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Attentional Capture by Context Cues, Not Inhibition of Cue Singletons, Explains Same Location Costs

Josef G. Schönhammer
University of Geneva and University College London

Stefanie I. Becker
The University of Queensland

Dirk Kerzel
University of Geneva

Recent attentional capture studies with the spatial cueing paradigm often found that target-dissimilar precues resulted in longer RTs on valid than invalid cue trials. These same location costs were accompanied by a contralateral positivity over posterior electrodes from 200 to 300 ms, similar to a P_D component. Same location costs and the P_D have been linked to the inhibition of cues with a unique feature (singleton cues) that do not match the target feature. In some studies reporting same location costs, the cue was surrounded by other cues (i.e., the context cues) that matched the physical or relative feature of the target. We hypothesized that the context cues might have captured attention and might have elicited data patterns that mimicked the inhibitory effects. To disentangle inhibition of the singleton cue from capture by the context cues, we added gray cues to the cue array, which we considered neutral because gray matched neither the target nor the nontarget color. In four experiments, the results consistently showed that the context cues in the nonmatching cue condition captured attention, as reflected in shorter RTs compared to neutral cues and a substantial N2pc to lateralized context cues. By contrast, the evidence for inhibition of the singleton cue was rather weak. Therefore, same location costs and lateralized positivity in the event-related potential of participants in several recent studies probably reflected attentional capture by the context cues, not inhibition of the singleton cue.

Public Significance Statement

How do we select relevant information from cluttered visual scenes? Many studies suggest that attentional control mechanisms facilitate processing of relevant and inhibit processing of irrelevant information. Several recent studies found evidence that supports the inhibition of irrelevant information. This study shows, however, that in a subset of these studies the findings are more likely associated with facilitation of context information than with inhibition.

Keywords: visual attention, attentional capture, contingent attentional capture, spatial cueing, visual search

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Natural visual environments usually contain more objects than our senses can consciously process at a single moment (Tsotsos, Rothenstein, Simine, & Zaharescu, 2012). Visual selective attention allows us to find target objects in such scenes when only their features (e.g., color, shape, etc.) are known, but not their spatial locations. Current theories of visual attention propose that attention can be guided by bottom-up, stimulus-driven processes and top-down, goal-driven processes (reviewed by Eimer, 2014; Gaspelin & Luck, 2018b). According to these theories, attention is bottom-up biased to features that strongly differ from the surrounding stimuli (Itti, Koch, & Niebur, 1998; Niebur & Koch, 1996). Moreover, attention is top-down biased to features that match the internal representation of the target features (Folk, Remington, & Johnston, 1992). The bottom-up and top-down biases are combined and spatial attention is first allocated to the item with the largest bias, which is then compared to the internal representation of the target (Carlisle, Arita, Pardo, & Woodman, 2011).

Importantly, recent studies showed that a top-down bias can also decrease the attention-driving capacity of items with nontarget features (Andersen & Müller, 2010; Zhang & Luck, 2009), and that inhibition can be deployed to these items in a spatially focused

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Josef G. Schönhammer, Faculty of Psychology and Education Sciences, University of Geneva, and Institute of Cognitive Neuroscience, University College London; Stefanie I. Becker, School of Psychology, The University of Queensland; Dirk Kerzel, Faculty of Psychology and Education Sciences, University of Geneva.

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Correspondence concerning this article should be addressed to Josef G. Schönhammer, Faculté de Psychologie et des Sciences de l'Éducation, Université de Genève, 40 Boulevard du Pont d'Arve, CH - 1205 Genève, Switzerland. E-mail: j.schoenhammer@ucl.ac.uk

manner (Gaspar & McDonald, 2014; Gaspelin, Leonard, & Luck, 2015; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006). Similarly, several studies that used spatial cueing paradigms revealed effects that would be consistent with inhibition of items with the nontarget feature.[1] These studies used behavioral (Becker, Harris, York, & Choi, 2017; Harris, Remington, & Becker, 2013; Kiss & Eimer, 2011; Schoeberl, Ditye, & Ansorge, 2018; Schönhammer, Becker, & Kerzel, 2017) and electrophysiological measures (Lien, Ruthruff, & Cornett, 2010; Schönhammer, Grubert, Kerzel, & Becker, 2016). However, as described below, the results of some of these studies are also consistent with an attentional capture by the *context items*.

Attentional Biases to Physical or Relative Features

Several different mechanisms have been proposed to explain how attention is top-down tuned to the target feature. According to a *feature similarity-gain* principle, attention is usually tuned to the exact target feature value in visual search (Bravo & Nakayama, 1992; Duncan & Humphreys, 1989; Treue & Martínez Trujillo, 1999). For instance, in search for a yellow-green target, attention is tuned to yellow-green. That is, the strongest top-down weight is assigned to the exact feature value of the target, and weights decrease with decreasing similarity to the target feature. Consequently, items that match the physical target feature should have the highest attention-driving capacity and should attract attention most strongly.

Contrary to this popular account, it has been shown that attention is often tuned to the relative target feature. This is the feature of an item in relation to the features of the context (Becker, 2008, 2010; Becker, Folk, & Remington, 2010, 2013). According to the *relational account*, the visual system evaluates the relationship between the features of the target and the dominant feature in the surround, and biases attention to the relative target feature. Possibly, tuning to relative features makes selection less susceptible to random fluctuations in feature values that occur in natural environments because of changes in brightness, distance, and perspective. Critically, the relational account predicts that stimuli with absolute features that differ from the target feature may attract attention if they share the target's relative feature.

Several studies tested the relational account against other feature-based theories of attention using Folk et al.'s (1992) modified spatial cueing paradigm (Becker et al., 2010, 2013; Becker et al., 2017; Harris et al., 2013; Schoeberl et al., 2018; Schönhammer et al., 2017; Schönhammer et al., 2016). In the modified spatial cueing paradigm, the cue display precedes the target display by about 150 ms and both displays are only briefly presented for about 50 ms. The cue location is spatially nonpredictive of the target location. Attentional capture by the cue is measured by a spatial validity effect, with faster response times (RTs) when the cue is presented at the same location as the target than when it is presented at a different location (valid vs. invalid trials; Folk & Remington, 1998; Jonides, 1981). In the variant of the spatial cueing paradigm that is of interest here, cue and target have a unique feature compared to the surrounding stimuli. In other words, cue and target are feature singletons (Folk & Remington, 1998). The stimuli surrounding the cue are referred to as cue context, whereas the stimuli surrounding the target are referred to as nontargets.

In one study, Becker et al. (2013) distinguished between the relational account and other feature-based theories by systematically varying the color of the singleton cue and the color of the context cues. According to the relational account, cues that share the target–nontarget relation with respect to the context cues should attract attention, irrespective of the physical color. While Becker et al.'s (2013) experiments were run on orange targets, we illustrate their findings with the colors of the current study. As shown in Figure 1A, the color relation among green, yellow-green, and yellow is "yellower." For instance, when a yellow-green target is presented among green nontargets, it is perceived as "yellower." Accordingly, a yellow-green critical cue among green context cues captures attention because both the color relation and the physical color match the target (Condition 1 in Figure 1B). In addition, a yellow critical cue with yellow-green context cues captures attention even though the physical color of the critical cue does not match the target (Condition 2 in Figure 1B). According to the relational account, capture with physically nonmatching colors may occur if the relative features match ("yellower"). In contrast, even physically matching cues may fail to capture attention if the relation between critical cue and context cues does not match the relation between target and nontargets. For instance, the yellow-green critical cue in Condition 3 of Figure 1B has the same color as the target, but is shown with yellow context cues. Therefore, the relation between critical cue and context cues ("greener") is opposite to the relation between target and nontargets ("yellower"). As a result, the critical cue fails to capture attention (Becker et al., 2013). Finally, inverting the color relation eliminates capture because the critical cue is both physically and relatively nonmatching. For instance, a green critical cue with yellow-green context cues has the opposite color relation and is physically nonmatching compared to a yellow-green target with green nontargets (see Condition 4 in Figure 1B).

A subsequent study used a similar paradigm and assessed event-related potentials (ERPs) in addition to validity effects (Schönhammer et al., 2016). In particular, the N2pc and P_D components were of interest. The N2pc is a negativity over posterior electrodes PO7/PO8 contralateral to candidate target objects about 175–300 ms after stimulus onset (therefore the acronym, as it appears in the time range of the second negative going deflection of the visual ERP, and at posterior electrodes contralateral to a candidate target object). The N2pc is thought to reflect attentional selection (Eimer, 1996, 2014; Jannati, Gaspar, & McDonald, 2013; Luck, 2012; Luck & Hillyard, 1994b) or the transient enhancement at the focus of attention to promote high-level processing (Zivony, Allon, Luria, & Lamy, 2018). In line with validity effects, the results showed a significant N2pc to cues that matched the relative color of the target, regardless of physical color. In contrast, there was no N2pc to cues that physically matched the target but had the opposite relative color.

Interestingly, several studies reported that nonmatching singleton cues resulted in same location costs. That is, RTs were slower on valid than invalid trials. In some studies, same location costs occurred irrespective of the match of the physical features (Becker et al., 2017; Harris et al., 2013, Experiment 1; Schoeberl et al.,

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[1] Note that target or nontarget *feature* refers to physical and relative features. These terms are defined below.

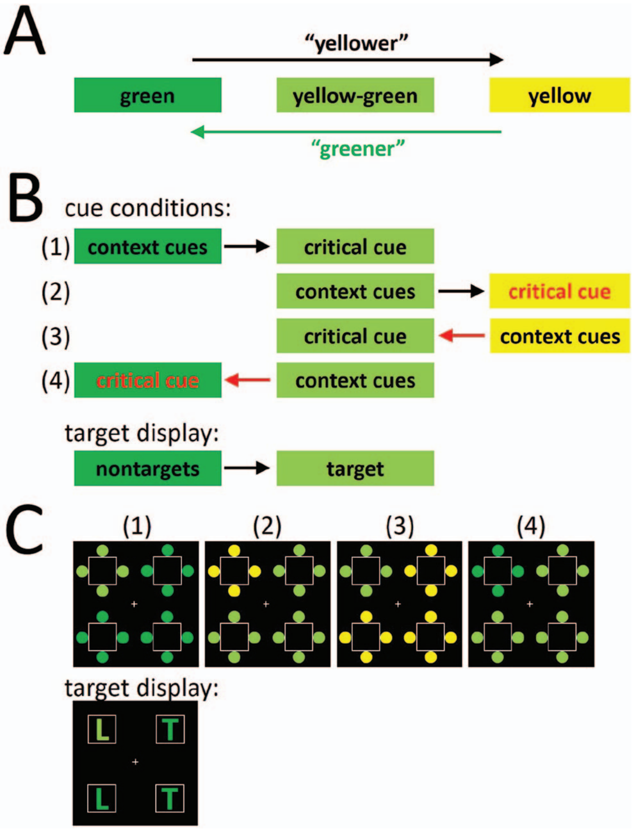

Figure 1. Illustration of experimental colors and conditions. (A) Colors and color relations used in the experiments. (B) Illustration of the four cue conditions when the target color was yellow-green and the target–nontarget relation was "yellower." Physically or relatively nonmatching conditions are in red (leftward pointing arrows). Critical cues in Conditions 1 and 2 were relatively matching with respect to the target–nontarget relation ("yellower"), whereas Conditions 3 and 4 were relatively nonmatching ("greener"). Cues in Conditions 1 and 3 were physically matching relative to the target color (yellow-green), whereas Conditions 2 and 4 were nonmatching (yellow and green, respectively). (C) The cue Conditions 1–4 and the "yellower" target display are illustrated. See the online article for the color version of this figure.

