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Salient-but-irrelevant stimuli cause attentional capture in difficult, but attentional suppression in easy visual search

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Abstract

Search for a shape target is difficult when its shape is similar to the shape of the surrounding nontargets and easy when it is dissimilar. We asked whether interference from a salient but irrelevant color singleton depended on search difficulty as manipulated by target-nontarget similarity. We found that interference was strong in difficult searches, and the occurrence of an electrophysiological index of attentional selectivity (the N2pc component) confirmed that attention was captured by the distractor. In contrast, interference from the distractor was weak with easy searches, and the occurrence of the P_D component confirmed that saliency signals from the distractor were suppressed. The results suggest that attentional suppression of salient but irrelevant distractors is only possible when search is efficient (i.e., with low target-nontarget similarity), otherwise, attentional capture occurs. Further, we analyzed the Ppc component, a positivity occurring between 100 and 200 ms after stimulus onset contralateral to a salient feature discontinuity. It has been suggested that the Ppc reflects bottom-up saliency signals, but we found the Ppc to occur only when the salient stimulus was unlikely to be selected, as in efficient searches. Thus, attentional requirements modulate the Ppc component.

KEYWORDS

attention, attentional capture, attentional suppression, N2pc, P_D, Ppc, visual search

1 | INTRODUCTION

Search for a particular target object is hard when it shares features with the surrounding nontarget objects, but easy when target and nontarget objects are distinct (Duncan & Humphreys, 1989). For instance, looking for a particular pen in a drawer full of pens is hard, but looking for an eraser in the same drawer is easy. Now imagine that one of the pens is in a salient, fluorescent color, would you be more distracted by it during search for the pen or during search for the eraser? Further, if you looked for the fluorescent pen, would the eraser cause any distraction? In the current contribution, we address two questions. First, is distraction by salient-but-irrelevant stimuli stronger during easy or hard search? Second, is stimulus saliency processed in the same manner when the salient element is the target as when the salient element is the distractor?

1.1 | Saliency in the additional singleton paradigm

To answer these questions, we will use the additional singleton paradigm developed by Theeuwes (1991) where target and distractor are defined along different perceptual dimensions, such as color and shape. In the most frequently replicated condition, observers searched for a shape singleton (i.e., a unique shape) and indicated the orientation of the line inside. On some of the trials, a response-irrelevant color singleton (i.e., a unique color) was shown. Reaction times (RTs) were longer when the color singleton was present, suggesting that attention was captured by the irrelevant color singleton (for alternative accounts, see Folk & Remington, 1998; Jannati, Gaspar, & McDonald, 2013; for review, see Lamy, Leber, & Egeth, 2012; Theeuwes, 2010). In contrast, when observers searched for a color-defined target, there was no interference from shape distractors. The reason for the asymmetric interference was that the color singleton was more salient than the shape singleton. When the difference in color was reduced and the difference in shape increased, the opposite pattern was observed: Search for the more salient shape singleton was unaffected by the less salient color singleton, and search for the less salient color singleton was strongly affected by the more salient shape singleton. Thus, distraction from irrelevant stimuli is limited to situations where the distractor is more salient than the target (but see Zehetleitner, Koch, Goschy, & Müller, 2013).

Interference from stimuli that are more salient than the target is consistent with saliency-map models of visual search (e.g., Cave & Wolfe, 1990; Itti & Koch, 2001; Li, 2002; Navalpakkam & Itti, 2007; Treisman & Sato, 1990). According to these models, feature maps (e.g., for features like red, green, vertical, horizontal) feed local contrast computations into a saliency map that represents saliency irrespective of the feature map. Consequently, a location may be salient, but the salient feature can no longer be identified. Further, it is assumed that attention is initially drawn to the location of highest saliency (see also Fellrath, Manuel, & Ptak, 2014; Theeuwes, 2010). To explain attentional capture by salient-but-irrelevant distractors, saliency-map models suggest that attention moves to a salient location even though its saliency derives from a task-irrelevant dimension. Saliency-map models also explain why distractors less salient than the target do not capture attention. If attention moves to the most salient location first, attention would avoid the location of a less salient distractor and move directly to the more salient target.

1.2 | Conditions resulting in attentional capture or suppression

Electrophysiological evidence for attentional captures relies on the most widely accepted electrophysiological correlate of attentional selection, the N2pc component. The N2pc is a negativity contralateral to the selected stimulus at posterior sites (PO7/PO8) between 200 to 300 ms after display onset (Eimer, 1996; Luck & Hillyard, 1994). The N2pc is easily observed for targets presented to the left or right of fixation, but may also indicate whether a distractor has been selected instead of the target (Hickey, McDonald, & Theeuwes, 2006; Woodman & Luck, 2003). To this end, the target is placed directly above or below central fixation so that no lateralized ERP results, and the distractor is placed on the left or right so that an N2pc will indicate whether the distractor has been selected. An N2pc to a salient-but-irrelevant stimulus has been reported (Burra & Kerzel, 2013; Hickey et al., 2006; Hilimire & Corballis, 2014; Kiss, Grubert, Petersen, & Eimer, 2012), suggesting that attention does indeed move to the most salient element.

However, other studies reported that a positivity instead of a negativity occurred contralateral to the distractor (e.g., Burra & Kerzel, 2013; Hickey, Di Lollo, & McDonald, 2009; Hilimire, Hickey, & Corballis, 2012; McDonald, Green, Jannati, & Di Lollo, 2013; Sawaki & Luck, 2010). The positivity was referred to as P_D and occurred at the same electrode sites and in about the same time interval as the N2pc. It was proposed that the P_D indicates attentional suppression of the distractor (Hickey et al., 2009). Attentional suppression may be implemented by optimally adjusting the weights of visual features (Navalpakkam & Itti, 2007) and may be preceded by an “attend-to-me” signal from the salient stimulus (Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010), corresponding to a positivity between 100 and 200 ms, which is referred to as Ppc (Barras & Kerzel, 2016; Fortier-Gauthier, Moffat, Dell’Acqua, McDonald, & Jolicœur, 2012; Gokce, Geyer, Finke, Mueller, & Töllner, 2014; Jannati et al., 2013).

Why did some studies observe attentional capture (N2pc) and others attentional suppression (P_D) of salient-but-irrelevant distractors? We recently suggested that the trial context may explain the different results (Burra & Kerzel, 2013). Attentional capture (i.e., an N2pc to the distractor) was observed when target and nontarget shapes swapped roles randomly from trial to trial and behavioral interference was large (Burra & Kerzel, 2013; Hickey et al., 2006; Hilimire & Corballis, 2014; Kiss et al., 2012). In contrast, attentional suppression (i.e., a P_D to the distractor) occurred reliably when the target was fixed and interference from the distractor was small (Burra & Kerzel, 2013; Jannati et al., 2013).

