation between yellow and blue cue capture was small, $r[23] = .20$, $p = .37$.)

Relational search and the wavelength model

If we assume that relational search of tuning into a particular direction is based on a wavelength principle that allows disregarding a maximum of the irrelevant cues, the relational search principle would predict more capture by red than green and blue cues in the yellow-target conditions. It was therefore also not supported by the ANOVA of the yellow-target conditions and it was also (partly) supported by the correlations between the capture effects in yellow-target conditions. In the correlations of the 4CC block with yellow targets, however, at odds with a relational search selecting yellow and red as above and ignoring green and blue as below the reference, no negative correlation between capture by blue and yellow cues was found (see above), although blue was also below the hypothetical reference.

In addition, the relational search model makes related predictions for the 4CC blocks with green targets (i.e., green and blue cues should capture, whereas the longer wavelength-colors yellow and red cues should not capture) that were not fully confirmed. In an ANOVA of these conditions, with the within-participant variables cue-target positions, and target-different cue color (blue, yellow, and red), we again observed significant attentional capture, $F(1, 22) = 12.76$, $p < .01$, partial $\eta^2 = .16$. RT was lower in SP (RT = 543 ms) than in DP conditions (RT = 564 ms). This cueing effect again did not interact with the target-different cue's color (interaction of cue color × cue-target positions: $F < 1.00$). The cueing effect was found with blue cues (cueing effect = 27 ms, $t[22] = 2.26$, $p < .05$), red cues (cueing effect = 17 ms, $t[22] = 1.84$, $p < .05$, one sided), and (marginally significant) with yellow cues (cueing effect = 19 ms, $t[22] = 1.67$, $p = .05$, one sided).

This is at odds with relational search if we assume that the choice of the relational search criterion was rational and prevented capture by red and yellow cues (and was only exceeded by relevant green and target-different blue cues, see Fig. 3).

Rational relational search also predicted positive correlations between capture by relevant green and target-different blue cues, plus negative correlations between capture by relevant green and target-different red and yellow cues (see Fig. 3, 3rd panel from left). These predictions were clearly falsified, too. There were predicted non-significant negative correlations of capture by green and yellow cues ($r[23] = -.34$, $p < .05$, one sided) and positive correlations by green and blue cues ($r[23] = .15$, $p = .49$), but the only significant correlation was unpredicted and positive between capture by green and red cues ($r[23] = .41$, $p < .05$, one sided).

Discussion

The present experiment demonstrates that attentional capture by irrelevant colors is (to a degree) determined by top-down task sets: cues similar to the currently relevant target-color template produced stronger cueing effects. With the exception of green targets, this was found regardless of cue or target color used. This compares to cues that were different from the currently relevant color template that produced smaller, still significant cueing effects. The overall cueing effect of target-different cues probably reflected bottom-up capture of attention by color contrasts (cf. Theeuwes, 1992) or by (unique) abrupt onsets (Yantis & Hillstrom, 1994), but the results also suggested that it was particularly difficult for the participants to selectively search for green (or set against red, blue and yellow). However, with the exception of the green-target condition, clearly participants more successfully ignored these cues than the target-similar cues.

With respect to the underlying responsible mechanism our data were clear: the results supported a feature-based template as being responsible for top-down control. The feature-based template would respond most to a searched-for color and the colors resembling this template, and, roughly, the template would equally disfavor capture by all different (non-template) colors. In contrast, the four-channel principle, the linear-separability model, and the wavelength model of the relational search principle were hardly supported by the present experiment. Whether adjacent cue colors in wavelength space were or were not used, whether or not the cues were linearly separable, and whether or not all color cues could be ignored by the same wavelength criterion (as was the case in all 2CC blocks and in the 4CC blocks with color targets of maximal [red] and minimal [blue] wavelength) were without significant or without the predicted effect for the capture by dissimilar color cues.

However, the linear separability principle and the wavelength model of relational search were partly supported by correlations between cueing effects of relevant and target-different color cues: we found that green cues were ignored and their capture negatively correlated with that of target-similar yellow cues when attentional capture by target-similar yellow and target-different red cues was correlated.