2018). In other studies, same location costs were only observed with physically and relatively nonmatching cues, that is, when the critical cue and context cues inverted the target and nontarget colors (Schönhammer et al., 2016). Notably, the same location cost in the latter case was accompanied by a positivity contralateral to the cue, which could be a cue-related P_D (see Kiss & Eimer, 2011; Lien et al., 2010). The P_D occurs at the same electrodes and in the same time window as the N2pc but has the opposite polarity. Because the P_D has been linked to inhibition of irrelevant items (therefore the acronym, as it is understood as positivity to a distractor; Hickey et al., 2009; Sawaki & Luck, 2013). Therefore, it is possible that the nonmatching cue was suppressed. However, the P_D to the cue is indistinguishable from an N2pc to the opposite side, because a positivity contralateral to the critical cue is equivalent to a negativity contralateral to the context cues on the other side. Thus, the P_D to the critical cue may in fact be an N2pc to the context cues on the opposite side (Kerzel & Burra, 2020).

Correspondingly, two different explanations were proposed to explain the same location cost and the positivity contralateral to singleton cues. First, according to a *cue inhibition account*, nonmatching singleton cues might have been inhibited (Gaspelin & Luck, 2018b; Schönhammer et al., 2016). In this case, the positivity contralateral to the cue was in fact a P_D to the cue, as originally assumed. According to Navalpakkam and Itti (2007), top-down weights for particular feature values are set depending on the target and nontarget features. Critically, when target and nontarget features are very similar, nontarget features may be suppressed below baseline level to improve the ratio of target to nontarget signals. Empirically, it was observed that identification of letter stimuli at distractor locations was worse than letter identification at nonsalient nontarget locations, confirming that salient distractors were inhibited (Gaspelin et al., 2015; Gaspelin & Luck, 2018a).

Alternatively, according to a *context capture account*, the context cues, or a subset of these, might capture attention because the context cues in these displays matched the relative target color (Becker et al., 2017; Harris et al., 2013; Schönhammer et al., 2016; also see Lien et al., 2010). According to this *context capture account*, the positivity to the critical cue should be interpreted as a negativity to the contextual cues on the opposite side. As the majority of context cues appeared in the visual hemifield opposite to that of the singleton cue, the correct interpretation of the positivity to the cue is in fact an N2pc to the context cues. In line with this suggestion, previous studies have shown that nonsingleton items with the target color can capture attention (Lamy, Leber, & Egeth, 2004; Schoeberl, Goller, & Ansorge, 2019). Furthermore, it should be noted that same location costs were also observed when the target was shown in a heterogeneous display that required feature search because the target was not a singleton (Carmel & Lamy, 2014; Kerzel, 2019; Schoeberl et al., 2019). Same location costs with nonsingleton displays have alternatively been ascribed to the cost of updating the target's object file on valid trials (Carmel & Lamy, 2014; but see Schoeberl et al., 2018) or increases in attentional selectivity that promote inhibition (Kerzel, 2019). As the present study used singleton displays, these explanations may not apply.

The Present Study

The central aim of the present study was to distinguish between the cue inhibition account and the context capture account. To examine the observed same location costs, we slightly modified the stimuli from previous studies (Becker et al., 2017; Harris et al., 2013; Schönhammer et al., 2017; Schönhammer et al., 2016). As in previous studies, the target and nontargets had constant colors, allowing top-down tuning either to the specific target color or its relative color. Each cue array contained one uniquely colored critical cue and several context cues in a different color (see Figure 2, upper panel). The colors of the critical cue and the cue context were chosen so that the cue either matched or mismatched the physical or relative color of the target. Importantly, however, we added one achromatic gray cue element to each cue array, henceforth called *neutral cue*. The resulting three types of trials are illustrated in Figure 2, upper panel, with a presumed target in the upper left. On valid trials, the critical cue was shown at the target location. On invalid trials, a context cue was shown at the target

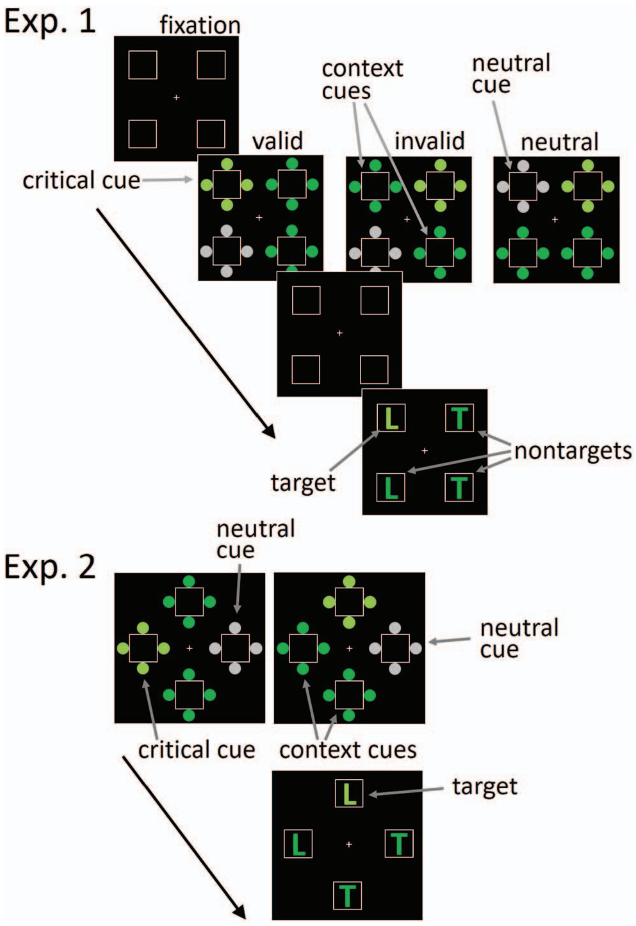

Figure 2. The upper panel shows the cue and target arrays in Experiment 1. On valid, invalid, or neutral trials, the stimulus shown at the target location was the critical cue, a contextual cue, or a neutral cue, respectively. The lower panel shows the stimulus arrays in Experiment 2. The critical cue or a context cue was shown on a lateral position and the neutral cue on the opposite side. See the online article for the color version of this figure.

location. On neutral trials, the neutral cue was shown at the target location.

Same location costs are expected when the relative color of the critical cue does not match the relative color of the target. If same location costs were due to inhibition of the critical cue, we would expect longer RTs on valid trials, where the target is preceded by the critical cue, than on neutral trials (neutral $<$ valid). The reason is that attentional suppression of the critical cue should make target processing less efficient. If same location costs were due to capture by the context cues, we would expect significantly faster RTs on invalid trials, where the target is preceded by a context cue, than on neutral trials (invalid $<$ neutral). The reason is that capture by context elements would ensure that attention is already allocated to the target location, which should facilitate responding to the target. The predictions of cue inhibition and context capture are nonexclusive. With respect to the neutral condition, cue inhibition predicts longer RTs on valid than neutral trials, whereas context capture predicts shorter RTs on invalid than neutral trials. Both hypotheses may be confirmed at the same time (invalid $<$ neutral $<$ valid). Note that these predictions are limited to critical cues that do not match the target, whereas attentional capture by a matching cue is typically reflected in the opposite order of RTs (valid $<$ neutral $<$ invalid).

In some experiments, we additionally measured lateralized ERPs. To isolate ERP components, the stimulus of interest (critical cue or context cue) was presented in the left or right hemifield while the neutral cue was shown in the opposite hemifield (Figure 2, lower panel). We expect the lateralized ERPs to reflect processing of the stimulus of interest, whereas stimuli on the vertical midline do not contribute to lateralized ERPs (see Woodman & Luck, 2003). To isolate processing of the critical cue, it was presented on the left or right and the neutral cue on the opposite side. The contextual cues were shown on the vertical midline, where they evoked no lateralized ERPs. Cue inhibition predicts a P_D to the critical cue. To isolate processing of the context cues, one context cue was presented on the left or right and the neutral cue was presented on the opposite side. The critical cue and the second context cue were shown on the vertical midline. Context capture predicts an N2pc to the context cue. As for the behavioral data, predictions of the cue suppression and context capture account are not exclusive. That is, both a P_D to the critical cue and an N2pc to the contextual cues may occur.

Overview of the Present Study

In the current study, we assessed whether recently observed same location costs and lateralized ERP positivities were due to cue inhibition or context capture, and conducted five experiments with either RT (Experiments 1, 3A, and 3B) or combined RT and ERP measurements (Experiments 2 and 4). In Experiments 1 and 2, the stimuli closely matched those of previous studies and only covered four stimulus positions (Harris et al., 2013; Schönhammer et al., 2017; Schönhammer et al., 2016). In Experiments 3 and 4, we used five and six stimulus positions, respectively, to distinguish between alternative explanations, which required more than a single neutral cue per display.

Experiment 1 (RT)

In Experiment 1, we aimed to replicate the same location costs observed previously (Schönhammer et al., 2016). Therefore, we used the same target and nontarget stimuli as previously, but included one neutral cue element in the cue array to examine whether the same location costs with relatively nonmatching singleton cues were due to cue inhibition or context capture. Experiment 1 comprised two target conditions to rule out possible differences in stimulus saliency. Half of the participants searched for a yellower target and the other half for a greener target. The yellower target is illustrated in Figure 1 and conditions for the greener target can be obtained by horizontally flipping the chart. The physical target color was the same in both groups (yellow-green), and only the nontarget color was changed. In each target condition, the target array was preceded by one out of four possible cue arrays (Figures 1B and 1C), which reflected the four combinations of physical and relative match between critical cue and target. To ensure that results reflected covert attention allocation and not overt gaze shifts, participants were instructed to maintain fixation on the central fixation cross, and fixation was monitored with an eye-tracker.