The absence of a fixed target may degrade the search goals (i.e., the “attentional set”) of the participant (see also Barras & Kerzel, 2016; Lamy & Yashar, 2008). For instance, in saliency-map models, the contribution of each feature map to the overall saliency map may be adjusted by the current top-down goals of the observer (Itti & Koch, 2001; Navalpakkam & Itti, 2007). With fixed target features, the weight of the relevant feature map may be increased, which will give it a higher activation in the saliency map and facilitate search. With unpredictable target features, feature weights cannot be adjusted before stimulus onset and search times will be longer. In sum, the stimuli in fixed and variable search were equally salient, but presented in a different order (random vs. blocked), which affected both target and distractor processing: When the search target varied unpredictably, search was difficult, behavioral interference was large, and attentional capture (as evidenced by an N2pc to the distractor) occurred. When the search target was fixed, search was easy, behavioral interference was small, and attentional suppression (as evidenced by a P_D to the distractor) occurred.

1.3 | Stimulus-driven differences in search difficulty

In Experiment 1, target predictability was fixed because the same target shape was used throughout. However, characteristics of the nontarget stimuli were manipulated to change search efficiency. Building on the difference between variable and fixed targets, we expect the impact of salient distractors to be larger with difficult than with easy searches. It is known that overlapping target and nontarget features result in difficult, while distinct target-nontarget features result in easy search (Duncan & Humphreys, 1989). To explain effects of target-nontarget similarity, saliency models (e.g., Navalpakkam & Itti, 2007) refer to differences in the signal-to-noise ratio. The ratio of signal strength (i.e., target salience) and noise strength (i.e., nontarget salience) is low with high target-nontarget similarity, which reduces the efficiency of search.

Little is known about the electrophysiological correlates of distractor processing as a function of target-nontarget similarity. In the most common version of the additional singleton paradigm, target-nontarget similarity refers to the similarity between the shape of the target singleton and the shape of the nontarget elements. For our purposes, it is important to understand that target-nontarget similarity is directly related to target saliency: Targets with high target-nontarget similarity do not stand out among the nontargets and are therefore less salient than targets with low target-nontarget similarity. In contrast, the saliency of the color distractor does not change as a function of shape-based similarity (see Experiment 2). Therefore, targets with high target-nontarget similarity are not only less salient relative to the nontarget shapes, but are also less salient relative to the color distractor. Looked at from the other side, the same color distractor is more salient relative to a target with high target-nontarget similarity than relative to a target with low target-nontarget similarity. Because distractors with relatively greater saliency will capture attention more (Theeuwes, 1991, 1992), stronger interference is expected with high than with low target-nontarget similarity. Thus, we predict that attentional capture, as evidenced by an N2pc to the target, will occur with high target-nontarget similarity (less salient target, difficult search). Based on the outcomes of studies with fixed versus variable targets, we may also expect attentional suppression, as evidenced by a P_D, for low target-nontarget similarity (salient target, easy search).

In contrast, current theories proposing mechanisms of signal suppression (Jannati et al., 2013; Sawaki & Luck, 2010) also stem from salience-map models, but would predict suppression of irrelevant distractors regardless of target-nontarget similarity because the difficulty of the primary search task is not considered. Further, a previous behavioral study reported results opposite to our predictions. Proulx and Egeth (2006) concluded that increasing target-nontarget similarity reduced the impact of a salient distractor. However, search in that study was inefficient even with low target-nontarget similarity. All search slopes in their study were larger than 22 ms/item, whereas search slopes were essentially flat (less than 10 ms/item) in research on the additional singleton paradigm (e.g., Theeuwes, 1991, 1992).

2 | EXPERIMENT 1

Thus, Experiment 1 attempted to resolve the contradiction between predictions derived from saliency-map models of visual search, current models of signal suppression, and the previous study of Proulx and Egeth (2006) by comparing efficient searches that are typical of the additional singleton paradigm to less efficient searches. Participants were asked to locate the target square in the stimulus array and to indicate the orientation of the line inside by key press. Target-nontarget similarity was low when the nontargets were circles, but it was high when nontargets were diamonds, that is, squares rotated by 45° (Von Grünau, Dube, & Galera, 1994). In order to measure ERPs to the distractor, we used a set size of eight so that two elements could be placed on the vertical midline, above and below the fixation point (see Figure 1). While elements placed on the vertical midline do not elicit lateralized ERP components, lateral elements do. Our focus was on a spatial configuration where the distractor was placed on a lateral position and the target on the vertical midline, allowing us to attribute any lateralized component to distractor processing (Hickey et al., 2006). We compared the configuration with lateral distractor to a control condition where the target was on a lateral position and the distractor was absent. The remaining spatial configurations were not analyzed and mainly served to make target and distractor positions unpredictable.

2.1 | Method

2.1.1 | Participants

Eighteen undergraduate psychology students at the University of Geneva participated in exchange for class credit. They were naive as to the purpose of the experiment. All had normal or corrected-to-normal vision. The experiment was approved by the local ethics committee, and informed consent was obtained from participants prior to the experiment. Three subjects were excluded because of eye movements or bad signal quality, leaving 15 participants in the final analyses.

2.1.2 | Stimuli

Subjects were seated in a dimly lit room at 80 cm from a 17" LCD monitor running at 60 Hz with 1,920 × 1,080 pixels resolution. The background was black with a central fixation cross and eight shapes presented at an eccentricity of 5°. The

