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Capture of attention by target-similar cues during dual-color search reflects reactive control among top-down selected attentional control settings

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Abstract

We investigated the origin of attention capture in the contingent-capture protocol during a search for two colors. When searching for the target color, cues similar to the target capture attention but cues dissimilar to the target do not capture attention. The results are typically explained by top-down contingent capture, a form of proactive control where participants set up attentional control settings (ACSs) for the target and cues matching the ACSs capture attention. However, based on recent research, we hypothesized that the situation could be more complicated during search for several features. Here, reactive control in the form of (cue) color-elicited selection of one of several separate pre-activated ACSs, one for each single searched-for feature, could contribute to performance. With the help of mixing and switch costs, we demonstrated that participants searched for two colors by separate pre-activated ACSs, and a closer inspection of the capture effects of the cues confirmed that reactive control contributed to ACS selection.

Keywords Mixing costs · Task switching · Contingent capture · Intertrial priming

Introduction

Is it possible to search for two features simultaneously (e.g., Chetverikov, Campana, & Kristjánsson, 2018) or is it necessary to always look for one feature only and change between features during a search for several features (e.g., Ort, Fahrenfort, & Olivers, 2017)? Ort et al. (2017) investigated this question and concluded that, under conditions of uncertainty about the target feature, *reactive control of attention* – that is, control over search imposed by the particular feature of the current stimulus, is achieved as search for a single feature at a time.

Here, we tested this possibility in the contingent-capture protocol, because reactive control could operate on top of the originally advocated proactive control principle of contingent capture. In a variant of contingent-capture experiments, participants search, for example, for red color-singleton

targets or for white onset-singleton targets (Folk, Remington, & Johnston, 1992). Under these conditions, capture by a nonpredictive cue is restricted to cues matching the top-down set of searched-for target features. Presenting cues either at target position (valid condition) or away from it (invalid condition), red color cues lead to validity effects (faster search times in valid than invalid conditions) during search for red targets, but not during search for onset targets, and the opposite pattern is found with onset cues. According to the contingent-capture explanation of these results, participants proactively set up attentional control settings (ACSs) to search for target features, and cues matching the ACSs capture attention toward target positions in valid but away from targets in invalid conditions. At the same time, participants ignore non-matching cues.

Contingent capture also seems to work with several to-be-searched-for features (e.g., Ansorge & Horstmann, 2007; Folk & Remington, 2008; Irons, Folk, & Remington, 2012). For example, during dual-color search for red and white targets, Ansorge and Horstmann (2007) found that red and white cues captured attention, but non-matching green cues did not. However, was this due to proactive control through the same unchanging ACS for both colors or by separate ACSs and reactive control? In the dual-color version of the contingent-

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capture protocol, participants cannot anticipate the next target with certainty. Therefore, as opposed to the contingent-capture theory, dual-color search would theoretically require reactive control and, hence, separate ACSs (cf. Ort et al., 2017). To be precise, even if participants proactively set up two task sets (here: ACSs) and hold them in working memory, they could select only one ACS at a time (cf. Yeung & Monsell, 2003) depending on the currently relevant stimulus.

To test if participants switched between separate ACSs in the dual-color contingent-capture protocol, we took two well-established criteria of dual-task performance: *switch costs* and *mixing costs* (Monsell, 2003). Switch costs are longer response times (RTs) for trial-by-trial switches than repetitions of a task (e.g., Monsell, 2003). In a dual-color contingent-capture protocol, trial-by-trial target-color changes should elicit switch costs if participants use two separate ACSs for the two different target colors but not if participants use a single joint ACS for the two colors. Mixing costs are slower responses for trial-by-trial task repetitions under dual- as compared to single-task conditions (e.g., Los, 1996). In the dual-color contingent-capture protocol, mixing costs by separate ACSs for different colors should lead to shorter RTs for trial-by-trial target-color repetitions during single-color blocks relative to the same trial-by-trial target-color repetitions during dual-color blocks.