Method

Participants. In all experiments, students from the University of Geneva, Switzerland, took part for course credit and gave informed consent prior to the experiment. All procedures were approved by the local ethics committee and were in accordance with the 1964 Declaration of Helsinki. All participants reported normal neurological health, color vision, and normal or corrected-to-normal visual acuity. Thirty-two participants completed Experiment 1. Sample size was determined on the basis of a previous study, in which we obtained a same location cost of 30 ms (*SD* valid = 54 ms, *SD* invalid = 36 ms, COR(valid, invalid) = 0.92) with relatively and physically nonmatching cues (Schönhammer et al., 2016, NONE condition, Experiment 1). Because we would also consider smaller validity effects as theoretically important, we wanted to be able to find differences half this size, which requires a sample size of 32, aiming for a power of .95 and a one-tailed hypothesis (Faul, Erdfelder, Lang, & Buchner, 2007). Sixteen participants searched for the yellower target (11 females, mean age of 20 years) and 16 for the greener target (13 females, mean age of 23 years). Participants were replaced if the percentage of response or fixation errors exceeded 15%. Two participants from the original sample were replaced for this reason.

Apparatus. Participants were seated in a dimly lit room, and viewed the stimulus display (23.6-in. LCD monitor, 100 Hz, 1,920 × 1080 pixels, VIEWPixx, VPixx Technologies Inc., Canada) from a viewing distance of 57 cm. The display's white point was D65. Observers pressed one of two designated response keys on a response box (RESPONSEPixx, Vpixx Technologies) using the index and middle finger of their preferred hand. Colors were measured with a Cambridge Research Systems ColorCAL MKII colorimeter, and are specified in CIE 1976 Lu'v' triplets with L in cd/m2. Eye movements were recorded at a sampling rate of 1000 Hz using the desktop-mounted EyeLink1000 (SR Research, Ontario, Canada).

Stimuli. Stimuli were generated using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) and were presented on a black background (0.30 cd/m2). Three types of displays were presented on each trial: fixation, cue, and target displays (see Figure 2, upper panel). The fixation display consisted of a central dark gray fixation cross (0.3° × 0.3°, line width: 0.03°; L = 10.1, u' = .20, v' = .47) and four dark gray placeholder squares (2° × 2°, line width: 0.03°), one in each quadrant of the display, positioned equidistantly on the outlines of an imaginary circle with a radius of 6° around fixation. The cue display consisted of the fixation display with the addition of four-dot cues (0.4° × 0.4°, each) positioned around each placeholder at the 12, 3, 6, and 9 o'clock locations (on an imaginary circle of 1.3° around the center of each placeholder).

The critical cue was a four-dot cue with a unique color. Two other four-dot cues constituted the context cues. The neutral cue was the remaining four-dot cue and was always gray. The possible colors in the cue display were green (L = 20.3, u' = .04, v' = .57), yellow-green (L = 21.0, u' = .13, v' = .56), and yellow (L = 20.1, u' = .20, v' = .55), or gray (L = 20.1, u' = .20, v' = .47). The colors were approximately equiluminant and equidistant in the CIE 1976 Lu'v' chromaticity diagram. The target display consisted of the fixation display and four letters (Ls or Ts; 1.0° × 1.4°, line width: 0.2°) that were centered inside the four placeholders. Each target display contained two Ls and two Ts. The specific color assignments in cue and target arrays are shown in supplementary Table 1.

Design. The color of the target and nontargets was fixed throughout the experiment, whereas the cue displays varied across trials. The cue condition (Condition 1 to 4), cue position (position 1 to 4), target position (position 1 to 4), and target identity (L, T) were fully counterbalanced across trials, resulting in 128 trials that were presented in random order. The neutral cue was randomly presented at one of the three positions that were not taken by the critical cue. Each participant completed 8 blocks of 128 trials, for a total of 768 experimental trials.

Procedure. Participants were instructed to report the identity of the yellow-green target letter in the target display (L or T) by pressing the corresponding left or right response key with their middle or index finger, respectively. The key-to-response assignment was counterbalanced across participants. Participants were instructed to maintain central fixation and to respond as fast and accurately as possible.

Each trial started with the presentation of a fixation display, in which the fixation cross was removed for 100 ms to remind participants to fixate. Then, the fixation display was randomly presented between 900 and 1,100 ms. The fixation display was followed by the cue display, another fixation display, and the search display, each presented for 100 ms. The total duration from cue onset to target offset was 300 ms. After presentation of the search array, a fixation display was presented until 500 ms after a response was registered. A correct response was followed by a high-pitched tone (1050 Hz, 100 ms), whereas incorrect, anticipatory, and delayed responses (RT <200 or RT >2,000 ms), as well as for fixation errors (blinks or saccades >1° away from fixation, in the interval from 200 ms before cue onset until target offset), were followed by a low-pitched tone (750 Hz, 100 ms). Participants had breaks after 64 trials during which they received feedback about their accuracy in the preceding block. After the break, calibration of the eye-tracker was checked and recalibration was performed if necessary.

Results

An alpha level of .05 was used to determine statistical significance. The *p* values were adjusted using the Greenhouse-Geisser epsilon correction for nonsphericity when necessary. For all pairwise comparisons, one-sided tests were chosen in accordance with the hypotheses.

Mean RTs and errors. Trials with anticipatory responses (<1% of all trials) and trials with eye-movements and blinks (median of 5%, ranging from 0% to 15%) were excluded from further analyses. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (3.0%).

The target condition (yellower, greener) did not interact with any of the other factors (cue condition or cue validity) in any of the dependent measures, hence, for all analyses, the data were pooled across the two target conditions. Average mean RTs as a function of cue condition and cue validity are shown in Figure 3. Significant *t* test of valid and invalid conditions against the neutral condition

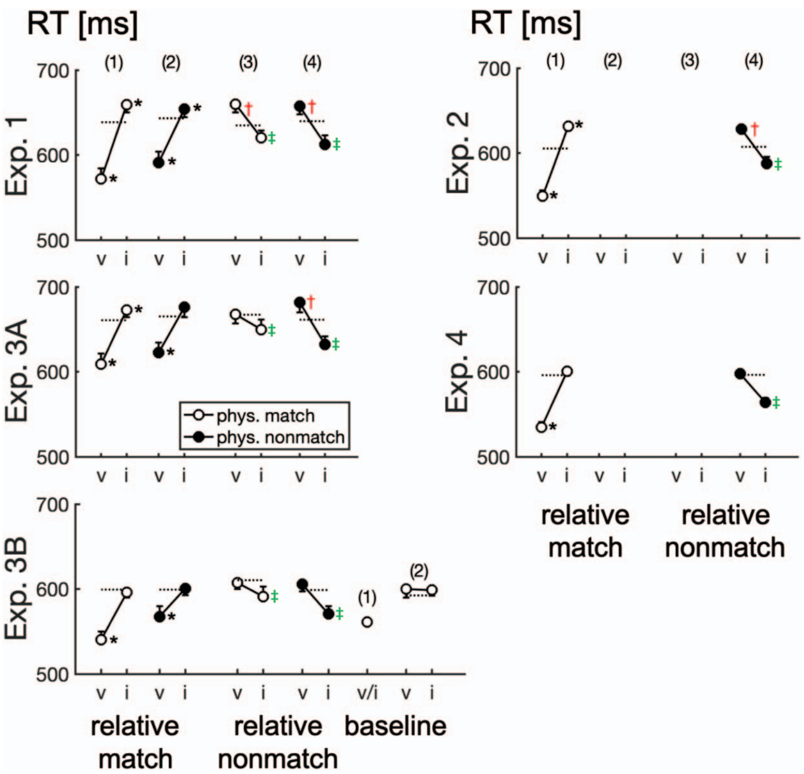

Figure 3. Mean response times (RTs) in Experiments 1–4 as a function of cue condition (1–4) and whether the critical cue (v = valid), a contextual cue (i = invalid), or a neutral cue (horizontal dashed lines) was shown at the target location. Error bars show the 95% confidence interval (one-sided) for the comparison of RTs between valid and neutral, or between invalid and neutral (Franz & Loftus, 2012). Significant differences are marked by an asterisk. Significant differences between valid and neutral are consistent with inhibition of the critical cue and are indicated by a dagger. Significant differences between invalid and neutral are consistent with context capture are indicated by a double dagger. See the online article for the color version of this figure.

are marked by an asterisk. As a manipulation check, we performed the same tests for relatively matching critical cues. Results from these tests are reported in Figure 3 and Table 1, but not in the text, because they are not the focus of the present investigation.

Mean RTs. The results of a 4 × 3 repeated-measures ANOVA with the factors Cue Condition (1 to 4) and Cue Validity (valid, invalid, neutral), computed over the mean correct RTs, showed significant main effects of Cue Condition, $F(3, 93) = 9.38$, $p < .001$, $\eta_p^2 = .23$, and Cue Validity, $F(2, 62) = 21.51$, $p < .001$, $\eta_p^2 = .41$. The main effects were modulated by a significant interaction, $F(6, 186) = 63.18$, $p < .001$, $\eta_p^2 = .67$, indicating that validity effects differed between the cue conditions. As shown in Figure 3, *t* tests confirmed that critical cues matching the relative target feature showed the expected shorter RTs on valid than neutral trials.[2] More important for our present purpose, the opposite pattern was obtained for relatively nonmatching critical cues. In line with earlier findings, mean RTs were significantly longer on valid than invalid trials, reflecting a same location cost. Furthermore, the results showed evidence for both cue inhibition and context capture. Consistent with cue inhibition, RTs were longer on valid than neutral trials, both for the physically matching cue (difference of −25 ms), $t(31) = -4.49$, $p < .001$, and for the physically nonmatching cue (difference of −17 ms), $t(31) = -3.16$, $p = .002$. Furthermore, consistent with context capture, RTs were shorter in invalid than neutral trials, both for the physically matching cue (difference of 15 ms), $t(31) = 2.89$, $p = .003$, and for the physically nonmatching cue (difference of 27 ms), $t(31) = 4.43$, $p < .001$.

Mean errors. The mean error proportions as a function of Cue Condition and Cue Validity are displayed in Table 1. The same 4 × 3 ANOVA computed on the mean error rates showed similar results, with a significant main effect of Cue Validity, $F(2, 62) = 4.05$, $p = .022$, $\eta_p^2 = .12$, and a significant interaction, $F(6, 186) =$

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[2] In Experiments 1 and 3B, validity effects (valid vs. invalid trials) were larger when the cue matched both relationally and physically than when only relationally, $ps < .012$, $t(31)\text{s} > 2.67$. However, only a tendency was found in Experiment 3A, $p = .142$, $t(31) = 1.50$. Likewise, same location costs were larger when the cue matched both relationally and physically than when only relationally. This effect was reliable in Experiment 3A and 3B, $ps < .030$, $t(31)\text{s} > 2.23$, but not in Experiment 3A, $p = .491$, $t(31) = 1.50$. In previous studies on the relational account, feature-specific effects have mostly been observed in late measures of attention, such as the dwell time on a distractor in eye-tracking studies (e.g., Becker, Harris, Venini, & Retell, 2014; Martin & Becker, 2018). That is, while the initial orienting to an irrelevant item seems to be determined by relational matches, later processes depend more on feature-specific matches, which elongates the time attention (or the eyes) dwells on a stimulus. In the spatial cueing paradigm, elongated dwelling on the cue(s) could increase the validity effects for cues that match both the relative and physical feature.