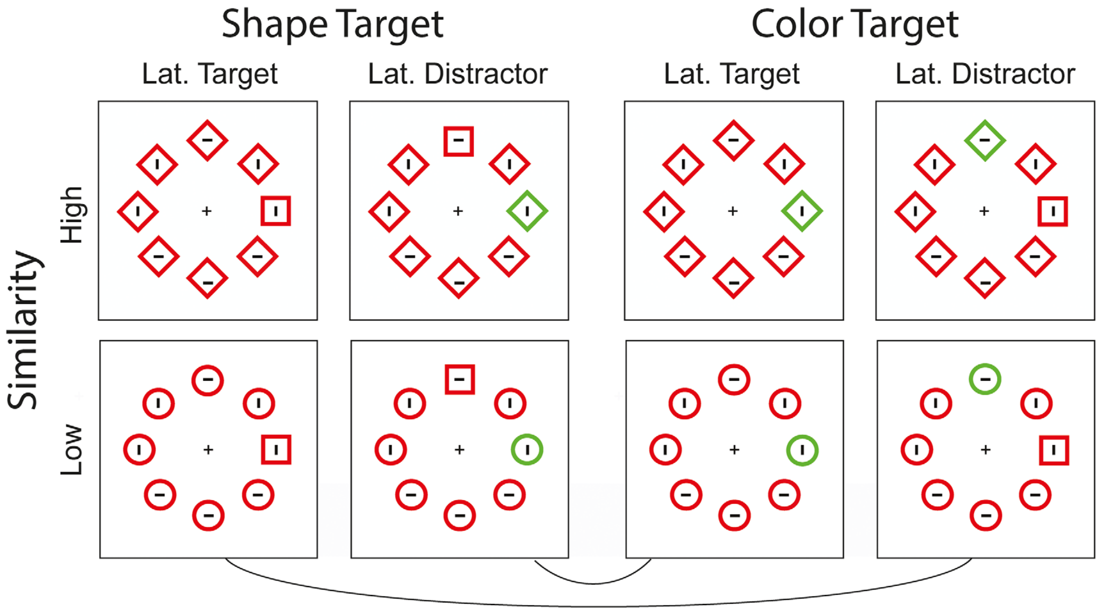

FIGURE 1 Illustration of experimental stimuli. In Experiment 1, the target was a shape singleton (a square) and the distractor a color singleton (left). In Experiment 2, the target was a color singleton (e.g., green) and the distractor was a shape singleton (a square, right). Shape-based similarity was high when nontargets were diamonds (top) and low when they were circles (bottom). Nontarget shape affected target-nontarget similarity in Experiment 1 because the target was a shape singleton. In contrast, nontarget shape affected distractor-nontarget similarity in Experiment 2 because the distractor was a shape singleton. We show spatial configurations where either the target or the distractor was shown on the same lateral position. In the experiments, all three lateral positions were equally frequent, but only the central position is shown for simplicity. The connecting lines below show columns with the same lateral element. Lat = lateral

target shape was always a square, whereas the nontarget shapes were unpredictably either diamonds or circles. The circle had a diameter of 2.2° and the square/diamond had a side length of 1.7°. Line width was ~0.06°. On 50% of the trials, one nontarget element, the distractor, had a distinct color, and these trials are referred to as distractor-present trials. In the remaining 50% of trials, only the target color was presented. Stimuli were either green with a red distractor or red with a green distractor. To avoid luminance differences, the size and line width of the shapes were adjusted to yield about the same number of lit pixels (1,047, 1,034, and 1,036 for the square, diamond, and circle, respectively). Thus, the luminance difference between the two nontarget shapes (diamond and circle) was negligible (2 pixels or 0.2%). Each shape contained either a vertical or a horizontal gray line of 0.7° length. The luminance of all stimuli was 16.6 cd/m^2. There was always a stimulus at the three o'clock position. Placement of target and distractor, nontarget shape, and distractor presence varied unpredictably from trial to trial. The color of nontargets and distractor was swapped randomly from trial to trial to increase interference effects compared to constant colors (Kerzel & Barras, 2016). The following configurations were shown to make target and distractor position appear random (see Gaspar & McDonald, 2014): lateral target, no distractor (33%); midline target, no distractor (17%); lateral target, midline distractor (11%); lateral target, ipsilateral distractor (11%); lateral target, contralateral distractor (11%); midline target, lateral distractor (11%); midline target, midline distractor (6%).

2.1.3 | Procedure

A trial started with the presentation of the fixation cross for a randomly selected duration between 0.85 and 1.2 s followed by the presentation of the stimuli that stayed on the screen until a response was registered. Participants were told to find the square and report the orientation of the line inside the shape by pressing one of two keys (left or right arrow keys). They were instructed to ignore the color distractor and to respond as quickly as possible while maintaining accuracy above 90%. False alarms, anticipations ($RT < 0.2$ s), late trials ($RT > 1.5$ s), or choice errors were reported to the subject by visual feedback. Participants performed 64 practice trials before the experiment and were forced to take breaks of 15 s after blocks of 48 trials. Performance feedback was shown during breaks. Participants completed two sessions at 2 weeks' interval (same day and same hour). In each session, 1,152 trials were acquired for a total of 2,304 trials.

2.1.4 | Electrophysiological recording and analysis

An actiCHamp amplifier (Brain Products, Gilching, Germany) with 32 active Ag/AgCl electrodes sampled at 1000 Hz was

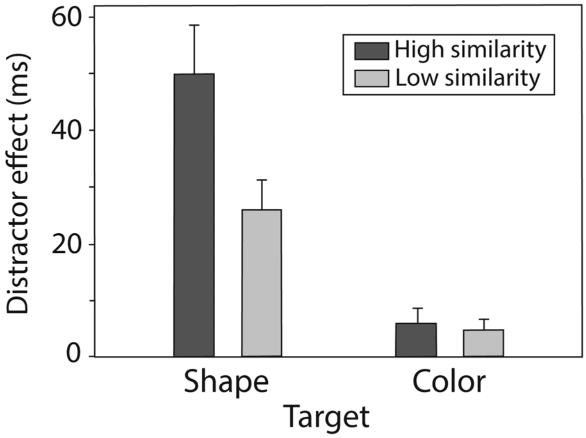

FIGURE 2 The distractor effects in Experiment 1 and 2 are shown on the left and right side of the graph as a function of shape-based similarity. The distractor effect is the difference between distractor-present and distractor-absent trials. In Experiment 1, the target was a shape singleton that was similar or dissimilar with respect to the nontarget shapes. The distractor was a color singleton. In Experiment 2, the target was a color singleton and the shape distractor was either similar or dissimilar with respect to the nontarget shapes. Error bars show the standard error of the mean

used. We fixed 26 electrodes on the scalp, two at the outer canthi of each eye (HEOG), one above and one below the right eye (VEOG), and one on each earlobe for offline reference. FCz served as online reference.

The data were rereferenced to the average earlobes, band-pass filtered between 0.1 and 30 Hz, and baseline-corrected using the first 100 ms of each epoch. EEG epochs extended from 100 ms before to 400 ms after stimulus onset. We excluded trials with blinks and vertical eye movements based on the difference between the upper and lower eye electrode (VEOG ± 60 mV), horizontal eye movements based on the difference between the right and left electrode (HEOG ± 50 mV), and muscular artifacts based on the remaining electrodes (± 100 mV). We computed the average for left and right distractor separately and rejected two subjects whose HEOG from 0 to 300 ms was larger than ± 3 mV. On average, 8.4% of the trials were removed due to incorrect responses or artifacts.