Our finding that cueing is not affected by the adjacency of colors and by the relational color or wavelength search principle shows that principles such as four-channel coding, linear separability and relational search cannot be extended to explain capture by colors from different color categories (e.g., Becker et al., 2010). However, the color search principles that we tested and falsified in the current study were originally all supported by results with concomitant distractors and target in visual search displays. In contrast, in the present cueing experiment, the distractor as a cue and the target were presented in succession. It is therefore possible that color search mechanisms, such as relational search, need to be reinforced by their utility during selection of concomitant targets or singletons among relatively similar to-be-ignored distractors. With respect to the linear separability principle, for example, prior research already suggested that irrelevant colors which are sufficiently distinct from the relevant target colors can be successfully ignored even under non-linearly separable conditions (cf. Bauer et al., 1998). The present study extends these findings, by showing that the four-channel principle and a relational principle based on different color wavelengths similarly both fail to provide a true account about how colors from different color categories are related to one another.

In any case, the present study showed that top-down contingent capture based on searched-for colors was all in all possible. In this respect, feature-based top-down contingent capture by colors appears more robust than the alternative refined top-down search principles for color that we have discussed. The reason for this could be the larger utility of color-based templates. In many situations, a target with a known feature (e.g., the fruit orange) has to be found in a color-variegated environment in which no single criterion allows disregarding all irrelevant distractor colors at once. During search for an orange in a fruit basket, for example, the observers might have to ignore both red apples and yellow plums. Feature search would allow this kind of visual selection but relational search criteria, for example, would not solve this problem. Recent research suggested that under these conditions, participants use a feature search rather than a relational search mode (Harris, Remington, & Becker, 2013). Second and related, it is often easy to anticipate relevant features of searched-for targets but more difficult to envisage the difference between target feature and irrelevant distractors. For example, if in a foreign city, looking for a letter box as blue helps finding the target (in the US). However, because an observer does not know the colors of the letter box's surround an offline or advance specification of top-down relational search criteria would be difficult.

In principle, our data were thus in line with the conclusions of studies like that of Irons et al. (2012). Irons et al. observed that participants are able to successfully ignore an irrelevant cue even in the difficult situation where there are two target colors and the target-different cue's color lies in-between these target colors. This finding of a strong influence of top-down control resonates with our observation that the capture elicited by target-similar cues trumped attention capture by any target-different color cue, with the exception of the situation where the participants searched for a green target. Yet, whereas Irons et al. (2012) did not find any capture by the target-different cues, we did so. One major difference between the studies was the cue-target SOA. With 68 ms, our SOA was much shorter than the 200-ms SOA of Irons et al. (or that of Worschech & Ansorge, 2012), and thus less deallocation after initial capture was possible in the present study as compared to Irons et al. (see also the discussion in Grubert & Eimer, 2013).

However, in search for green targets we failed to find clear evidence of top-down contingent capture. Instead, both target-similar and target-different cues captured attention. Prior research also showed that if participants searched for a green target attention capture by red could not be suppressed (Fortier-Gauthier, Dell'Acqua, & Jolicœur, 2013). Fortier-Gauthier et al. attributed their effect to the alerting function of red. This interpretation, however, would not be supported by the present study because our participants successfully ignored red cues when searching for yellow and blue targets. Jointly, the findings thus point to a weaker top-down control in search for green. Maybe the green channel is the least selective. Spectral absorption curves of the retinal M ('green') photoreceptors show a larger overall overlap with spectral sensitivity of the neighboring photoreceptors than L ('red') and S ('blue') cones.

One limitation of the present study is that capture effects may not have been due to top-down tuning but to automatic feature priming effects: the target-colored cue may have captured more than the target-dissimilar cues because attention was automatically primed (or biased) to this color by virtue of selecting the target color on the previous, $n - 1$ trial (Awh, Belopolsky, & Theeuwes, 2012; Becker, 2007, 2010b; Becker, Ansorge, & Horstmann, 2009; Maljkovic & Nakayama, 1994). In the present study, it is impossible to rule this out because for each participant the target color was always the same.

This limitation, however, does not call into question the top-down influence altogether because inter-trial priming itself depends on top-down settings: priming of capture is restricted to the relevant colors in the top-down set (cf. Ansorge & Becker, 2012; Ansorge & Horstmann, 2007; Folk & Remington, 2008). This is demonstrated by the fact that priming of singleton colors outside the set decreases the capture effect: when a singleton with a target-different color repeats, capture by this singleton is more efficiently suppressed (cf. Geyer, Krummenacher, & Müller, 2008; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). Töllner, Müller, and Zehetleitner (2012) showed that this reduced capture effect was reflected in the N2pc. Therefore, attention capture can only be primed with top-down relevant colors (see also Fecteau, 2007; Folk & Remington, 2008).