Table 1
Mean Error Proportions (%) on Valid, Invalid, and Neutral Trials and Differences as a Function of Cue Condition

		Cue condition				Baseline 1	Baseline 2
Exp.	Cue validity	1	2	3	4		
E1	valid	3.3^{*}	3.6^{*}	7.5	7.0		
	invalid	8.4^{*}	7.2	3.7	$5.0^{\ddagger}$		
	neutral	6.6	7.8	5.9	6.4		
E2	valid	2.9^{*}			5.6		
	invalid	5.5			$4.6^{\ddagger}$		
	neutral	5.9			6.0		
E3A	valid	5.5^{*}	4.8^{*}	$11.3^{\dagger}$	9.0		
	invalid	8.6	9.8	8.0	7.1		
	neutral	7.5	8.4	8.0	7.7		
E3B	valid	3.2	4.8	7.4	5.3	1.6	5.2
	invalid	5.5^{*}	5.0	$4.0^{\ddagger}$	$3.6^{\ddagger}$		4.1
	neutral	3.7	5.8	5.8	4.9		4.8
E4	valid	2.8^{*}			4.3		
	invalid	4.2			$3.1^{\ddagger}$		
	neutral	4.3			4.3		

Note. Asterisks shows a significant *t*-test between valid and neutral, or between invalid and neutral. Significant differences between valid and neutral are consistent with inhibition of the critical cue and are indicated by a dagger. Significant differences between invalid and neutral are consistent with context capture and are indicated by a double dagger.

11.51, $p < .001$, $\eta_p^2 = .27$ (other $F < 1$). Inspection of Table 1 showed no signs of speed–accuracy trade-off.

Discussion

Experiment 1 replicated the finding that cues matching the relative feature of the target capture attention, irrespective of the physical cue color. These findings are in line with the relational account and show that attention was tuned to the relative color of the target (e.g., "yellower").

More relevant to the present study, we observed same location costs with relatively nonmatching critical cues, also irrespective of the physical cue color. We observed slower responses on valid compared to neutral trials (neutral < valid), suggesting that relatively nonmatching critical cues were inhibited, which led to costs when the relatively nonmatching critical cue was presented at the target location. In addition, we observed faster responses on invalid trials than neutral trials, indicating that the context cues captured attention, which facilitated responses when one of the context cues was at the target location, rather than when the neutral cue was at the target location (invalid < neutral). Thus, Experiment 1 points to the conclusion that both cue inhibition and context capture contribute to the same location costs with relatively nonmatching critical cues, whereby both inhibition and context capture depend on the match between cue–context and target–nontarget relation rather than the physical features.

Experiment 2 (RT and ERP)

In Experiment 1, the RT effects indicated that same location costs with relatively nonmatching critical cues were the result of both inhibition of the critical cue and capture by the context cues. However, these results were obtained with behavioral measures where attentional effects of the cues are inferred rather indirectly, by assessing the effects of valid, invalid, and neutral cues on target processing. To obtain a more direct, neurophysiological measure of cueing effects, in Experiment 2, we measured lateralized ERPs to critical and context cues when a neutral cue was shown on the opposite side (see Figure 2, lower panel). Because the measurement of lateralized ERPs requires a large number of trials, we focused on conditions that were most frequently tested in the previous literature and were expected to yield the strongest effects—that is, the cue conditions with either completely matching or completely nonmatching cues (i.e., cue Conditions 1 and 4). The latter condition is expected to reliably result in same location costs (Schönhammer et al., 2016). Note that Experiment 1 established that attention was tuned to the relative target feature. Because the target arrays in Experiment 2 were almost identical to those in Experiment 1, we assumed that attention was tuned to the relative target color in Experiment 2 as well.

Experiment 1 suggested that same location costs with nonmatching critical cues were in part due to inhibition, which should be reflected in a contralateral positivity (P_D) to the critical cue. In addition, Experiment 1 indicated that same location costs with nonmatching critical cues were also in part due to capture by the context cues, which should be reflected in a contralateral negativity (N2pc) to the context cues.

Based on our previous studies, we expected that both of these effects would occur in the N2pc time window (Schönhammer et al., 2016). In addition, we also explored lateralized ERPs before and after the N2pc time window, to check whether the data contain other components that might be related to attentional inhibition or capture of critical or context cues. Previous studies suggest that lateralized ERPs at posterior electrodes are not only evoked within the typical N2pc time window (180–300 ms). Earlier contralateral positivities were observed in the P1 range (75–125 ms, Luck & Hillyard, 1994b) or in the N1 range (140–190 ms, Leblanc, Prime, & Jolicoeur, 2008; 125–225 ms, Sawaki & Luck, 2010). Different studies arrived at different interpretations of these ERP positivities. The positivities were interpreted as color-specific sensory adaptions because they were only present when items with the same colors were repeated frequently and disappeared when colors alternated (Luck, 2012). Similar contralateral positivities were interpreted as attend-to-me signals, because they were observed even when colors were intermixed (Pomerleau, Fortier-Gauthier, Corriveau, Dell'Acqua, & Jolicoeur, 2014), or as evidence for suppression when they only appeared in response to to-be-ignored colors (Barras & Kerzel, 2017; Sawaki & Luck, 2010). In later time windows, positive voltage deflections have been attributed to disengagement and suppression after attentional capture by the cue (Sawaki & Luck, 2013), or enhancement of the subsequent element in the target array (Livingstone, Christie, Wright, & McDonald, 2017). Moreover, negative deflections were also observed in later time windows with cues that did not match the task set (265–330 ms), and were considered to reflect late N2pcs (Eimer & Kiss, 2008; Schönhammer et al., 2016). To cater for the possibility that positive or negative potentials occur outside the typical time window of the N2pc, we also examined lateralized ERPs at occipital electrodes before (from 70 to 170 ms) and after (from 310 to 500 ms) the typical N2pc time range (from 180 to 300 ms).

Method

Participants. Twenty-eight participants completed Experiment 2. Fourteen searched for the yellower target (10 females, mean age of 26 years) and 14 for the greener target (9 females, mean age of 20 years). Participants were replaced if the percentage of response errors was larger than 15%, or if the percentage of trials with EEG artifacts was larger than 25%. Four participants were replaced for the latter reason. Sample size was determined on the basis of a previous study (Schönhammer et al., 2016), in which we obtained a lateralized ERP positivity of 0.29 μV with a standard deviation of 0.45 μV in the physically and relatively nonmatching condition. Detecting an effect of this magnitude requires a sample size of 27 participants, aiming for a power of .95 and one-tailed hypothesis testing.

Apparatus, stimuli, design and procedure. The method was the same as in Experiment 1, with the following exceptions. The EEG was recorded using scalp electrodes, and eye movements were monitored with external electrodes, not with the eyetracker. Only cue Conditions 1 and 4 were presented. The placeholders and the associated stimuli were presented at the 12, 3, 6, and 9 o'clock positions. The neutral cues only appeared at the 3 and 9 o'clock positions. Thus, on each trial, either the critical cue was lateral and the context cues were on the vertical midline, or one of the context cues was lateral and the other context cue and the critical cue were on the vertical midline. These events occurred with equal probability. The total number of trials was 1,536, and participants were encouraged to take a break after each block of 256 trials.

EEG recording and analysis. The EEG was recorded using active Ag/AgCl electrodes of a 32-channel EEG system and digitized at 1,000 Hz (actiCAP electrodes, actiCHamp amplifier, PyCoder software; Brain Products, Gilching, Germany). The EEG system uses several hardware filters (see actiChamp user manual) and software filters (see PyCoder source code) for antialiasing. The electrooculogram (EOG) was recorded from electrodes placed at the outer canthus of each eye, and above and below the right eye. Cz served as online reference and AFz as ground. Data were analyzed using EEGLAB (Delorme & Makeig, 2004), ERPLAB (Lopez-Calderon & Luck, 2014), the Mass Univariate Toolbox (Groppe, Urbach, & Kutas, 2011), and the Factorial Mass Univariate ERP Toolbox (Fields, 2017).

Offline, the raw EEG was re-referenced to the average of the left and right mastoids, band-pass filtered (noncausal Butterworth filter, 0.1–30 Hz, half-amplitude cut-off at 30 Hz, roll-off of 12 dB/octave), and downsampled to 100 Hz. The EEG was segmented from 100 ms prior to 500 ms after cue onset and baseline corrected with respect to the prestimulus interval (−100 to 0 ms). Trials were excluded from analysis if the response was anticipated, delayed, or incorrect, if RTs exceeded the individual cell mean by more than 3.0 standard deviations, or if EEG traces were contaminated with artifacts. Trials with horizontal EOG exceeding 16 μV in a step function with a 200 ms window width and a 10 ms window step (Luck, 2014), or vertical EOG exceeding 50 μV, or any other channel exceeding 80 μV, were discarded. To assess residual eye movements, we computed individual horizontal EOG waveforms for left- and right-cue trials. For all participants, the averaged horizontal EOG did not exceed 3.2 μV, which suggests that residual eye movements were less than 0.28° in size (Lins, Picton, Berg, & Scherg, 1993; McDonald & Ward, 1999).

Results

Mean RTs. Trials with anticipatory responses (<0.1% of all trials) and trials with EEG artifacts (median of 17%, ranging from 3% to 25%) were excluded from further analyses. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.6%). Average mean RTs as a function of cue condition and cue validity, as well as the full set of *t* tests against the neutral condition, are shown in Figure 3.

The results of a 2 × 3 repeated-measures ANOVA with the factors Cue Condition (matching, nonmatching) and Cue Validity (valid, invalid, neutral) computed on the mean correct RTs showed significant main effects of Cue Condition, $F(1, 27) = 41.89$, $p < .001$, $\eta_p^2 = .61$, and Cue Validity, $F(2, 54) = 43.56$, $p < .001$, $\eta_p^2 = .62$, as well as a significant interaction, $F(2, 54) = 212.22$, $p < .001$, $\eta_p^2 = .89$, indicating that validity effects differed between the cues. RTs with nonmatching critical cue provided evidence for both cue inhibition and context capture. RTs were significantly longer on valid than neutral trials (difference of −21 ms), $t(27) = -10.02$, $p < .001$, which supports cue inhibition. In addition, RTs were shorter on invalid than neutral trials (difference of 19 ms), $t(27) = 4.42$, $p < .001$, which supports context capture.

Mean errors. The mean error proportions as a function of Cue Condition and Cue Validity are displayed in Table 1. The same 2 × 3 ANOVA computed on the mean error rates showed significant main effects of Cue Condition, $F(1, 27) = 7.77$, $p = .010$, $\eta_p^2 = .22$, and Cue Validity, $F(2, 54) = 11.21$, $p < .001$, $\eta_p^2 = .29$, and a significant interaction, $F(2, 54) = 15.35$, $p < .001$, $\eta_p^2 = .36$. Inspection of Table 1 shows no sign of speed–accuracy trade-off.