In addition, we tested if top-down matching cues elicit ACS selection. If they do, top-down matching cues color-similar to the target of the same trial should facilitate search compared to top-down matching cues color-dissimilar to the following target because only the target-similar matching cue would allow selection of the finally required ACS. This was tested while looking at an alternative origin of stronger validity effects with matching than non-matching cues: The target in trial $n-1$ could prime capture of attention by a cue of the same color in trial n (Awh, Belopolsky, & Theeuwes, 2012). As priming of capture is only possible for matching cues resembling the target in $n-1$, but not for non-matching cues that are always dissimilar from the target in $n-1$, top-down matching cues could capture more attention due to intertrial priming rather than top-down contingent capture. The current dual-target blocks allowed testing if priming of capture accounted for the results by looking at validity effects of top-down matching cues (1) of the same color as the target in $n-1$ versus (2) of a different color than the target in $n-1$ (Folk & Remington, 2008). Importantly, in these analyses with the additional variable trial-by-trial target-color switch versus repetition, cue-elicited ACS selection should show up as an advantage for trials in which cues have the same color as the following target (cue-target color similar or CTS conditions) compared to trials in which cues have a color different from the following target (cue-target color dissimilar or CTD conditions) – that is, as an interaction of priming and target-color switch (see column 3 of Table 1), with faster responses for two CTS conditions, primed/target-color repetition and unprimed/target-color change

conditions, compared to two CTD conditions, unprimed/target-color repetition and primed/target-color switch conditions.

Methods

Participants

Seventy psychology students (39 female; M_{age} = 23.5 years, SD_{age} = 4.7) were tested in exchange for course credits. All reported normal color vision and normal or corrected-to-normal visual acuity. Informed consent was obtained from all participants. One participant aborted the experiment. Another was excluded due to an error rate (ER) exceeding mean ERs by two SDs.

Apparatus

Stimuli were presented on LCD monitors, with a vertical refresh rate of 60 Hz. Viewing distance was 57 cm. Responses were given via a conventional QWERTZ-keyboard. Stimulus presentation and response collection was managed by OpenSesame (Mathôt, Schreij, & Theeuwes, 2012).

Stimuli

Stimuli were presented against a black background. During fixation, inter-stimulus interval (ISI), and response display, a gray fixation cross (0.6° × 0.6°) was displayed. Additionally, four gray circles (outline width: 0.1°; radius: 1.2°) were shown as placeholders at 2.7° eccentricity at the corners of an imaginary square centered on the screen. In cue and target displays, outlines of placeholders increased to 0.3°. During the cue display, one of the circles was a color singleton, with a color matching or non-matching the ACSs. In the dual-color block, cues were equally likely to be matching or non-matching the ACS(s) (for red and green). In the single-color block, depending on the target color, cues were either always red or always green on half of the trials or non-matching (blue) the ACS on the other half of the trials.

In the target display, the non-singleton color target was equally likely green or red (in the dual-color block), or always either red or always green (in the single-color blocks). To prevent participants searching for singletons and to enforce target color search, two non-target circles in the target display were yellow and one non-target circle was equally likely to be magenta or cyan. The used colors were equally bright (L = 70 in L*ab color space) red (CIE coordinates: x = .65, y = .34), green (.28, .59), blue (.14, .07), cyan (.21, .33), magenta (.33, .17), yellow (.43, .50), and gray (.31, .33).

Furthermore, each of the four colored circles contained a white 90° left- or right-tilted T (0.5° × 0.4°) at its center.

Procedure

Participants reported the orientation of the *T* within the target-color circle via a button press (key *y* for left- and *m* for right-tilted). Each trial (see Fig. 1) started with a fixation display (1,500 ms), followed by the cue display (50 ms), the cue-target interval (100 ms; identical to the fixation display), the target display (150 ms), and a response display (for 2 s; also identical to the fixation display).

Wrong answers and response times exceeding 1,200 ms prompted the feedback (500 ms) "Falsch" ("Wrong") and "Schneller antworten!" ("Respond faster!"), respectively. Participants responded as quickly and accurately as possible while fixating the cross at the center. We allowed self-paced breaks every 120 trials. See the online publication for the color version of this figure.

Design

Target conditions (single-color or dual-color) were blocked and ordered A – B – A – B or B – A – B – A, balanced across participants. All remaining conditions were pseudo-randomized within blocks. Blocks consisted of 24 practice and 240 data-collection trials (960 data-collection trials in total). Cue- and target-positions were uncorrelated, leading to 25% valid and 75% invalid trials. Participants were informed about this relationship prior to the experiment and asked to ignore the cues.

Results

Response times

RTs deviating more than 2.5 *SD*s from individuals' means were excluded (2.6% of data). For RT analysis, only correct trials were used. To avoid effects of location priming (e.g., Campana & Casco, 2009), we excluded trials in which cues were at the same location as targets in a preceding trial. All reported *p*-values are Bonferroni-adjusted.