2.2 | Results

2.2.1 | Behavioral performance

The mean difference between distractor-present and distractor-absent trials (distractor effects) are shown in Figure 2. A 2 (Target-Nontarget Similarity: high, low) × 2 (Color Distractor: present, absent) repeated measures analysis of variance (ANOVA) showed that RTs were shorter with low than with high target-nontarget similarity (682 vs. 771 ms), $F(1,14) = 37.55$, $p < .001$, $\eta_p^2 = .728$, confirming that our manipulation of nontarget shapes was successful. RTs were shorter when the distractor was absent compared to when it was present (688 vs. 725 ms), $F(1,14) = 31.25$, $p < .001$, $\eta_p^2 = .691$. Importantly, the interaction, $F(1,14) = 20.69$, $p < .001$, $\eta_p^2 = .597$, showed that the distractor effect was larger with less salient targets in the high target-nontarget similarity condition (50 ms) than with salient targets in the low similarity condition (25 ms). Both means were significantly different from zero, $ts(14) > 4.62$, $ps < .001$. The analysis of choice errors (3.8%) provided no evidence for speed-accuracy tradeoff.

2.2.2 | N2 interval

Mean ERPs and difference waves are shown in Figure 3a,c, respectively. The N2pc/P_D time window corresponds to 240–280 ms, which is shown as the colored area in Figure 3a and as the darkest gray area in Figure 3c. The time window was chosen to be close to the peak of the N2 and to include the maximal N2pc amplitude. The time range was adapted to 270–310 ms for lateral distractors with high target-nontarget similarity to reflect the later peak of the difference waves (see Figure 3c and analysis of latencies below). A 2 (Lateral Stimulus: target, distractor) × 2 (Target-Nontarget Similarity: low, high) repeated measures ANOVA was run on the voltage difference between contra- and ipsilateral ERPs at electrodes PO7/PO8. The voltage difference was more negative with lateral targets than with lateral distractors (−0.98 vs. −0.11 μV), $F(1,14) = 7.08$, $p = .019$, $\eta_p^2 = .336$, indicating that an N2pc occurred with lateral targets. The interaction of lateral stimulus and similarity, $F(1,14) = 13.87$, $p = .002$, $\eta_p^2 = .498$, showed that the N2pc to lateral targets was larger with low than with high target-nontarget similarity (−1.21 vs. −0.75 μV), $t(14) = 1.80$, $p = .094$, whereas there was a P_D to lateral distractors with low but an N2pc with high target-nontarget similarity (0.40 vs. −0.63 μV), $t(14) = -3.41$, $p = .004$. Results of t tests against zero for each of the four conditions showed that, with lateral targets, the N2pc was significant for low, $t(14) = -3.47$, $p = .004$, and high target-nontarget similarity, $t(14) = -2.28$, $p = .039$. With lateral distractors, there was a significant P_D with low, $t(14) = 3.03$, $p = .009$, and a significant N2pc with high target-nontarget similarity, $t(14) = -2.92$, $p = .011$. The four t tests were significant after controlling the false discovery rate of a family of hypothesis tests (Benjamini & Hochberg, 1995).

2.2.3 | Latency of N2pc

We compared the jackknife-averaged latencies with 70% of the peak amplitude as criterion (Ulrich & Miller, 2001). Only the conditions with an N2pc were included in a one-way ANOVA (lateral target with low or high target-

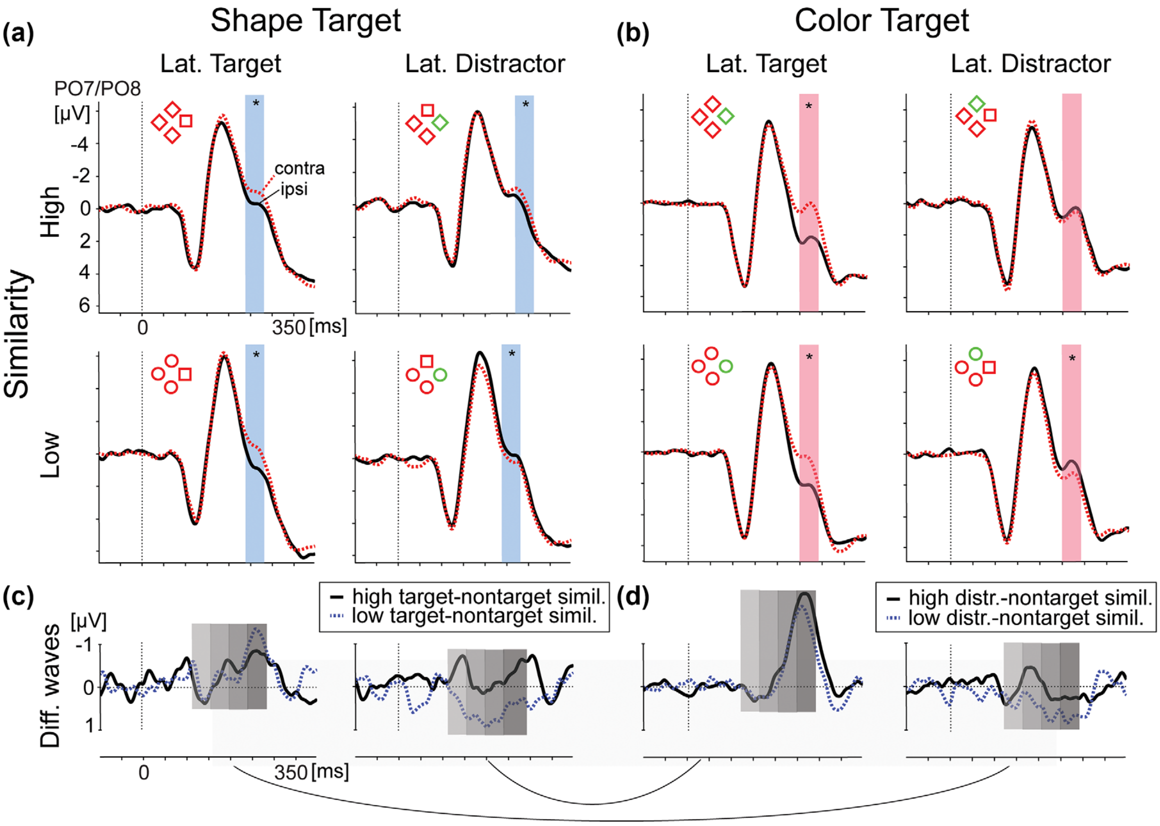

FIGURE 3 Electrophysiological results from (a,c) Experiment 1 with shape target and from (b,d) Experiment 2 with color target. The upper diagrams show the grand-averaged contralateral and ipsilateral ERPs at electrodes PO7 and PO8 as a function of shape-based similarity (high, low) and lateral stimulus (target, distractor). The difference waves show the difference between contra and ipsilateral ERPs for the four experimental conditions. The shaded areas indicate the averaging intervals. The interval with the N2pc component is shown in blue and red in Panel a,b, respectively, and in the darkest shade of gray in Panel c,d (Experiment 1: ~240–280 ms; Experiment 2: 250–290 ms). The three intervals with the Ppc component are shown in light gray in Panel c,d (Experiment 1: 120–160, 160–200, 200–240 ms; Experiment 2: 130–170, 170–210, 210–250 ms). Lat = lateral; Simil = similarity; Distr = distractor

nontarget similarity, lateral distractor with high target-nontarget similarity). The main effect of condition was significant, $F_{adjusted}(2,28) = 5.9$, $p = .007$, showing that the N2pc occurred later to the lateral distractor with high target-nontarget similarity (272 ms) than to lateral targets with low (240 ms) or high (239 ms) target-nontarget similarity.