Lateralized ERPs. Individual average waveforms (ERPs) at electrode sites PO7 and PO8 were calculated for each of the eight combinations of cue–target match (nonmatching, matching), lateral cue type (critical cue, context cue), and laterality of the electrode (contralateral, ipsilateral). From the 192 trials for each combination, between 123 and 189 trials remained after artifact rejection.

Conventional analyses often used the group-average ERP to select the time window for analysis when the time window for a component was unclear a priori. However, this approach implicitly conducts multiple comparisons (Luck, 2014; Luck & Gaspelin, 2017). Hence, we used *F*max and *t*max analyses, because these correct for multiple comparisons. The *t*max procedure conducts a *t* test against zero at each time point and compares the *t*-value to a critical *t*-value that is obtained in a permutation test and, thereby, is corrected for multiple comparisons (Groppe et al., 2011). The *F*max procedure is analogous (Fields, 2017). Instead of reporting the *F*- and *t*-values at each time point, we report the critical *F*- and *t*-values, the corrected alpha level associated with these values, and the significant time points (see Table 2). The difference between contralateral and ipsilateral electrode sites for the four configurations is represented by the black lines in Figure 4. Significant time points are marked by gray bars in Figure 4 and are additionally listed in Table 2.

First, we analyzed the critical time interval from 180 to 300 ms after cue onset, where we expected a P_D to nonmatching critical

Table 2

Fmax and Tmax Permutation Test Results for Experiment 2 in the Time Window of 180–300 ms, in Which N2pc or P_D Components Were Expected, and Before (70–170 ms) and After (310–500 ms) This Time Window

Time window (ms)	Test	Effect	Critical *F* or *t*	Testwise alpha level	Significant time points (ms)	*M* voltage (μV)
180–300	ANOVA	configuration	3.80	.01	180–300	n/a
		laterality	7.37	.01	180–220, 290–300	n/a n/a
		interaction	4.16	.009	290–300	n/a
	t-test	matching:				
		-cue lateral	−2.47	.01	180–240	−0.17
		-context lateral	2.46	.01	—	—
		nonmatching:				
		-cue lateral	2.52	.004	—	—
		-context lateral	−2.47	.01	180–210	−0.26
70–170 & 310–500	ANOVA	configuration	4.77	.004	310–410	n/a
		laterality	9.29	.005	110–140, 310–450	n/a n/a
		interaction	4.83	.004	310–460	n/a
	t-test	matching:				
		-cue lateral	±2.50	.009	120–140, 310–450	0.44, 2.38
		-context lateral	±3.24	.003	110–140	0.43
		nonmatching:				
		-cue lateral	±3.30	.002	120–140	0.42
		-context lateral	±3.15	.004	120–140, 310–450	0.42, 1.21

Note. N2pc = time range of the second negative going deflection of the visual ERP, and at posterior electrodes contralateral to a candidate target object; P_D = positivity to a distractor. The mean voltage is the mean voltage difference between contra- and ipsilateral electrodes.

cues and an N2pc to the corresponding contextual cues[3] (lower panels in Figure 5). Individual ERPs were entered into a four-cue configuration (nonmatching cue: critical cue lateral, context cue lateral; matching cue: critical cue lateral, context cue lateral) × two laterality (contralateral, ipsilateral) repeated-measures *F*max test. As shown in Table 2, we obtained significant main effects of cue configuration and laterality for most or all time points, indicating that the average voltage differed significantly among the four cue configurations and between contra- and ipsilateral electrodes. However, we were looking for an interaction of configuration and laterality to show that contralateral positivities (P_D) or negativities (N2pc) changed as a function of cue configuration. The interaction was only significant at two time points in the N2pc time window (290–300 ms). Nonetheless, we examined whether the difference waves were significantly different from zero at all timepoints in the N2pc time window as planned.

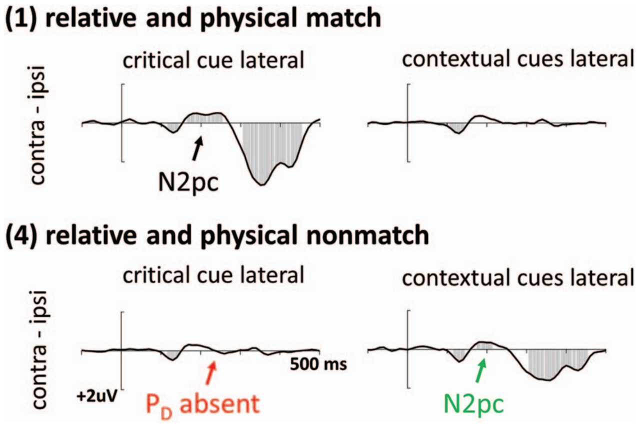

Figure 4. Group mean difference waveforms (contralateral–ipsilateral) at electrode sites PO7and PO8 for each cue configuration. Timepoints at which the difference waveforms significantly differed from zero are marked by gray columns. N2pc = time range of the second negative going deflection of the visual ERP, and at posterior electrodes contralateral to a candidate target object; P_D = positivity to a distractor. See the online article for the color version of this figure.

Unsurprisingly, the lateralized critical cue in the matching cue condition elicited a small N2pc (upper left panel), indicating attentional capture by the critical cue. By contrast, the lateralized context cues in the matching cue condition did not lead to a significant N2pc (upper right panel).

More important, the lateralized critical cue in the nonmatching cue condition did not result in a significant positive voltage deflection in the N2pc time window (lower left panel), which provides no support for the view that nonmatching singleton cues are inhibited. Conversely, the lateralized context cue in the nonmatching critical cue condition resulted in a small N2pc (lower right panel), suggesting capture by the context cue.

Next, we analyzed time points from 70 to 170 ms, which preceded the critical P_D/N2pc interval. The *F*max test showed only a significant main effect of laterality at the time points from 110 to 140 ms, and the *t*max tests confirmed the corresponding positivities from 110 to 140 or 120 to 140 ms for all cue configurations.

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[3] Even though the time window to assess the N2pc was large, all observed N2pcs were also significant in the often used, narrower time window from 200 to 300 ms.

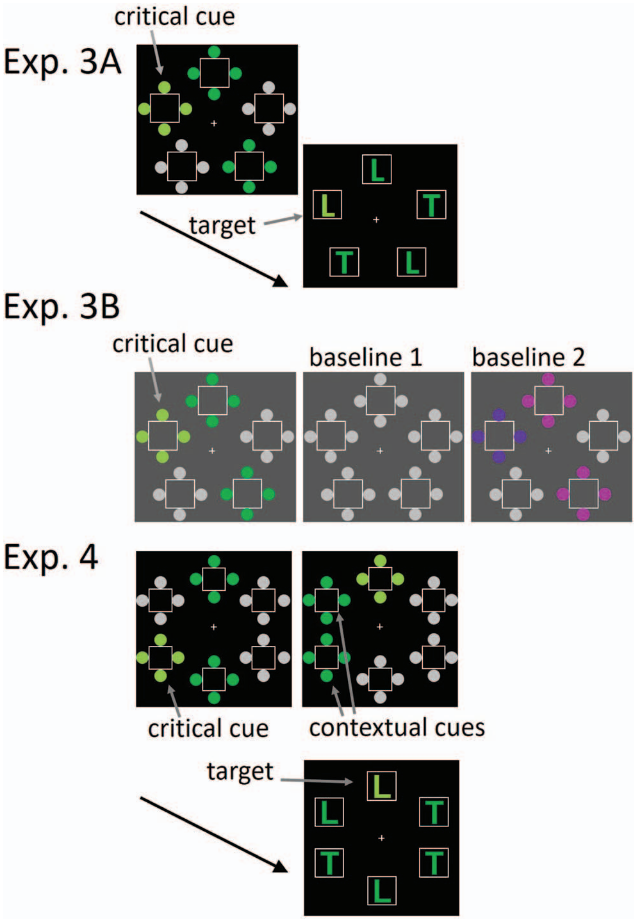

Figure 5. Cue and target arrays in Experiments 3A, 3B and 4. In Experiments 3A and 3B, two neutral elements were added to avoid attentional capture by a single neutral cue. In Experiment 3B, the background was gray and two baseline conditions were added. In Experiment 4, the singleton cue was on a lateral position and the contextual cues on the vertical midline (or vice versa). See the online article for the color version of this figure.

Thus, there was an early contralateral positivity, consistent with an attend-to-me signal or sensory adaptation.

Finally, we analyzed time points after the N2pc time interval from 310 to 500 ms. From 310 to 460 ms, the main effects of configuration and laterality were qualified by a significant interaction of configuration and laterality, suggesting that the contralateral positivity only occurred in selected cue configurations. Notably, *t* tests confirmed late positivities with a lateral context cue in the matching cue condition (upper left panel), and with a lateral cue in the nonmatching critical cue condition (lower right panel).

Discussion

The behavioral results of Experiment 2 replicated those from Experiment 1. A critical cue that matched the relative and physical target feature captured attention, as reflected in a significant validity effect, whereas a nonmatching critical cue elicited a same location cost. More precisely, RTs with nonmatching critical cues were longer on valid than neutral trials, and shorter on invalid than neutral trials, which supports the notions that the nonmatching critical cue was inhibited and that the relatively matching context cue feature captured attention.

However, lateralized ERPs in the time window from 180 to 300 ms in the condition with nonmatching cues only revealed an N2pc to the lateralized context cue, but no significant positivity for the nonmatching critical cue. Thus, in contrast to the RT results, the ERP results indicate that the context cues captured attention, whereas there was no evidence for inhibition of nonmatching critical cues.

We additionally observed early ERP positivities. These have been linked to inhibition, but alternatively to sensory adaption (Jannati et al., 2013; Luck & Hillyard, 1994a). We surmise that the current early ERP positivity cannot be linked to inhibition, because it was present in all conditions, regardless of the cue type. In contrast, the inhibition account would have predicted ERP positivities only in response to a lateralized, nonmatching critical cue. We think that sensory adaption most likely explains the early positivities because the stimulus colors were very similar and were repeated in each array.

Moreover, a late positivity was obtained that has been interpreted as inhibition after disengagement (Mertes, Wascher, & Schneider, 2016; Sawaki & Luck, 2013). However, it cannot be linked to inhibition to explain the same location cost, because the late positivity was observed when the matching contextual cue was lateralized, but not when the nonmatching critical cue was lateralized. Moreover, recent research suggests that the late positivity reflects enhancement of the target stimulus rather than a potential time-locked to the cue (Livingstone et al., 2017).

Finally, the N2pc elicited by the lateralized, matching critical cue was much smaller than in previous studies (Schönhammer et al., 2016), potentially suggesting that the neutral cue may have competed for attention instead of being completely neutral. After all, the neutral cue was the only achromatic cue in the display and therefore might have been salient. Strong competition by the neutral cue may have reduced the allocation of attention to matching critical cues. Furthermore, the neutral cue might have matched an attentional set for a singleton so that it received top-down enhancement (Bacon & Egeth, 1994). In either case, this would have facilitated responding on neutral trials, where the neutral cue was presented at the target location. Thus, attentional capture by the neutral cues may explain the significantly shorter RTs on neutral compared to valid trials in the nonmatching cue condition. In contrast, we interpreted this difference as evidence for inhibition.

