

# P<sub>D</sub> components and distractor inhibition in visual search: New evidence for the signal suppression hypothesis

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## Abstract

The hypothesis that salient distractors in visual search are actively suppressed is supported by the fact that these objects elicit P<sub>D</sub> components believed to be associated with inhibition. This account was challenged by researchers who found that a P<sub>D</sub> to lateral color singleton distractors was followed by a contralateral negativity, which they interpreted as an N2pc indicative of attentional capture. As this would be at odds with successful distractor suppression, they proposed an alternative lateral-first serial scanning hypothesis, which assumes that the P<sub>D</sub> might actually be an N2pc elicited when a lateral context item is selected. We tested this hypothesis by measuring lateralized ERP components to search displays with two lateral and two vertical midline items, including a color singleton and a shape-defined target. Color singletons triggered P<sub>D</sub> components not only in blocks where attention was unfocused because target location was unpredictable, but critically also in blocks where targets only appeared on the midline and participants had no reason to attend to lateral items. This is inconsistent with the serial scanning hypothesis and supports the idea that the P<sub>D</sub> reflects signal suppression. P<sub>D</sub> components to singleton distractors were followed by a contralateral negativity, which we interpreted as a second P<sub>D</sub> elicited by non-salient distractors on the opposite side. Our sequential inhibition account reconciles conflicting results of recent studies and emphasizes the role of inhibitory processes during attentional target selection in visual search.

## KEYWORDS

attentional capture, event-related brain potentials (ERP), inhibition, P<sub>D</sub> component, signal suppression hypothesis

## 1 | INTRODUCTION

The question whether salient but irrelevant objects capture attention automatically remains the subject of intense debate. Stimulus-driven models propose that such objects always attract attention, regardless of current selection intentions (Franconeri & Simons, 2003; Theeuwes, 1991, 1992; Yantis & Jonides, 1984), while goal-dependent models assume that this is only the case when they have at least one features that is relevant in the current task context (Folk et al., 1992; Lien

et al., 2008). While this controversy is ongoing, there is some recent progress toward a resolution (see Luck et al., 2021). For example, Sawaki and Luck (2010) have proposed a signal suppression account that contains elements of both stimulus-driven and goal-dependent models. In line with stimulus-driven models, this account postulates that salient objects such as feature singletons automatically generate saliency signals. However, and in line with goal-dependent accounts, these signals can be suppressed if they do not match a currently active task set, thereby preventing attentional capture.

This signal suppression hypothesis is supported by behavioral (Gaspelin et al., 2015; Vatterott & Vecera, 2012), oculomotor (Gaspelin et al., 2017; Gaspelin & Luck, 2018b; Ipata et al., 2006), and ERP (Gaspelin & Luck, 2018a) studies. For example, using an oculomotor search task, Gaspelin et al. (2017) demonstrated that gaze was less likely to be directed to a task-irrelevant color singleton than to other non-singleton distractor objects, indicating that the singleton was actively suppressed. Analogous results were obtained by Gaspelin et al. (2015) in experiments using a capture-probe paradigm with interleaved search and probe trials. More direct evidence for the active suppression of salient distractors was obtained on the basis of ERP components measured in response to visual search displays that contained a lateral color singleton distractor. Gaspelin and Luck (2018a) found that these singletons triggered an enhanced positivity at contralateral posterior electrodes ( $P_D$  component), which has previously been associated with the inhibition of distractor processing (Gaspar & McDonald, 2014; Hickey et al., 2009; Jannati et al., 2013). Importantly, the magnitude of this component was correlated with the magnitude of behavioral suppression effects, supporting the hypothesis that the  $P_D$  component is an electrophysiological signature of active suppression of salience signals during visual search.

However, this interpretation of the  $P_D$  has recently been challenged by results reported by Kerzel and Burra (2020). Using four-item search displays with a task-irrelevant color singleton similar to Gaspelin and Luck (2018a), but without interleaved probe trials, they confirmed the presence of an early positivity contralateral to a lateral color singleton in search displays where the target appeared on the vertical midline and thus did not elicit any lateralized ERP components. However, and critically, this positivity was followed by a contralateral negativity, similar to the N2pc component observed in many previous studies of visual search. The N2pc is triggered by search targets and other objects with target-defining features, and is generally assumed to be a marker of the deployment of attention to these objects (Eimer, 1996; Luck & Hillyard, 1994a, 1994b). Kerzel and Burra (2020) interpreted the contralateral negativity triggered by color singleton distractors in their study as an N2pc reflecting attentional capture by these singletons. This pattern of results is difficult to reconcile with the idea that the preceding contralateral positivity ( $P_D$ ) reflects active singleton suppression, since it is unclear why a singleton should still be able capture attention after it has been suppressed.