Mixing costs Mixing costs were calculated as mean correct RTs to trial-by-trial target-color repetitions in dual-color blocks minus mean correct RTs in single-color blocks. For this analysis, we selected only trials from dual-color blocks in which the cues were of the same color as the targets (as this was also the case in single-color blocks). RTs in target-color repetition trials were 24 ms longer than corresponding trials in single-color blocks, $t(67) = 5.26$, $p < .001$, $d = 0.37$, indicating mixing costs.

Switch costs Switch costs were calculated (for dual-color blocks only) as mean correct RTs following trial-by-trial target-color switches minus mean correct RTs following trial-by-trial target-color repetitions. In dual-color blocks, responses to trial-by-trial color switches were 14 ms longer than to trial-by-trial color repetitions, $t(67) = 7.35$, $p < .001$, $d = 0.21$, reflecting switch costs.
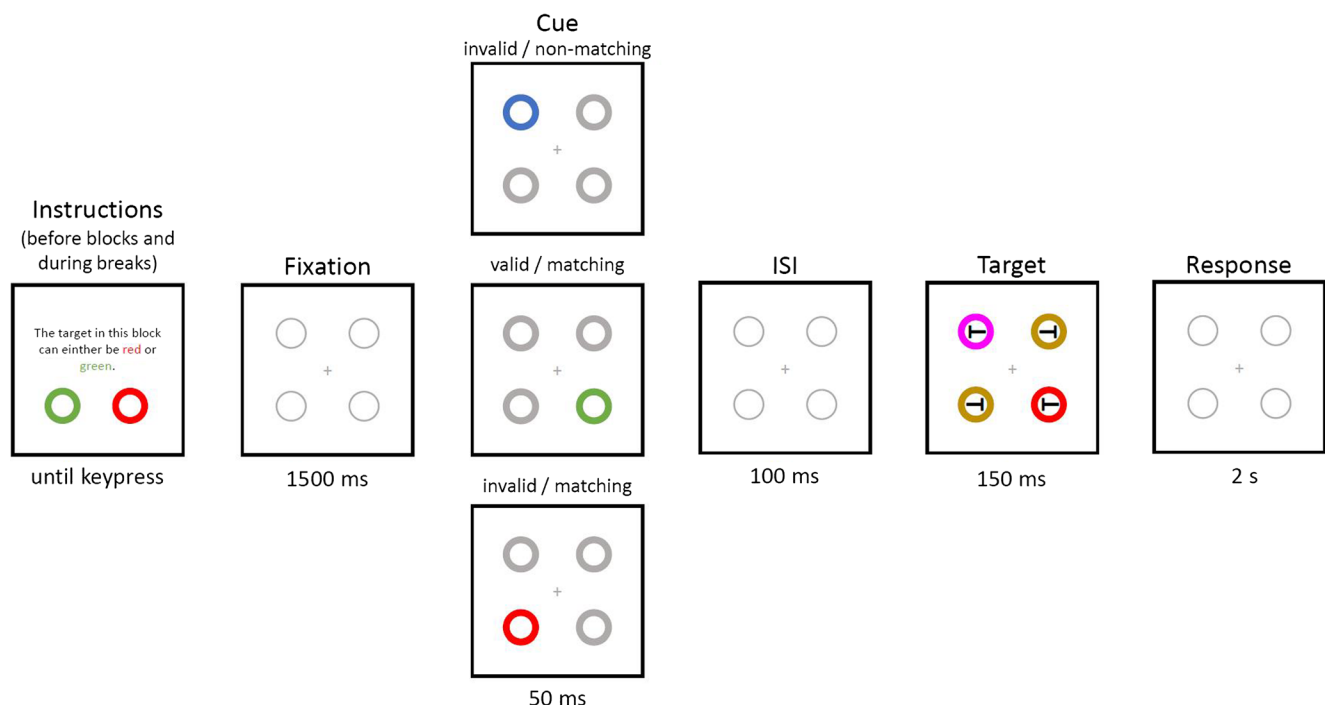

Fig. 1 Exemplary trial from a dual-color block. A cue matching participants' ACSs was presented in 50% of the trials, while a non-matching cue was presented in the other 50%. The cue was on average uninformative regarding the target location

Table 1 Mean response times (*SD*s) per condition. Whether there was cue-target color similarity (CTS) or dissimilarity (CTD) between cue and target in the same trial (column 3) was determined by the combination of the levels of the variables *intertrial priming* (column 2) and *trial-by-trial target-color switch* (column 1). See the online publication for the color version of this figure