2.2.4 | N1 interval

We calculated the mean voltage difference (contra − ipsi) in three consecutive time ranges from 120 to 240 ms, which covers the N1 interval and comprises the Ppc component. Time intervals are shown as light shades of gray in Figure 3c. Shortening the interval to 120–200 ms instead of 120–240 ms did not affect the results. A 2 (Lateral Stimulus: target, distractor) × 2 (Target-Nontarget Similarity: low, high) × 3 (Time Range: 120–160, 160–200, 200–240 ms) repeated measures ANOVA was run. The voltage difference was more negative with lateral targets than with lateral distractors (−0.18 vs. 0.24 µV), $F(1,14) = 11.77$, $p = .004$, $\eta_p^2 = .457$, and with high compared to low target-nontarget similarity (−0.18 vs. 0.24 µV), $F(1,14) = 12.77$, $p = .003$, $\eta_p^2 = .477$. The interaction of lateral stimulus with time, $F(2,28) = 14.98$, $p < .001$, $\eta_p^2 = .517$, showed that the voltage difference became more negative over time with lateral targets (0.17, −0.31, −0.4 µV), indicating the onset of the N2pc, whereas it became more positive with lateral distractors (−0.07, 0.4, 0.4 µV) indicating the onset of the P_D. Importantly, the interaction of lateral stimulus and similarity was significant, $F(1,14) = 5.28$, $p = .038$, $\eta_p^2 = .274$, showing that low and high target-nontarget similarity did not differ for lateral targets (−0.17 vs. −0.18 µV), whereas the lateralized ERP was more positive with low than high target-nontarget similarity for lateral distractors (0.66 vs. −0.18 µV).

To follow up on the interactions, we ran 2 (Target-Nontarget Similarity: low, high) × 3 (Time Range: 120–160, 160–200, 200–240 ms) ANOVAs, separately for lateral targets and lateral distractors. The ANOVA on the voltage difference to lateral targets revealed a main effect of time, $F(2,28) = 8.47$, $p = .001$, $\eta_p^2 = .377$, and no effect of target-nontarget similarity, $p = .973$. The ANOVA for lateral distractors revealed a main effect of time, $F(2,28) = 7.54$, $p = .002$, $\eta_p^2 = .35$, and confirmed the effect of target-nontarget similarity, $F(1,14) = 11.26$, $p = .005$, $\eta_p^2 = .446$. The absence of an interaction between time and target-nontarget similarity showed that the contralateral positivity to distractors with low target-nontarget similarity was present early in the N1 interval and persisted into the N2 interval. To evaluate whether the Ppc to distractors in the condition with low target-nontarget similarity was significant, we ran *t* tests against zero and found the means for all time intervals to be significantly different, $ts(14) > 2.81$, $ps < .014$.

2.3 | Discussion

Behaviorally, we observed larger interference from a salient color singleton with high than with low target-nontarget similarity. That is, inefficient search (less salient shape target, high target-nontarget similarity) was more strongly disrupted by salient-but-irrelevant stimuli than efficient search (salient shape target, low target-nontarget similarity). This result is at odds with a previous study by Proulx and Egeth (2006) who reported the opposite pattern. Most likely, the discrepancy results from the different search types. In a related study (Barras & Kerzel, in press), we observed that the search slopes with the present stimuli were 5.9 and 16.4 ms/item for low and high target-nontarget similarity, respectively, while all search slopes were larger than 22 ms/item in Proulx and Egeth's study. Further, the electrophysiological results confirm the predicted effect of target-nontarget similarity on visual interference. With high target-nontarget similarity and difficult search, behavioral interference was large and an N2pc to the color distractor occurred, signaling attentional capture. With low target-nontarget similarity and easy search, behavioral interference was smaller and a P_D to the color distractor occurred, signaling attentional suppression.

Surprisingly, analysis of the N1 interval showed that the effects of target-nontarget similarity occurred earlier in distractor than in target processing. Differences between ERPs to lateral targets with high and low similarity to the nontargets were not visible in the N1 time interval. In contrast, there was an early positivity to the lateral color distractor with low target-nontarget similarity, but not with high target-nontarget similarity. The positivity between 120 and 200 ms poststimulus is consistent with the time interval of the Ppc component between 140–190 ms (Barras & Kerzel, 2016; Fortier-Gauthier et al., 2012; Gokce et al., 2014; Jannati et al., 2013). The Ppc was thought to reflect initial processing of the stimuli based on feature discontinuities (attend-to-me signal), which may later guide attentional selection or suppression as indexed by the N2pc and P_D. The current results suggest that occurrence of the distractor-related Ppc is restricted to efficient searches that result from low target-nontarget similarity. Overall, the Ppc does not reflect the raw saliency signal, but is modulated by attentional requirements. Some authors have proposed to label the early positivity between 100–200 ms as P_D instead of Ppc in case the component shows effects of attention (Weaver, van Zoest, & Hickey, 2017), but we adhere to the label Ppc to designate a positivity in the N1 time range and reserve the label P_D for a positivity in the N2 time range.

3 | EXPERIMENT 2

In Experiment 2, we addressed two issues. First, it may be that the perceived saliency of the color singleton was reduced when the shape target was distinct from the nontargets, which resulted in a more heterogeneous visual context than shape targets that were similar to the nontarget (Duncan & Humphreys, 1989; Feldmann-Wüstefeld & Schubö, 2015; Mazza, Turatto, & Caramazza, 2009). The reduced saliency of the color distractor with low target-nontarget similarity may have reduced behavioral interference and eliminated attentional capture, as indexed by the N2pc. To rule out this possibility, we asked observers to search for the color singleton and evaluated whether search times differed between shape distractors that were similar or distinct from the nontarget shapes (i.e., high and low distractor-nontarget similarity). In other words, we used the same search displays as in Experiment 1, but swapped the roles of target and distractor. Second, we wondered whether a Ppc or a P_D component would occur to shape distractors less salient than the color target. In principle, a shape singleton is expected to elicit an attend-to-me signal (Ppc) that is subsequently suppressed (P_D), but the results from previous study are mixed: Hickey et al. (2009) observed a P_D to a single line distractor with a larger and probably more salient shape target. Gaspar and McDonald (2014) observed no P_D to a color distractor that was less salient than the color target. Most relevant to the present experiment, Jannati et al. (2013) observed a P_D to a shape distractor with a more salient color target. While previous studies present mixed evidence for a P_D to distractors less salient than the target, there is presently no evidence for a Ppc to distractors that are less salient than the target.