In addition, studies intermixing two target colors already ruled out inter-trial priming of capture as the only possible origin of the stronger capture effect of the target-similar cues (e.g., Irons et al., 2012). In these studies, the color of the top-down matching cue can be the same as the preceding target color (and was thus primed) or different from the preceding target color (and was unprimed). In this situation, the top-down matching cue captured more attention than the non-matching cue, even if the matching color was not inter-trial primed (Ansorge & Horstmann, 2007; Ansorge, Kiss, & Eimer, 2009; Becker et al., 2009; Irons et al., 2012; Worschech & Ansorge, 2012).

In conclusion, based on the present study and prior studies by Becker et al. (2010) as well as others (Navalpakkam & Itti, 2007; Torralba, Oliva, Castelhano, & Henderson, 2006), there seems to be more than one principle linking top-down control and attention. For example, many theories highlighted the importance of likely positions of objects in natural contexts (e.g., Eckstein, Drescher, & Shimozaki, 2006; Torralba et al., 2006), a factor that is mitigated in typical contingent capture research with randomized target positions. To detail the exact situations in which different mechanisms contribute to top-down search, with a focus on the differences and similarities between highly controlled experiments and ecological conditions (cf. Einhäuser, Spain, & Perona, 2008) will be a major research task of the near future.

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Appendix

See Table 1.

Table 1 Results of mixed-model ANOVAs of the meas corret reaction times (RTs) and of the error rates (ERs) as a function of the within-participant variables cue-target positions (SP vs. DP), block (2CC vs. 4CC) and cue-target color similarity (target-similar vs. target-different), and the between-participants variables target color (red, yellow, green, or blue) and dissimilar cue color in the 2CC block (red, yellow, green, or blue)

Variable/interaction	RTs		ERs	
	F	*p*	*F*	*p*
Cue color	1.37	.26	.72	.54
Target color	.29	.83	.75	.53
Cue color × target color	.67	.65	1.52	.29
Block	.01	.93	.01	.92
Block × cue color	.98	.41	.09	.96
Block × target color	1.78	.16	.13	.94
Block × cue color × target color	1.25	.30	.40	.85
Cue-target colors	.49	.49	1.04	.31
Cue-target colors × cue color	1.14	.34	.25	.86
Cue-target colors × target color	.96	.42	*3.23*	*.03*
Cue-target colors × cue color × target color	1.01	.42	1.38	.24
Cue-target positions	**74.23**	**<.01**	.82	.37
Cue-target positions × cue color	1.21	.31	1.18	.32
Cue-target positions × target color	.54	.66	1.11	.35
Cue-target positions × cue color × target color	.35	.88	1.30	.27
Block × cue-target colors	.58	.45	.01	.91
Block × cue-target colors × cue color	1.87	.14	.80	.50
Block × cue-target colors × target color	1.47	.23	1.54	.21
Block × cue-target colors × cue color × target color	1.11	.36	.62	.69
Block × cue-target positions	.01	.95	.11	.74
Block × cue-target positions × cue color	.40	.75	1.65	.18
Block × cue-target positions × target color	.41	.74	1.17	.33
Block × cue-target positions × target color × cue color	.52	.76	1.78	.13
Cue-target positions × cue-target colors	**16.21**	**<.01**	1.49	.23
Cue-target positions × cue-target colors × cue color	.43	.73	.57	.64
Cue-target positions × cue-target colors × target color	1.04	.38	.27	.85
Cue-target positions × cue-target colors × cue color × target color	.43	.83	1.68	.15
Block × cue-target positions × cue-target colors	*.48*	*.49*	*4.03*	*<.05*
Block × cue-target positions × cue-target colors × cue color	.54	.65	.71	.55
Block × cue-target positions × cue-target colors × target color	.43	.73	1.19	.32
Block × cue-target positions × cue-target colors × cue color × target color	.90	.31	.90	.48

Bold: significant in RT ANOVA, italics: significant in ER ANOVA

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