Experiment 3A (RT)

In Experiment 3, we reduced the attention-driving capacity of the neutral cue by eliminating its singleton status. Experiment 3 was the same as Experiment 1, except that five stimulus positions were presented and each cue array contained one additional neutral cue (see Figure 5). Consequently, the neutral cues were not unique, which rendered them less salient. In addition, two gray cues do not match an attentional set for a single item, which should reduce their capacity to drive attention in a top-down manner (Bacon & Egeth, 1994).

Method

Participants. Thirty-two participants completed Experiment 3. Sixteen completed the greener target condition (12 females, mean age of 23 years) and 16 the yellower target condition (14 females, mean age of 22 years). Four participants were replaced because of excessive fixation errors.

Apparatus, stimuli, design, and procedure. The experimental setup was the same as in Experiment 1, except that five stimulus positions were included, and that each cue array contained one additional neutral cue, so that each cue display contained two gray four-dot cues. Moreover, the total number of trials was 800, and participants were encouraged to take breaks after blocks of 50 trials. The singleton cue positions were separated by 72° starting at the 12 o'clock position.

Results

Mean RTs. Trials with anticipatory responses ($<$1% of all trials) and trials with eye-movements and blinks (median of 6%, ranging from 0% to 15%) were excluded from further analyses. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.7%). Average mean RTs as a function of cue condition and cue validity are shown in Figure 3.

The results of a 4 × 3 repeated-measures ANOVA with the factors Cue Condition (cue Conditions 1 to 4) and Cue Validity (valid, invalid, neutral) computed over the mean correct RTs showed significant main effects of Cue Condition, $F(3, 93) = 6.55$, $p < .001$, $\eta_p^2 = .18$, and Cue Validity, $F(2, 62) = 12.02$, $p < .001$, $\eta_p^2 = .28$. Both main effects were modulated by a significant interaction, $F(6, 186) = 38.89$, $p < .001$, $\eta_p^2 = .56$, indicating that validity effects differed between the cues.

For relatively nonmatching cues, the difference between valid and neutral trials was not reliable with physically matching cues (difference of -0.4 ms), $t(31) = -0.06$, $p = .947$, whereas it was reliable with physically nonmatching cues (difference of -21 ms), $t(31) = -2.91$, $p = .003$. Thus, there was only partial evidence for cue inhibition. In contrast, RTs were significantly faster on invalid than neutral trials with physically matching cues (difference of 17 ms), $t(31) = 2.55$, $p = .008$, and with physically nonmatching cues (difference of 29 ms), $t(31) = 5.23$, $p < .001$, providing robust evidence for context capture.

Mean errors. The mean error proportions as a function of Cue Condition and Cue Validity are displayed in Table 1. The same 4 × 3 ANOVA computed on the mean error rates showed similar results, with significant main effects of Cue Condition, $F(3, 93) = 4.53$, $p = .011$, $\eta_p^2 = .13$, and a significant interaction, $F(6, 186) = 10.15$, $p < .001$, $\eta_p^2 = .25$ (other $F < 1$). Inspection of Table 1 shows no sign of speed–accuracy trade-off.

Discussion

In line with earlier studies, relatively nonmatching cues elicited same location costs. In line with context capture, RTs were faster on invalid than neutral trials, for all cues that mismatched the relative target feature. In turn, the inhibition hypothesis was only partially supported. Relatively and physically nonmatching cues showed slower RTs on valid compared to neutral trials, which supports the cue inhibition account. However, in the condition with relatively nonmatching, but physically matching, cues, RTs on valid trials did not differ from neutral trials. Thus, the cue inhibition account was only partially supported.

Experiment 3B (RT)

In the previous experiments, attentional capture and inhibition were inferred by comparing performance on valid and invalid trials with performance on neutrals trials, where a gray cue element preceded the target location. The gray cues were considered neutral and served as baseline to evaluate effects of capture and inhibition. However, it may be that the neutral conditions used in the previous experiments were insufficient to remove unwanted attentional effects. Experiment 3B aimed to validate the conclusions from Experiment 3A by adding two different baseline conditions.

In baseline Condition 1, the cue array contained only light gray cue elements, following the logic of previous studies (Carmel & Lamy, 2014; Sawaki & Luck, 2013). The all-gray cues matched neither the target nor the nontarget color and are therefore not expected to capture attention.

A problem with baseline Condition 1 is that all cues were homogeneous, which strongly reduces nonspatial filtering costs that may arise from heterogeneous displays (Folk & Remington, 1998). To remedy this potential shortcoming, we created a cue condition with colors sampled from the blue-red spectrum. Because these colors are unrelated to the yellow-green spectrum used for target and nontargets, no capture or inhibition was expected. At the same time, the displays were heterogeneous, so that nonspatial filtering costs were balanced. We focused on the invalid condition in which a colored nonsingleton item preceded the target to rule out attentional capture by singletons or gray. Thus, baseline 2 measured RTs to colored contextual cues for which no attentional set exists.

Method

Participants. Thirty-two participants completed Experiment 3B. Sixteen completed the greener target condition (12 females, mean age of 21 years) and 16 the yellower target condition (13 females, mean age of 22 years). When the target was yellower, the critical cue in baseline 2 condition was blue-purple and the context cues were red-purple. When the target was greener, the colors in the baseline 2 condition were swapped. One participant was replaced because of excessive fixation errors.

Apparatus, stimuli, design, and procedure. The experimental setup was the same as in Experiment 3A, except that the background was dark gray (L = 9.0, u' = 0.20, v' = .47) and that two additional cue displays were presented. Overall, there were 810 trials, and cue Condition 1–4 and baseline Condition 2 contained 150 trials each. In baseline Condition 1, the cue array contained only gray cues and was presented on 60 trials to match the number of neutral cue trials in any of the other conditions.

In baseline Condition 2, the cue array consisted of a blue-purple critical cue (L = 20.1, u' = 0.16, v' = .26), two red-purple context cues (L = 19.8, u' = .23, v' = .31), and two light gray context cues in the greener target condition. In the yellower target condition, the cue array contained one blue-purple, two red-purple, and two light gray cues.

Results

Mean RTs. Trials with anticipatory responses (<1% of all trials) and trials with eye movements and blinks (median of 4%, ranging from 0% to 13%) were excluded from further analyses. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.6%). Average mean RTs as a function of cue condition and cue validity are shown in Figure 3.

The results of a 4 × 3 repeated-measures ANOVA with the factors Cue Condition (cue Conditions 1 to 4) and Cue Validity (valid, invalid, neutral) computed over the mean correct RTs showed significant main effects of Cue Condition, $F(3, 93) = 22.33$, $p < .001$, $\eta_p^2 = .42$, and Cue Validity, $F(2, 62) = 28.56$, $p < .001$, $\eta_p^2 = .48$. Both main effects were modulated by a significant interaction, $F(6, 186) = 29.82$, $p < .001$, $\eta_p^2 = .49$, indicating that validity effects differed between the cues.

First, we used RTs on neutral trials as benchmark for valid and invalid trials with relatively nonmatching cues. RT differences between valid and neutral trials failed to reach significance for the physically matching cue (difference of 3 ms), $t(31) = 0.73$, $p = .763$, and the physically nonmatching cue (difference of −6 ms), $t(31) = -1.39$, $p = .087$. Thus, there was no evidence for cue inhibition. In contrast, RTs were significantly shorter on invalid than neutral trials with physically matching cues (difference of 19 ms), $t(31) = 2.76$, $p = .005$, and with physically nonmatching cues (difference of 28 ms), $t(31) = 5.19$, $p < .001$, providing robust evidence for context capture.

Next, we compared RTs in valid and invalid trials in cue Conditions 1–4 with RT in baseline Condition 1. Almost all comparisons showed slower RTs than on baseline 1 trials (all *p*s < .05, $|ts| > 2.04$), which would indicate that all other cue elements were inhibited. Only the physically and relatively matching critical cue resulted in faster RT on valid trials than on baseline 1 trials (difference of 20 ms), $t(31) = 3.77$, $p = .001$, which would suggest that only this cue captured attention. As this conclusion is implausible, we analyzed RTs from the relatively and physically matching conditions in more detail. The relatively matching condition is expected to provide robust evidence for capture. Consistently, there was capture by the critical cue irrespective of its physical match to the target. RTs were faster on valid than neutral trials with physically matching critical cues (difference of 59 ms), $t(31) = 10.93$, $p < .001$, as well as with physically nonmatching critical cues (difference of 32 ms), $t(31) = 4.40$, $p < .001$. Despite the solid evidence for attentional capture in both conditions, only valid trials with relatively and physically matching cues were faster than the baseline 1 condition, suggesting that only physically matching, but not physically nonmatching, cues captured attention. Because this conclusion is implausible, the baseline 1 condition may not be an adequate benchmark condition.

The cue array in baseline Condition 2 did not elicit a cue validity effect, as RTs on valid and invalid trials did not differ, $p = .561$. As planned, invalid trials in baseline Condition 2 were used as a benchmark for the relatively nonmatching cue conditions. The difference between valid and baseline 2 trials reached significance neither for the physically matching cue (difference of −8 ms), $t(31) = -1.41$, $p = .083$, nor for the physically nonmatching cue (difference of −7 ms), $t(31) = -1.58$, $p = .061$, providing no evidence for cue inhibition. In contrast, RTs were significantly shorter on invalid than baseline 2 trials with the physically nonmatching cue (difference of 28 ms), $t(31) = 8.02$, $p < .001$, whereas with physically matching cues, the difference only approached significance (difference of 6 ms), $t(31) = 1.61$, $p = .057$, providing only partial evidence for context capture.

Mean errors. The mean error proportions as a function of Cue Condition and Cue Validity are displayed in Table 1. The same 4 × 3 ANOVA computed on the mean error rates showed similar results, with significant main effects of Cue Condition, $F(3, 93) = 3.85$, $p = .012$, $\eta_p^2 = .11$, and a significant interaction, $F(6, 186) = 3.49$, $p = .003$, $\eta_p^2 = .10$ (other $F < 1$). Inspection of Table 1 shows no sign of speed–accuracy trade-off.

Discussion

In Experiment 3B, three different benchmarks were used to examine whether attentional capture or inhibition occurred. First, the same neutral trials as in Experiment 3A were used. In line with context capture, RTs were shorter on invalid than neutral trials, for all cues that mismatched the relative target feature. Conversely, no evidence for cue inhibition was obtained.

Second, an all-gray cue array was used, which is probably inadequate. RTs in this condition were shorter than in most of the other conditions, which may be due to the absence of nonspatial filtering costs (Folk & Remington, 1998) with homogeneous displays.

Third, a cue array was presented in which critical and context cues had entirely irrelevant colors (shades of purple). Performance on invalid trials of this cue array was used as alternative benchmark (baseline 2). Baseline 2 led to similar conclusions as neutral trials. In line with context capture, RTs with relatively nonmatching cues were shorter on invalid than baseline 2 trials, at least when the physical color was also nonmatching (cue Condition 4). Conversely, we obtained no support for the cue inhibition account.