3.1 | Method

3.1.1 | Participants

Eighteen students from the same pool as in Experiment 1 participated. Two subjects were excluded because of eye movements, leaving 16 participants in the final analyses.

3.1.2 | Stimuli

The stimuli were the same as in Experiment 1 except that the roles of the color and shape singleton were swapped. That is, the color singleton was always present because it was the target, whereas the shape singleton was shown only in distractor-present trials (50% of the trials).

3.1.3 | Procedure

The procedure was as in Experiment 1; participants completed two sessions at 2 weeks' interval (same day and same hour). In each session, 1,152 trials were acquired for a total of 2,304 trials. The major change in this experiment concerned the task. Participants were told to find the color singleton and ignore the shape singleton. As before, they reported the orientation of the line in the target element by pressing one of two keys (left or right arrow key).

3.1.4 | Electrophysiological recording and analysis

Based on the same criterion as in Experiment 1, we rejected two subjects whose HEOG from 0 to 300 ms was larger than ± 3 mV. On average, 17% of the trials were removed due to incorrect responses or artifacts.

3.1.5 | Behavioral performance

The distractor effects are shown in Figure 2. A 2 (Distractor-Nontarget Similarity: high, low) × 2 (Shape Distractor: present, absent) repeated measures ANOVA showed that RTs were shorter when the shape distractor was absent compared to when it was present (641 vs. 647 ms), $F(1,15) = 8.10$, $p = .012$, $\eta_p^2 = .351$. The effect of similarity and the interaction failed to reach significance ($p = .413$ and $p = .623$, respectively). The distractor effect was significant with low (6 ms), $t(15) = 2.17$, $p = .046$, and high distractor-nontarget similarity (5 ms), $t(15) = 2.84$, $p = .012$.

Further, we ran a 2 (Target-Nontarget or Distractor-Nontarget Similarity: high, low) × 2 (Color or Shape Distractor: present, absent) × 2 (Experiment: 1, 2) mixed factors ANOVA. RTs were shorter in Experiment 2 than in Experiment 1 (644 vs. 707), $F(1,29) = 4.74$, $p = .038$, $\eta_p^2 = .141$, showing that it was easier to locate the color than the shape singleton. The effect of distractor presence, $F(1,29) = 40.74$, $p < .001$, $\eta_p^2 = .58$, the effect of similarity, $F(1,29) = 40.07$, $p < .001$, $\eta_p^2 = .58$, the interaction between experiment and similarity, $F(1,29) = 37.32$, $p < .001$, $\eta_p^2 = .563$, and the interaction between similarity and distractor presence, $F(1,29) = 15.71$, $p < .001$, $\eta_p^2 = .351$, were significant. Importantly, the interaction between experiment and distractor presence reached significance, $F(1,29) = 22.40$, $p < .001$, $\eta_p^2 = .436$, showing that the distractor effect was smaller in Experiment 2 than in Experiment 1. Also, the triple interaction was significant, $F(1,29) = 19.42$, $p < .001$, $\eta_p^2 = .401$, confirming that effect of distractor presence was modulated by similarity in Experiment 1, but not in Experiment 2.

3.1.6 | N2 interval

Mean ERPs are shown in Figure 3b,d. We calculated the mean voltage in the time range from 250–290 ms, which corresponds to the N2pc. A 2 (Lateral Stimulus: target, distractor) × 2 (Distractor-Nontarget Similarity: low, high) repeated measures ANOVA was run. The voltage difference was more negative with lateral targets than with lateral distractors (−1.82 vs. 0.48 μV), $F(1,15) = 52.64$, $p < .001$, $\eta_p^2 = .778$, indicating an N2pc to the lateral targets and a P_D to the lateral distractor. Moreover, the voltage difference was more negative with high compared to low distractor-nontarget similarity (−0.89 vs −0.44 μV), $F(1,15) = 10.48$, $p = .006$, $\eta_p^2 = .411$, irrespective of lateral stimulus ($p = .939$). Paired t tests confirmed that the difference between high and low distractor-nontarget similarity was significant for lateral targets, $t(15) = -3.22$, $p = .006$, and approached significance with lateral distractors, $t(15) = -2.07$, $p = .056$. Further, independent samples t tests against zero for each of the four conditions showed that, with lateral color targets, the N2pc was significant for low (−1.60 μV), $t(15) = -5.95$, $p < .001$, and high distractor-nontarget similarity (−2.04 μV), $t(15) = -6.64$, $p < .001$. With lateral shape distractors, there was a significant P_D with low similarity (0.71 μV), $t(15) = 3.88$, $p = .001$, but not with high similarity (0.26 μV), $p = .139$.

3.1.7 | N1 interval

We calculated the mean voltage in three time ranges before the N2 interval (Figure 3d). Running the analysis on only the first two intervals did not change the results. A 2 (Lateral Stimulus: target, distractor) × 2 (Distractor-Nontarget Similarity: low, high) × 3 (Time Range: 130–170, 170–210, 210–250 ms) repeated measures ANOVA was conducted. The voltage difference was more negative with lateral targets than with lateral distractors (−0.25 vs. 0.21 μV), $F(1,15) = 9.82$, $p = .007$, $\eta_p^2 = .396$. The voltage difference was more negative with high compared to low distractor-nontarget similarity (−0.15 vs. 0.11 μV), $F(1,15) = 7.8$, $p = .014$, $\eta_p^2 = .342$. The interaction of similarity and time, $F(2,30) = 3.97$, $p = .029$, $\eta_p^2 = .209$, showed that the difference between high and low distractor-nontarget similarity was largest in the second interval (differences of 0.12, 0.41, and 0.26 μV). The effect of time interval, $F(2,30) = 11.95$, $p < .001$, $\eta_p^2 = .443$, was further modulated by lateral stimulus, $F(2,30) = 18.8$, $p < .001$, $\eta_p^2 = .556$, showing that the voltage difference became more negative over time with lateral targets (0.2, 0.05, −0.99 μV), indicating the onset of the

N2pc to the color target, but more positive with lateral distractors (0.21, 0, 0.44 µV), indicating a P_D to the shape distractor. Most important, the interaction of lateral stimulus and distractor-nontarget similarity, $F(1,15) = 6.44$, $p = .023$, $\eta_p^2 = .3$, showed that low and high distractor-nontarget similarity did not differ for lateral targets (−0.27 vs. −0.22 µV), whereas the voltage difference for lateral distractors was more positive with low than high distractor-nontarget similarity (0.45 vs. −0.02 µV).