Target-Color Switch: n − 1 target color = n-target color?	Inter-Trial Priming: n − 1 target color = n-cue color?	Cue-Target Color Similarity: n-cue color = n-target color?	valid	invalid	p	Exemplary sequences of target-display in trial n − 1, cue-display in trial n, and target-display in trial n (f.l.t.r.)
Yes	Yes	Yes (CTS)	422 (84)	451 (70)	<.001	
Yes	No	No (CTD)	484 (84)	495 (69)	.39	
No	Yes	No (CTD)	508 (93)	523 (82)	.19	
No	No	Yes (CTS)	431 (78)	464 (70)	<.001	

Dual-color blocks[1] We computed a repeated-measurements analysis of variance (ANOVA), with *validity* (valid vs. invalid), *top-down match* (matching vs. non-matching), and whether or not a trial was a *trial-by-trial target color-switch* trial (repetitions: target color in $n − 1$ = target color in n; switches: target color in $n − 1 \neq$ target color in n) as independent within-participant variables. The ANOVA yielded a significant effect of *trial-by-trial target color-switch/repetition*, $F(1, 67) = 31.29$ $p < .001$, $\eta_p^2 = .32$, with 14-ms faster responses to target-color repetitions than switches. Furthermore, the two-way interaction between *top-down match* and *validity* was significant, $F(1, 67) = 125.00$, $p < .001$, $\eta_p^2 = .65$. Paired *t*-tests indicated a contingent-capture effect: a significant validity effect for top-down matching cues of 23 ms, $t(67) = 6.51$, $p < .001$, $d = 0.35$, and a lower (here: inverted) validity effect for non-matching cues of 26-ms faster RTs in invalid

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[1] Besides for the calculation of mixing costs, single-color blocks were of no further interest in the present study, but they showed contingent-capture effects in both mean correct RTs, $F(1, 67) = 266.05$, $p < .001$, $\eta_p^2 = .8$ (matching/valid RTs minus matching/invalid RTs = 51 ms, $t[67] = 13.05$, $p < .001$, $d = 0.83$; non-matching/valid RTs minus non-matching/invalid RTs = − 20 ms, $t[67] = 8.47$, $p < .001$, $d = − 0.22$) and arc-sine transformed ERs, $F(1, 67) = 43.22$, $p < .001$, $\eta_p^2 = .39$, where more errors were made in invalid (10.1%) than in valid (8.5%) trials, but where validity was only significant for matching, $t(67) = 8.37$, $p < .001$, $d = 0.46$, and not for non-matching trials, $t(67) = 1.65$, $p = .2$).

than valid trials, $t(67) = 7.89$, $p < .001$, $d = -0.39$; $t(67) = 10.36$, $p < .001$, $d = 1.74$, for the difference between validity effects. In addition, the two-way interaction between *top-down match* and *trial-by-trial target color-switch* was significant, $F(1, 67) = 7.53$, $p = .008$, $\eta_p^2 = .1$. This reflected higher switch costs (RT difference of 18 ms) when the cue in trial *n* was non-matching, $t(67) = 6.8$, $p < .001$, $d = 0.27$, compared to when it was matching (RT difference of 9 ms), $t(67) = 3.6$, $p < .01$, $d = 0.14$; $t(67) = 2.5$, $p = .014$, $d = 0.42$ for the switch-cost difference.

Intertrial priming of capture Only trials with matching cues were entered into an additional repeated-measurements ANOVA, with the variables *validity* (valid vs. invalid), *intertrial priming of cue color* (i.e., primed: target color in *n* − 1 = cue color in *n* vs. unprimed: target color in *n* − 1 ≠ cue color in *n*), and *trial-by-trial target-color switch* (repetition: target color in *n* − 1 = target color in *n* vs. switch: target color in *n* − 1 ≠ target color in *n*). In this analysis, cue-target color similarity within a trial (CTS) was given for primed/repetition and unprimed/switch conditions, while cue-target color dissimilarity (CTD) within a trial was realized in primed/switch and unprimed/repetition conditions (see Table 1). There was a significant effect of *validity*, $F(1, 67) = 32.43$, $p < .001$, $\eta_p^2 = .33$, reflecting 23-ms shorter RTs in valid than invalid conditions. The effect of *trial-by-trial target-color switch* was also significant, $F(1, 67) = 40.8$, $p < .001$, $\eta_p^2 = .38$, due to 9-ms shorter RTs in target-color repetition than switch trials. A significant interaction between *intertrial priming* and *trial-by-trial target-color switch*, $F(1, 67) = 201.45$, $p < .001$, $\eta_p^2 = .75$, indicated that cue color signaled an updating of different ACSs for different colors (see column 3 of Table 1): Pairwise *t*-tests revealed that CTS or primed/repetition conditions facilitated RTs compared to CTD or unprimed/repetition conditions by 49 ms, $t(67) = 11$, $p < .001$, $d = 0.71$, and that CTS or unprimed/switch conditions were also 63 ms faster than CTD or primed/switch conditions, $t(67) = 10.13$, $p < .001$, $d = 0.86$. Finally, the three-way interaction between all variables was significant, $F(1, 67) = 8.82$, $p = .004$, $\eta_p^2 = .12$.