Kerzel and Burra (2020) concluded that their results are incompatible with the signal suppression hypothesis, and that the apparent  $P_D$  was actually an N2pc that was triggered as a result of deploying attention to the lateral item opposite to the color singleton. They claimed that when search display set size is small (e.g., two items on the horizontal and two on the vertical midline), participants will adopt a serial scanning

strategy (see also Liesefeld & Müller, 2019; see also Wang & Theeuwes, 2020) where lateral items are scanned prior to vertical items, even when the target appears vertically. Kerzel and Burra (2020) argued that the  $P_D$ -N2pc sequence observed in their study reflects the initial allocation of attention to the lateral context item (early N2pc) followed by the deployment of attention to the color singleton on the opposite side (late N2pc). In support of this serial scanning account, they found generally shorter RTs to lateral as compared to vertically located search targets.

This argument by Kerzel and Burra (2020) is important for current debates about stimulus-driven versus goal-dependent attentional capture. If the contralateral positivity observed by Gaspelin and Luck (2018a) is not a  $P_D$  component triggered by the proactive suppression of salient singleton distractors, this would remove a central piece of evidence in support of the signal suppression hypothesis. However, as acknowledged by Kerzel and Burra (2020), there is no direct data-driven way to distinguish a  $P_D$  associated with singleton suppression from an N2pc associated with the deployment of attention to the context item on the opposite side, since both lateralized components have very similar scalp distributions and only differ in their polarity. In the current study, we therefore used an alternative approach to adjudicate between the suggestions by Kerzel and Burra (2020) and the original interpretation of the  $P_D$  as a marker of active suppression proposed by Gaspelin and Luck (2018a). We measured  $P_D$ /N2pc components in one search task that was similar to the one employed in these previous studies, and in another task that was modified in order to make it highly improbable that observers would adopt a lateral-first serial search strategy.

Search displays were similar to Kerzel and Burra (2020) and Gaspelin and Luck (2018a). They included two lateral items to the left and right of fixation and two items on the vertical midline (above and below fixation), and one of these could be a salient color singleton distractor. In one task condition (unfocused attention), all four locations (including the two lateral positions) were equally likely to contain the search target, as in the two previous studies. Here, participants could in principle have adopted the serial search strategy postulated by Kerzel and Burra (2020). In another condition (focused attention [midline]), search targets only ever appeared at one of the two vertical locations, but never laterally. Here, participants could focus their attention entirely on the vertical midline and had no incentive to attend to or start scanning either of the two lateral locations. The critical question was whether lateral color singletons would elicit a contralateral positivity only with unfocused attention, or also in the focused [midline] condition where lateral locations were entirely task-irrelevant. If the  $P_D$  was actually an N2pc to the context element, as suggested by Kerzel and Burra (2020), it should only be found in the unfocused attention condition where lateral locations were potential target locations, but not in the

focused attention [midline] condition. In contrast, if the  $P_D$  was linked to distractor suppression, as proposed by Gaspelin and Luck (2018a), it should also be elicited by lateral color singletons when attention is focused on the midline, since attentional capture by these singletons might interfere with the processing of vertical search targets. In this case, the question remains whether these  $P_D$  components would still be smaller in the focused attention [midline] compared to the unfocused attention condition, as inhibition might be stronger for salient distractors at potentially task-relevant locations.

To maximize the number of trials available for ERP analyses, we used a multiple frames procedure, where four visual search displays were presented sequentially on each trial, and participants were subsequently prompted to indicate the number of frames containing a target (e.g., Aubin & Jolicoeur, 2016; Drisdelle & Jolicoeur, 2018). Using small display sizes is advantageous for EEG studies that employ a lateralized ERP marker of suppression (e.g.,  $P_D$  component), as they result in a large number of trials where the target is presented on the midline and the salient distractor laterally, thereby improving the signal-to-noise ratio. Moreover, four unique shapes were presented in each frame (encouraging feature search mode rather than singleton search mode; Bacon & Egeth, 1994), and the color of the singleton distractor was held constant (Vatterott & Vecera, 2012). These two factors are critical for observing distractor suppression rather than attentional capture by an irrelevant color singleton (see Luck et al., 2021, for discussion). In addition to the unfocused and focused attention [midline] conditions, we also ran a focused attention [lateral] condition, where search targets could only appear at the two lateral positions and never on the vertical midline. This condition was included to equate possible target locations across the whole experimental session, and to allow for additional control analyses (see below). Each attention condition was presented in consecutive blocks, with order of conditions counterbalanced across participants. Prior to the first block of each condition, participants were explicitly informed about possible target locations.