To follow up on the interactions, we ran 2 (Distractor-Nontarget Similarity: low, high) × 3 (Time Range: 130–170, 170–210, 210–250 ms) ANOVAs, separately for lateral targets and lateral distractors. The ANOVA on the voltage difference to lateral targets revealed a main effect of time, $F(2,30) = 19.66$, $p < .001$, $\eta_p^2 = .567$, but no effect of distractor-nontarget similarity, $F(1,15) = 0.26$, $p = .619$, $\eta_p^2 = .017$. The ANOVA for lateral distractors revealed a main effect of time, $F(2,30) = 6.88$, $p = .003$, $\eta_p^2 = .315$, and confirmed the effect of similarity, $F(1,15) = 10.24$, $p = .006$, $\eta_p^2 = .406$. The absence of an interaction between time and distractor-nontarget similarity showed that the positivity to distractors with low distractor-nontarget similarity was present early in the N1 interval and persisted into the N2 interval. To evaluate whether the Ppc with low distractor-nontarget similarity was significant, we ran *t* tests against zero and found the means for all time intervals to be significantly different, $ts(14) > 2.28$, $ps < .037$.

3.2 | Discussion

The 5-ms interference from the shape distractors in the present experiment was smaller than the 25–50 ms interference from the color distractor in Experiment 1. Additionally, there was no effect of distractor-nontarget similarity. Both observations confirm that the color singleton was more salient than the shape singleton. Thus, we may conclude that the saliency of the color distractor in Experiment 1 did not change as a function of target-nontarget similarity. Otherwise, we should have observed longer RTs to the color target when the shape distractor was distinct from the nontarget shapes (low distractor-nontarget similarity) and the visual context was therefore more heterogeneous. This was not the case.

Further, we found a change in the amplitude of the target-related N2pc depending on distractor-nontarget similarity. We think that this effect is unrelated to distractor-nontarget similarity, but reflects differences in the saliency of the horizontal or vertical target line with respect to the lines making up the surrounding shape. The color singleton target in the condition with high distractor-nontarget similarity was a diamond composed of straight lines, whereas it was a circle composed of a round line in the low distractor-nontarget similarity condition. Therefore, there was more feature overlap between the straight target line and the surrounding shape in the condition with high compared to low distractor-nontarget similarity. Hopf, Boelmans, Schoenfeld, Heinze, and Luck (2002) reported that the amplitude of the N2pc increased with stronger feature overlap. In a similar vein, the larger N2pc with a diamond compared to circle shapes (i.e., high vs. low distractor-nontarget similarity) may reflect increased suppression of features similar to the straight target lines. However, it is noteworthy that the increased suppression did not have repercussions on RTs.

While Experiment 2 mostly served as a control experiment to rule out changes in saliency of the color distractor in Experiment 1, it nonetheless provides some novel insights into the electrophysiological correlates of distractor processing. Despite the absence of behavioral differences between distractors that were similar or distinct with respect to the nontarget shape (i.e., high and low distractor-nontarget similarity), the lateralized ERPs clearly indicate a Ppc and a P_D to distinct, but not to similar shape distractors. While the sequence of Ppc and P_D is predicted based on distractor suppression theory, it is nonetheless puzzling that there were no behavioral effects. Further, the P_D to the salient shape distractor is consistent with a similar experiment by Jannati et al. (2013), but the occurrence of the Ppc is not. Possibly, methodological differences contribute to this difference. Colors were fixed in Jannati et al. (2013), but varied randomly in the present experiment. As interference increases with randomly changing features (Kerzel & Barras, 2016), it may be that the Ppc was increased with randomly changing colors in the present study compared to the fixed colors in Jannati et al. (2013).

4 | GENERAL DISCUSSION

The present experiments investigated interference from a salient color distractor in easy and difficult searches. The search difficulty was manipulated by target-nontarget similarity. Easy searches resulted from low target-nontarget similarity (i.e., salient targets) and difficult searches resulted from high target-nontarget similarity (i.e., less salient targets). We observed that target-nontarget similarity determined distractor processing. The distractor could be suppressed when search was easy, as indicated by a P_D to the distractor, whereas the distractor resulted in attentional capture when search was difficult, as indicated by an N2pc to the distractor. While the present research shows that stimulus-related, bottom-up factors determine whether attentional capture or attentional suppression occurs, previous research has demonstrated the same for target predictability (see introduction, reviewed in Barras & Kerzel, 2016). Both stimulus-driven and expectancy-driven results converge on the notion that difficult searches result in attentional capture by salient distractors whereas easy searches allow for attentional suppression of salient distractors. In terms of saliency-map models (Navalpakkam & Itti, 2007), attentional capture is more likely for low signal-to-noise ratios, whereas attentional suppression is more likely for high signal-to-noise ratios. The reason may be that the relative saliency of the same distractor is higher with low signal-to-noise ratio (i.e., with targets similar to the nontargets) than with high signal-to-noise ratio (i.e., with targets distinct from the nontargets). Further, the present results are incompatible with theories proposing mechanisms of signal suppression that neglect the difficulty of the primary search task and predict suppression of salient elements regardless of search difficulty (Jannati et al., 2013; Sawaki & Luck, 2010).

Thus, the results show that attentional suppression, as indexed by the P_D component, is limited to efficient searches. Similarly, Weaver et al. (2017) observed a P_D only when search was easy because target and distractor were spatially separated. When search was difficult because target and distractor swapped positions randomly, attentional suppression as indexed by the P_D was absent.

Somewhat surprisingly, the current results also suggest that the early saliency signal between 100 and 200 ms (attend-to-me signal, Sawaki & Luck, 2010) only occurred during efficient search, suggesting that the early evaluation of saliency does not proceed in a strictly bottom-up manner. In contrast to previous suggestions (Barras & Kerzel, 2016; Fortier-Gauthier et al., 2012; Gokce et al., 2014; Jannati et al., 2013), we conclude that the Ppc does not reflect the raw saliency signal, but shows modulations by attentional requirements of the task. Similarly, Weaver et al. (2017) observed that the occurrence of the Ppc varied with behavioral target selection. In difficult searches, the Ppc occurred to a lateral stimulus when a saccade was made to the alternative location above or below fixation, but not when a saccade occurred to the lateral stimulus, suggesting a link between the Ppc and attentional selection.