Pairwise *t*-tests revealed significant contributions of intertrial priming to validity effects in target-color repetition trials, where unprimed cues had a weaker, nonsignificant, validity effect (12 ms, $t[67] = 1.68$, $p = .39$, $d = 0.15$) than primed cues (29 ms, $t[67] = 4.48$, $p < .001$, $d = 0.38$). However, in target-color switch trials, validity effects for unprimed trials (33 ms, $t[67] = 5.09$, $p < .001$, $d = 0.44$) were not diminished compared to primed trials (15 ms, $t[67] = 2.01$, $p = .19$, $d = 0.17$; see Fig. 2), $t(67) = 1.97$, $p = .053$, for the difference between validity effects.

Error rates

Arcsine-transformed ERs were entered as the dependent variable into a similar repeated-measurements ANOVA as RTs.

Mixing costs We found no mixing costs in ERs ($p = .54$).

Switch costs Participants made more errors in target-color switch trials than target-color repetition trials (15.4% vs. 14%, $t[67] = 3.15$, $p = .002$, $d = 0.23$).

Dual-color blocks[1] The ANOVA yielded main effects of *validity*, $F(1, 67) = 6.90$, $p = .011$, $\eta_p^2 = .09$, *top-down match*, $F(1, 67) = 82.92$, $p < .001$, $\eta_p^2 = .55$, and *trial-by-trial target-color switch*, $F(1, 67) = 16.06$, $p < .001$, $\eta_p^2 = .19$. Participants made fewer errors in valid than invalid trials (13.6% vs. 15.1%) and when cues matched the ACS(s) than when not (14% vs. 15.2%). Additionally, participants made fewer errors for target-color repetition than change trials (13.1% vs. 15.6%).

Furthermore, we observed a significant interaction between validity and match, $F(1, 67) = 48.46$, $p < .001$, $\eta_p^2 = .42$. This interaction reflected contingent capture: a significant positive validity effect on ERs in matching trials (valid: 11.9% vs. invalid: 15.9%, $t[67] = 6.33$, $p < .001$, $d = 0.65$) and the reverse pattern in non-matching trials, with more errors in valid than in invalid trials (valid: 17.7% vs. invalid: 12.8%, $t[67] = 3.54$, $p = .001$, $d = 0.32$). All other ps > .16.
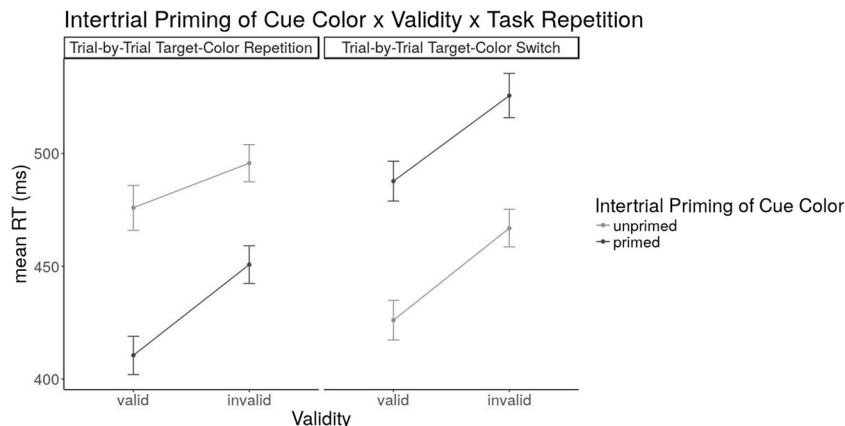

Fig. 2 Interaction between intertrial priming of cue color, validity, and trial-by-trial target-color switch. Error bars represent *SE*s