Experiment 4 (RT and ERP)

In sum, the evidence from the previous experiments favors capture by context cues as an explanation for same location costs with relatively nonmatching cues. Initially, Experiments 1 and 2 seemed to provide support from RTs for both context capture and cue inhibition. However, ERP measurements in Experiment 2 found no further support for inhibition. In Experiments 3A and 3B, we evaluated the idea that the gray neutral cue was not neutral, but in fact attracted attention because it was a singleton. The resulting shorter RTs for the neutral cue would yield spurious RT evidence for inhibition (neutral < valid). To eliminate the singleton status of the neutral cue, we presented two gray elements in Experiment 3A, and two additional baselines in Experiment 3B. The results supported the context capture account, but provided little evidence for cue inhibition.

To provide more conclusive evidence in favor of context capture and against cue inhibition, we reran the fully matching and fully nonmatching conditions from Experiment 3 with ERP measurements. Similar to Experiment 2, cue inhibition predicts a P_D when the critical cue is lateral, whereas context capture predicted an N2pc when the context cues are lateral. To isolate lateralized ERPs to the critical cue, the two context cues had to be arranged on the vertical midline. Thus, we added a vertical position below central fixation to accommodate the two context cues on the vertical midline (see Figure 5).

Method

Participants. Twenty-eight participants completed Experiment 4. Fourteen searched for the yellower target (12 females, mean age of 22 years) and 14 for the greener target (11 females, mean age of 23 years). Four participants were replaced because the percentage of trials with EEG artifacts was larger than 25%.

Apparatus, stimuli, design and procedure. The methods were the same as in Experiment 2 with the following exceptions. There were six stimulus positions and placeholders, and the associated stimuli were presented in a hexagonal arrangement. On each trial, the critical cue was lateral and the context cues were on the vertical midline, or vice versa. The stimuli were presented in these two configurations with equal probability.

Results

Mean RTs. Trials with EEG artifacts (median of 15%, ranging from 3% to 25%) were excluded from further analyses. RTs exceeding the mean of a cell by more than 3 standard deviations were trimmed (1.4%). Average mean RTs as a function of cue condition and cue validity are shown in Figure 3.

The results of a 2 × 3 repeated-measures ANOVA with the factors Cue Condition (matching, nonmatching) and Cue Validity (valid, invalid, neutral) computed on the mean correct RTs showed significant main effects of Cue Condition, $F(1, 27) = 58.35$, $p < .001$, $\eta_p^2 = .68$, and Cue Validity, $F(2, 54) = 103.65$, $p < .001$, $\eta_p^2 = .79$, as well as a significant interaction, $F(2, 54) = 171.44$, $p < .001$, $\eta_p^2 = .86$, indicating that validity effects differed between the cues. For nonmatching cues, the comparison between valid and neutral was not significant ($p = .19$), providing no evidence for inhibition of the nonmatching cue. In contrast, RTs were shorter on invalid than neutral trials (difference of 32 ms), $t(27) = 10.18$, $p < .001$, suggesting capture by the context cues.

Mean errors. The mean proportion of errors as a function of Cue Condition and Cue Validity are displayed in Table 1. The same 2 × 3 ANOVA computed on the mean error rates showed similar results, with significant main effects of Cue Validity, $F(2, 54) = 3.91$, $p = .026$, $\eta_p^2 = .13$, and a significant interaction, $F(2, 54) = 10.81$, $p < .001$, $\eta_p^2 = .29$. Inspection of Table 1 shows no sign of speed–accuracy trade-off.

Lateralized ERPs. Individual averages for each of the eight conditions were based on 192 trials (range from 136 to 191 trials after artifact rejection). The results of the *F*max and *t*max tests are shown in Table 3. Mean difference waveforms and the *t*max statistics are shown in Figure 6.

The N2pc to lateral matching critical cues were larger than in Experiment 2 (upper right panel in Figures 4 and 6) and comparable to previous studies, indicating that presenting two neutral cues was an effective manipulation to reduce the saliency of the neutral gray cues. Individual ERPs were entered into a 4-cue configuration (nonmatching cue: critical cue lateral, context cue lateral; matching cue: critical cue lateral, context cue lateral) × 2 laterality (contralateral, ipsilateral) repeated-measures *F*max test.

First, we analyzed the N2pc time window (180 – 300 ms). The *F*max test found a significant main effect of configuration from 210 to 300 ms, a significant main effect of laterality from 180 to 280 ms, and a significant interaction of configuration and laterality from 180 to 280 ms. The interaction shows that effects of laterality were limited to lateral critical cues in the matching cue condition

Table 3
Fmax and Tmax Permutation Test Results for Experiment 4

Time window (ms)	Test	Effect	Critical *F* or *t*	Testwise alpha level	Significant time points (ms)	*M* voltage (μV)
180–300	ANOVA	configuration	4.06	.01	210–300	n/a
		laterality	6.98	.01	180–280	n/a
		interaction	3.86	.01	180–280	n/a
	t-test	matching:				
		-cue lateral	−2.29	.01	180–280	−1.28
		-context lateral	2.46	.01	—	—
		Nonmatching:				
		-cue lateral	2.57	.008	—	—
		-context lateral	−2.26	.01	180–280	−1.54
70–170 & 310–500	ANOVA	configuration	5.03	.003	310–420	n/a
		laterality	10.05	.004	110–140,	n/a
					160–170,	n/a
					330–460	n/a
		interaction	4.88	.004	310–450	n/a
	t-test	matching:				
		-cue lateral	±3.16	.003	120–130,	0.28,
					320–450	2.21
		-context lateral	±3.25	.003	110–130,	0.60,
					170,	−0.29,
					320–340	−0.45
		nonmatching:				
		-cue lateral	±3.29	.002	100–130,	0.27,
					330–350	−0.39
		-context lateral	±3.19	.003	110–130,	0.44,
					330–450,	1.65,
					490–500	−0.61

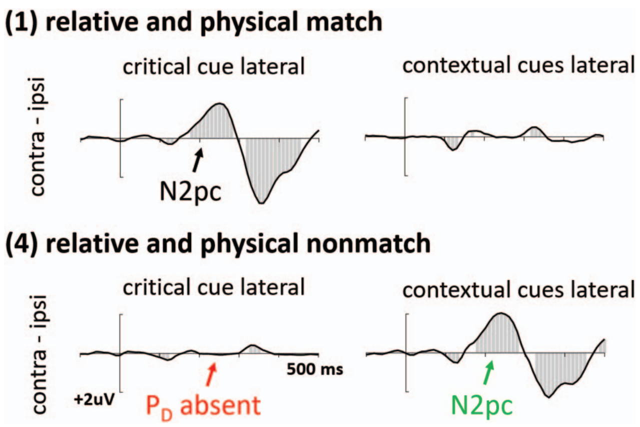

Figure 6. Group mean contra- minus ipsilateral difference waveforms in Experiment 4. contra - ipsil = contralateral, ipsilateral; N2pc = time range of the second negative going deflection of the visual ERP, and at posterior electrodes contralateral to a candidate target object; P_D = positivity to a distractor. See the online article for the color version of this figure.

(upper left panel in Figure 6) and to lateral context cues in the nonmatching cue condition (lower right panel).

We examined each of the four difference waves at all time points by *t*max tests as planned. In the conditions with nonmatching critical cues (lower panels), there was a negative deflection (N2pc) to contextual cues, as suggested by the context capture account. In contrast, there was no positive deflection (P_D) to critical lateral cues, which is at odds with the cue inhibition account.

In the matching cue conditions (upper panels), there was a substantial N2pc to the critical cue, indicating (unsurprising) attentional capture. In contrast, there was no positivity to the lateral context cues, providing no evidence for inhibition.

Second, we analyzed the interval before the N2pc time window. The *F*max test found a significant main effect of laterality in the time windows from 110 to 140 ms and from 160 to 170 ms. The *t*max tests of the difference waves revealed positivities from about 100 to 130 ms, for all cue configurations, corresponding to the main effect of laterality in that time window.

Third, we analyzed the interval after the N2pc time window. The main effects of configuration (from 310 to 420 ms) and laterality (from 330 to 460 ms) were modulated by a significant interaction (from 310 to 450 ms). The interaction suggests that positivities or negativities occurred as a function of configuration. For nonmatching cues, the *t*max tests confirmed positivities from 330 to 450 ms to lateral context cues, whereas there were negative deflections from 330 to 350 ms to the lateral critical cue. The opposite pattern was observed for matching cues where the critical cue yielded a positive deflection from 320 to 450 ms, whereas the contextual cues yielded a negative deflection from 320 to 340 ms.

Discussion

In the matching critical cue condition, the N2pc to the cue was comparable to earlier studies (Schönhammer et al., 2016), indicating that the addition of a neutral cue to the cue display was successful in reducing the attention-driving capacity of the neutral cue, which allowed for a better assessment of the cue inhibition and context capture hypotheses. Both the behavioral and electrophysiological results of Experiment 4 provided stronger support for context capture than inhibition. In the nonmatching condition, RTs were shorter on invalid than neutral trials, as predicted by context capture, but contrary to the inhibition hypothesis, RTs were not elevated on valid compared to neutral trials. Thus, there was no evidence for inhibition of the nonmatching items.

The ERP findings supported this conclusion. In the nonmatching cue condition, there was a significant N2pc to the lateral context cues, providing clear evidence that they captured attention. However, no P_D was observed to the critical cue, providing no evidence for cue inhibition. Thus, Experiment 4 suggests that same location costs are mainly the result of context capture.

As in Experiment 2, we obtained early and late ERP positivities. However, as in Experiment 2, the early positivity cannot be interpreted as evidence for cue inhibition, because it occurred indiscriminately across all conditions, and was not limited to nonmatching critical cues. The same was true of the late positivity, which followed a significant N2pc. Even though some studies linked the early and late positivities to inhibition (e.g., for de-allocating attention), recent research suggests that the early positivity reflects sensory adaption and the late positivity reflects enhancement of items in the target array (Livingstone et al., 2017). In conclusion, the results of Experiment 4 indicated that the same location cost is not due to inhibition of the critical cue, but attentional capture by the context cues.

General Discussion

Recent attentional capture studies found that cue arrays with nonmatching singleton cues resulted in effects that are consistent with cue inhibition. That is, cue arrays with nonmatching cues resulted in same location costs and a positive lateralized ERP, similar to a P_D. We asked whether these effects indeed arose because the singleton cue was inhibited (Gaspelin & Luck, 2018b; Harris et al., 2013; Schönhammer et al., 2016) or because the context cues captured attention (Becker et al., 2017; Harris et al., 2013; Schönhammer et al., 2017).