4.1 | Ppc reflects imbalanced saliency of distractors only in efficient searches

The lines in Figure 3 connect conditions with the same lateral element but in different roles, once as target and once as distractor. When the lateral element served as target, the difference waves are mostly negative, indicating an N2pc, but when it served as distractor, the difference waves are sometimes positive, indicating a P_D. The most remarkable feature of this graph is that early differences in the N1 range are visible for lateral distractors, but not for lateral targets despite identical stimuli. For lateral shape targets, there were no early differences between low and high target-nontarget similarity (Column 1 in Figure 3), but early differences did occur for lateral shape distractors between low and high distractor-nontarget similarity (Column 4). Why didn't target selection capitalize on the greater saliency as early as distractor suppression did? A previous study demonstrated that target selection was susceptible to saliency. Töllner, Zehetleitner, Gramann, and Müller (2011) reported that the N2pc to orientation and color singletons with higher saliency had a shorter latency and a larger amplitude. While this result is consistent with the tendency for a larger N2pc with distinct compared to similar shape targets in Experiment 1, the latency effect in Töllner et al. (2011) was only on the order of 20–30 ms and cannot explain why differences between similar and distinct shapes occurred about 150 ms earlier when they were distractors compared to when they were targets. Rather, the question is why the positivity occurring between 100 and 200 ms, which we refer to as Ppc (Barras & Kerzel, 2016; Fortier-Gauthier et al., 2012; Gokce et al., 2014; Jannati et al., 2013), occurred in some conditions but not in others.

We think the results may be summarized by saying that the Ppc occurs to salient stimuli, but only when they are unlikely to be selected. Thus, no Ppc occurred to the salient shape target (low target-nontarget similarity in Column 1 of Figure 3), because it was the target and therefore very likely to be selected. In contrast, a Ppc occurred to the same salient shape when it was a distractor (low distractor-nontarget similarity, Column 4), because the highly efficient search for the color target made it unlikely that the shape distractor was selected. In the same context, there was no Ppc to the shape distractor when it was not salient (high distractor-nontarget similarity in Column 4). Further, there was a Ppc to the salient color distractor when it was unlikely to be selected because the shape target was salient and search was efficient (low target-nontarget similarity in Column 2). In contrast, the Ppc to the color distractor was absent when the shape target was not salient (high target-nontarget similarity in Column 2), which made it likely that the color distractor was selected, as evident in the N2pc to the distractor.

In sum, we confirm that the Ppc only occurs to salient stimuli, which is consistent with the previous notion that it reflects imbalanced saliency (Fortier-Gauthier et al., 2012). Additionally, the present results suggest that the Ppc is not purely a bottom-up signal, but is modulated by the difficulty of the search. Notably, the Ppc to distractors is eliminated if search is inefficient and the distractor is likely to be confused with the target.

4.2 | Effects of target saliency and feature overlap

Our results are somewhat contradictory with respect to the relation between saliency and the amplitude of the N2pc. There was a tendency for a larger N2pc with the more salient shape target in Experiment 1 (i.e., low target-nontarget similarity), but there was a smaller N2pc to the color target in Experiment 2 when the target line was more salient with respect to the surrounding shape (i.e., the circles in the condition with low distractor-nontarget similarity). The difference is evident in Figure 3 when the dotted lines in Column 1 and 3 are compared in the N2 interval. These seemingly contradictory results correspond to equally contradictory reports in the literature. Hopf et al. (2002) suggested that the N2pc reflects suppression of competing distractors and is therefore larger when there is more feature overlap. That is, a larger N2pc occurs with less salient targets that require more suppression of the competing distractors. In contrast, Töllner et al. (2011) observed that a larger N2pc occurred with more salient targets. They argued that the larger and earlier N2pc reflects expedited shifts of attention to more salient stimuli, in accordance with saliency-map theories. The apparent contradiction may be resolved by looking at the cognitive process that was concerned by the saliency manipulation. In Hopf et al. (2002), participants located the target on the left or right side of the screen based on the instructed color. Importantly, the target and the distractor were located on opposite sides of the screen and were equally salient. Subsequently, participants had to make a fine discrimination on the target stimulus. The feature overlap between the target and the immediately surrounding stimuli (on the same side of the screen) determined the "local" saliency of the target. In Töllner et al. (2011), the target had a higher saliency than the remaining nontarget elements ("global" saliency) and the task of the participants was only to locate the salient element. Thus, target saliency in the two studies affected two different processes. In Hopf et al. (2002), saliency was important after the target had been localized and a fine discrimination was required. In Töllner et al. (2011), participant relied on saliency to locate the target. Because we employed a compound task, our results may combine the two effects. The somewhat larger N2pc to salient shape targets (i.e., low target-nontarget similarity) in Experiment 1 may reflect enhanced target localization. In contrast, the larger N2pc to target shapes showing more feature overlap with the target line inside the target shape (i.e., diamonds in the condition with high distractor-nontarget similarity) in Experiment 2 may reflect distractor suppression during fine discrimination. Thus, our results are in line with the idea that different cognitive processes are differently affected by saliency.

4.3 | Conflicting findings

Finally, we need to discuss the previous study that has reached the opposite conclusion, namely, that interference was stronger with low than high target-nontarget similarity. There are numerous methodological differences between the current and the previous study that may account for the discrepancy. As already pointed out, the most important difference may be that the current study compared efficient and inefficient search (5.9 vs. 16.4 items/ms) according to the criterion of 10 ms/item for efficient search (Wolfe & Horowitz, 2004). In contrast, search was always highly inefficient (search slopes between 22 and 114 ms/item) in Proulx and Egeth (2006). Further, Proulx and Egeth used the irrelevant singleton paradigm where the target stimulus was allowed to coincide with the salient color singleton according to baseline probability, creating a small incentive to pay attention to the salient stimulus. In contrast, target and color singleton never coincided in the additional singleton paradigm used in the present study, which encouraged observers to ignore the color singleton (Becker, 2007). Further, Proulx and Egeth used search slopes to measure the distractor effect, which is not possible in the additional singleton paradigm because the target never coincides with the distractor. Also, the manipulation of target-nontarget similarity was run within subject in the present study, but between subjects in Proulx and Egeth. Thus, the many differences preclude a final answer to the question why target-nontarget similarity had opposite effects.

In sum, we observed that distraction by a salient color singleton was stronger when search was difficult as a result of high target-nontarget similarity. The larger interference was accompanied by an N2pc to the distractor, showing that attentional capture occurred. In contrast, the small interference with low target-nontarget similarity and easy search was accompanied by a P_D to the distractor, suggesting attentional suppression of the distractor. Further, we observed that an early positivity, the Ppc component, occurred to salient distractors, but only when search was efficient and it was unlikely that the distractor was selected.

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