Intertrial priming of capture To investigate effects of intertrial color priming, we conducted an ANOVA on matching trials only. We found a significant validity effect, $F(1, 67) = 54.15$, $p < .001$, $\eta_p^2 = .45$, due to more errors in invalid (16.4%) than valid (11.9%) trials. *Trial-by-trial target-color switch* interacted with *intertrial color priming*, $F(1, 67) = 49.92$, $p < .001$, $\eta_p^2 = .43$. Participants made fewer errors on target-color repetition trials compared to switch trials when a cue was primed by the target-color in trial $n - 1$, (10.7% vs. 18.4%, respectively; $t[67] = 6.67$, $p < .001$, $d = 0.69$). However, when the cue was not primed by the target-color in trial $n - 1$, participants made more errors in repetition trials than in switch trials (11.9% vs. 15.8%; $t[67] = 6.67$, $p < .001$, $d = 0.39$).

Discussion

We tested whether participants searched for two colors simultaneously within one ACS or whether they switched between two separate ACSs. As a main finding, we observed mixing costs following trial-by-trial target-color repetitions in a dual-color target relative to a single-color target block, indicative of the use of different ACSs for different colors (cf. Monsell, 2003). One could argue that mixing costs reflected (1) the increased demands of keeping in mind two target colors rather than one or (2) cumulative priming by more frequent across-trial repetitions of target colors in single- than dual-color blocks (e.g., Maljkovic & Nakayama, 1994). With respect to the latter possibility, however, it is unclear if cumulative priming of target processing would generalize to (nonpredictive) cueing studies, as participants even suppress top-down matching color cues presented in-between successive targets to some extent (i.e., if invalid; Goller & Ansorge, 2015). Hence, cueing should have compromised cumulative target-color priming even in the present single-color blocks. In addition, we also found switch costs: A trial-by-trial change of target color in the dual-color blocks of the contingent-capture protocol delayed searching. Together, our results are in line with the notion of Ort et al. (2017) that if upcoming targets cannot be anticipated with certainty, reactive control applies, and only a single-color ACS was used at a time.

Our interpretations are also supported by the intertrial priming analysis of the matching conditions: If the cue indicated the correct ACS (i.e., in CTS, where n-cue color = n-target color; see column 3 of Table 1), the cue provided a net search advantage of 58 ms, $t(67) = 13.88$, $p < .001$, $d = 0.87$, relative to the conditions in which the cue indicated the incorrect ACS and the required ACS could only be selected following the target (i.e., in CTD, where n-cue color $\neq$ n-target color; see Table 1). Our results thus

also suggest a revision of the explanation of top-down search for several features in the dual-color contingent-capture protocol: On top of preceding top-down setting-up of ACSs, capture by matching cues during search for several features reflects reactive control–that is, stimulus-elicited selection of an ACS for a single feature.

In addition, we found evidence that intertrial priming of capture did not account for the validity effect, as capture by top-down matching cues was found in unprimed target-color switch trials. However, priming played a role as we found no effect of validity of unprimed cues during target-color repetition trials. To account for the different fate of the unprimed cues' validity effect in target-color switch versus repetition conditions, one should note that the unprimed cue would have activated the required correct ACS only in target-color switch trials. In contrast, in target-color repetition trials, the unprimed cue would have activated the incorrect ACS. The fact that the validity effect in the latter conditions was absent is therefore suggestive of active suppression of the cue following target onset and a second switch ("back") to the correct ACS. In general agreement with this sketched explanation, former research found evidence of active suppression of cues following target onset (Gaspelin, Ruthruff, & Lien, 2016). Importantly, in the current study such inhibition was successful only when intertrial priming of capture was absent demonstrating that priming was involved. This can be seen in comparison to the situation in which there was a like color-dissimilarity between cue and its following target but in which the cue was primed: In this target-color switch/primed condition, priming evidently prevented such successful post-target inhibition (see Table 1). Together, these dependencies of priming of capture on additional factors such as cue-target color similarity might hint at why intertrial priming of capture in contingent-capture studies cannot always be found (Lamy & Kristjánsson, 2013).

Conclusion

During a search for two colors, we found that cue-elicited ACS selection entails a spatial capture effect by top-down matching cues. This form of reactive control (Braver, 2012) seems to work on top of the originally proposed proactive control principle advocated in the contingent-capture account (Folk et al., 1992). However, proactive control is still a likely explanation during search for single features and proactive control also plays a role during a search for several features in the form of preloading of relevant colors into a "passive" visual working-memory representation following the instructions.

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