RT Validity Effects Indicated Context Capture (and Misleading or Spurious Effects of Inhibition)

To distinguish between cue inhibition and context capture, we added gray cues to the cue arrays, which we considered neutral relative to the target and nontarget colors. RTs on trials where these gray cues were shown at the target location (neutral trials) were used as benchmark for RTs on valid and invalid trials. We first checked that matching cues captured attention and facilitated subsequent target selection, as postulated by current theories of attentional capture (Folk et al., 1992; Posner, 1980). We found that cue arrays with a relatively matching cue yielded shorter RTs in valid than neutral trials (see black asterisks in Figure 3), which corresponds to the expected result. Then, we proceeded to the crucial test of the context capture account. For relatively nonmatching cues, we found shorter RTs when the context cues were shown at the target location (invalid trials) than when a neutral cue was shown at the target location. Similar to valid trials with matching cues, we observed reduced RTs on invalid trials with nonmatching cues. Taken together, these findings indicate that context cues captured attention in the nonmatching cue conditions where the context feature corresponded to the relative target feature. Evidence for the context capture account was consistent across Experiments 1–4.

In contrast, initial support for the cue inhibition account turned out to be compromised by the flawed neutral condition. In Experiments 1 and 2, cue arrays with a nonmatching critical cue showed longer RTs on valid than neutral trials. However, the neutral cues in Experiments 1 and 2 probably had some attention-driving capacity because they were the only achromatic items, which may have made them salient or rendered them more similar to the target by virtue of being a singleton. Thus, the shorter RTs on neutral than on invalid trials in the relatively nonmatching cue conditions might have resulted from facilitated target processing on neutral trials, rather than from inhibition on invalid trials. The ERP results of Experiment 2 and the results of Experiments 3A/B and Experiment 4 supported this interpretation. When two gray cues were shown in Experiments 3A/B and 4 to reduce the saliency of the neutral cues and eliminate their singleton status, RTs were not consistently longer with valid than neutral cues in the relatively nonmatching conditions. Only the relatively and physically nonmatching cue condition in Experiment 3A yielded slower RTs on valid than neutral trials, indicative of inhibition, and the relatively nonmatching and physically matching cue only showed a small effect in the errors (see Table 1). Finally, in Experiment 4, effects of inhibition were entirely absent. Importantly, Experiment 4 had almost four times as many trials as Experiment 3A in the cue condition with relatively and physically nonmatching. Thus, the effects in support of inhibition obtained in Experiment 3A may have been spurious.

ERPs in the N2pc Time Window Indicated Context Capture

In addition to RTs, we examined ERPs in Experiments 2 and 4. For each cue array, the critical cue was presented laterally and the context cues vertically (or vice versa), to isolate the lateral ERPs to the critical singleton cue and the context cues. Experiment 2 indicated that a matching critical cue and the context cues with nonmatching critical cues captured attention, since we obtained N2pcs in these conditions. However, the observed N2pcs were unusually small. Experiments 3 and 4 indicated that this may have been the case because the neutral cue competed strongly for attention, either because it was salient or because it matched an attentional set for singletons, which, consequently, decreased the magnitude of the N2pc to contralateral items. Nonetheless, Experiment 2 showed reliable negativities in both cases. Furthermore, we did not obtain significant ERP positivities for nonmatching critical cues, suggesting that the singleton cue was not inhibited.

In Experiment 4, we reduced competition from the gray neutral cues and obtained larger N2pcs, suggesting that matching critical cues and, more importantly, the context cues in the nonmatching cue condition captured attention. These findings again supported the context capture account and indicated that the N2pc-components in Experiment 2 were in fact reduced due to competition from the neutral cue. As in Experiment 2, we did not observe any ERP positivities for the critical cue in the nonmatching condition, indicating that nonmatching features were not inhibited. Thus, in sum, the ERPs in the N2pc time window supported the hypothesis that context cues capture attention, whereas evidence for the inhibition of nonmatching singleton cues was sparse or absent.

ERP Modulations Outside the N2pc Time Window

In both ERP Experiments, we found early lateralized positivities in the P1 range across all cue conditions, irrespective of whether the lateralized item matched the relative target color or not. Hence, the findings do not support the idea that the positivity was due to the suppression of an attend-to-me signal (Sawaki & Luck, 2010). Moreover, these early positivities occurred irrespective of whether the lateralized cue element was a feature singleton. Thus, the current findings also do not support the hypothesis that the early positivities occur in response to the most salient item in an array (Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012) or that they indicate the initial spatial selection of salient items (Fortier-Gauthier et al., 2012). Instead, the positivity might indicate sensory adaption (Luck & Hillyard, 1994a). Sensory adaption might have occurred because very similar colors were repeated in the cue and target arrays.

Moreover, in a later time window, we obtained a large lateralized positivity after the N2pc, and only for those cues that produced a significant N2pc (i.e., relatively matching critical cues or context cues). The first studies attributed these positives to the suppression of a selected item after attentional capture, possibly reflecting disengagement of attention from the cue location (Mertes & Schneider, 2018; Mertes et al., 2016; Sawaki & Luck, 2013). In subsequent research, the time interval between cue and target array was varied, and it was found that the positivity is time-locked to the target array and is therefore unrelated to attentional capture by the cue. Instead it was concluded that the positivity indicated the enhancement of the item in the target array that was presented at the attended location (Livingstone et al., 2017). This interpretation would align with the context capture account, as the ERP modulations outside the N2pc time window would show that context cues or critical cues with the (relative) target color resulted in enhancement of the subsequent item in the target array, in line with the behavioral results. However, further research would be required to pinpoint the source of the nonpredicted early and late negative and positive deflections. Overall, the results of the present study strongly support the view that the context cues attract attention and produce the pattern of results that has often been interpreted as evidence for inhibition of the critical cue. In contrast, evidence for inhibition of the critical cue was absent or could not be interpreted as such with certainty.

Implications for Theories Feature Weighting

The RT experiments (Experiments 1, 3A, 3B) support the relational account, which proposes that features are encoded in a relational manner when target and nontarget colors are fixed across trials. Critical cues captured attention when they matched the relative target color (cue Conditions 1 and 2) and did not capture attention when they had the opposite relative target color (cue Conditions 3 and 4). The ERP experiments

(Experiments 2 and 4) are in line with the relational account as well, even though they do not unequivocally support this model. Conversely, we did not find evidence for the inhibition of items with the physical or relative nontarget color, which would have supported models of feature-specific enhancement and inhibition (e.g., Navalpakkam & Itti, 2007). Importantly, however, evidence for the latter models was observed in previous studies using the additional singleton paradigm coupled with a probe task (e.g., Chang & Egeth, 2019; Gaspelin, Leonard, & Luck, 2017; Gaspelin & Luck, 2018a, 2018b). Studies reporting evidence for suppression in early attentional measures (ERPs and eye movements; e.g., Gaspelin et al., 2017; Gaspelin & Luck, 2018a, 2018b) have, however, been criticized for being unable to distinguish between distractor suppression and enhancement of the target color (cf. Chang & Egeth, 2019). The study of Chang and Egeth (2019) disentangled target enhancement from distractor suppression by introducing neutral colors and presenting either only the target color or only the distractor color in the probe display. However, this study was based on behavioral measures, leaving it open whether slower responses to distractor-colored probes were due to early attentional suppression or delayed responding due to interference in later processes, such as response selection. That is, it may have been more difficult to respond to the distractor color because it was associated with an irrelevant item that needed to be ignored on search trials. Moreover, most of the search arrays providing evidence for suppression (e.g., Gaspelin et al., 2015; Gaspelin & Luck, 2018a, 2018b; Chang & Egeth, 2019) contained nontargets with inhomogeneous features. Consequently, these results do not directly contradict our findings because our target arrays contained homogenous nontargets. In sum, more research is required to examine whether performance decrements in the probe task are due to attentional suppression of the distractor color, attentional prioritization of the context items, or later processes (e.g., response inhibition).

Implications for Theories of the Spatial Distribution of Attention

Traditionally, theories of attention have conceptualized attention as a single focus that is allocated to a single item at a time (Folk et al., 1992; Jonides, 1981; Treisman, 2006). However, the present results clearly indicate that the context cues in the relatively nonmatching conditions capture attention, even though all cue displays contained two context cues, which calls for a split, divided, or enlarged focus of attention (Jans, Peters, & De Weerd, 2010). How can current theories of attention deal with the finding that RTs were shorter at two locations (context cues in cue Conditions 3 and 4) and that N2pcs were obtained to two lateral context cues (cue Condition 4)?

One possibility is that, on each trial, only one of the two context cues captured attention. Because the mean RTs and N2pcs result from averaging across trials, these measures cannot clearly discriminate between this account and accounts that claim parallel attentional selection of two context cues. However, if only one context cue had captured attention, one might have expected more variable context capture effects than actually observed, because the target was equally likely to follow at the location of any of the two cues (which would have been randomly attended vs. nonattended). Another possibility is that all cue elements were quickly scanned in a serial manner. It has been demonstrated that attention can move very rapidly from one item to the next (Eimer, 2014; Grubert & Eimer, 2015). However, these rapid serial attention shifts were found in response to items with different onsets and, hence, attention might have been allocated at a slower speed in the current study. Finally, attention might have been deployed to both matching context cues simultaneously, either only when the two cues were at adjacent locations, or even when they were separated by nonmatching or neutral cue elements (Experiment 3). In line with this possibility, it has been argued that attention can be allocated in parallel to candidate target items (Eimer, 2014). Additionally, it has been demonstrated that attentional facilitation can cover large sets of items across the visual field simultaneously, even when these are not contiguous (Belopolsky, Schreij, & Theeuwes, 2010; Kerzel, Born, & Schönhammer, 2012). The results of the present study do not allow deciding between the different possibilities, but indicate that target-matching items can strongly attract attention regardless of whether they are singletons with a unique feature or not.

Conclusion

Recent studies examined how attention is tuned to a predefined color target by assessing attentional capture in the modified spatial cueing paradigm. Curiously, cues that did not match the relative target feature resulted in same location costs and a P_D-like ERP. Both findings were previously linked to spatial inhibition. Here, we examined whether the nonmatching critical cues were indeed inhibited, or whether the effect was instead due to attentional capture by the context cues. The results clearly favored the context capture hypothesis, rendering it likely that context cues also captured attention in previous studies where they were presented together with a nonmatching singleton cue. By contrast, we found only little evidence for inhibition of the nonmatching singleton cue. The context capture hypothesis can explain a wide range of same location costs obtained in studies that examined relational (Becker et al., 2017; Harris et al., 2013; Schoeberl et al., 2018; Schönhammer et al., 2016; Schönhammer & Kerzel, 2020) and feature-specific search settings (Lien et al., 2010; Schönhammer et al., 2017; Schönhammer et al., 2016). However, further research is required to examine why context cues with the relative target feature sometimes fail to capture attention (e.g., Becker et al., 2013). Moreover, further research is required to clarify whether other same location costs are due to genuine inhibition (Belopolsky et al., 2010; Folk & Remington, 2008) or different mechanisms (Carmel & Lamy, 2014), and how attention is allocated to multiple context cues.

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