## 2 | METHOD

### 2.1 | Participants

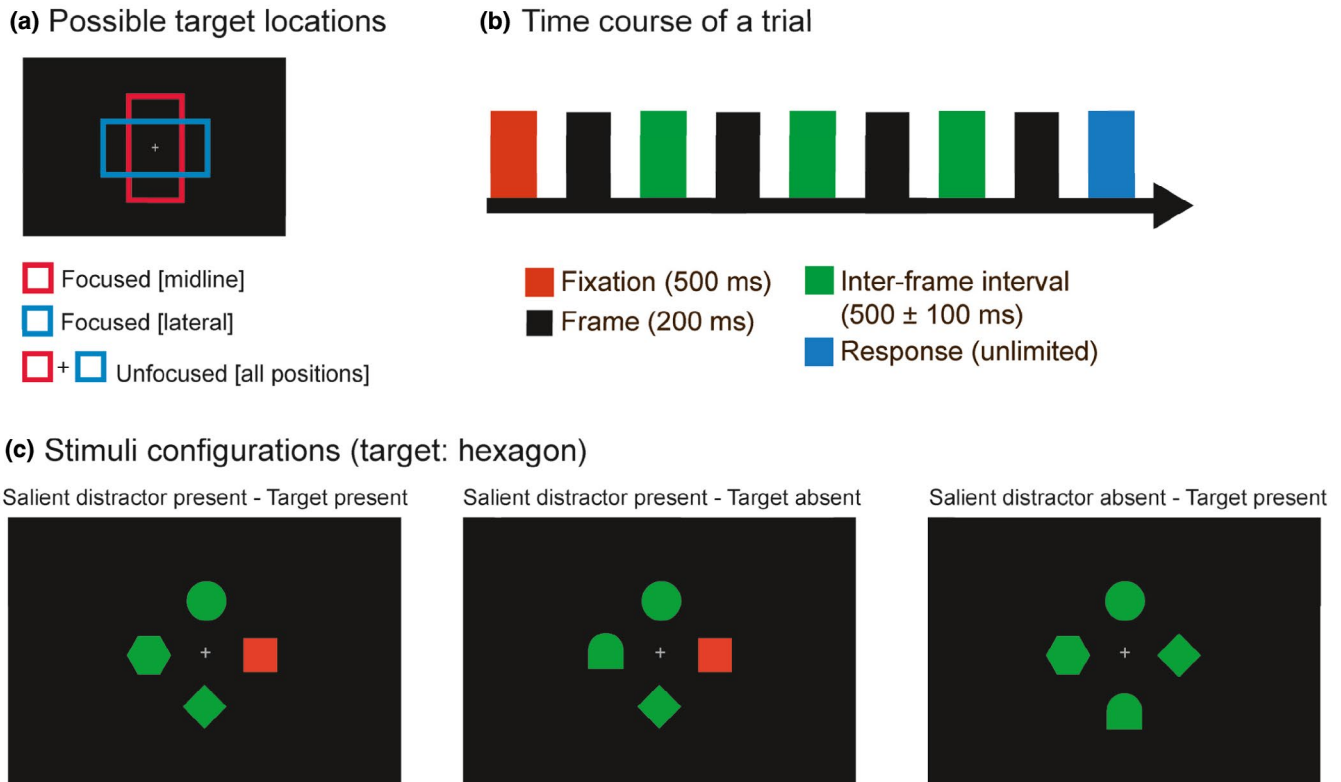
Twenty-four (24) participants were recruited. Sample size selection was based on Experiment 1 of Gaspelin and Luck (2018a), which had 20 participants, and Experiment 2 of Kerzel and Burra (2020), which had 22 participants. In Kerzel and Burra (2020), the critical  $t$ -test showing the presence of a  $P_D$  component for a lateral distractor with a midline target had a Cohen's  $d_z$  of 1.39. To replicate this effect with a power of 0.95, a minimum sample size of 9 is necessary (determined using  $G^*$ power; Faul et al., 2007). Six participants

were removed from our initial sample due to excessive eye movements (a combination of rejected epochs and/or exceeding HEOG deflection cut-off; see *EEG recording and analysis* for details), resulting in a final sample of 18 participants (age:  $M = 30.28$  years,  $SD = 8.28$  years, 10 female). This sample size allowed for a full counterbalancing of all between-subject factors (see *Procedures* for a breakdown). All participants had normal or corrected-to-normal vision. Methods were approved by the departmental ethics committee at Birkbeck, University of London.

### 2.2 | Stimuli and procedures

Stimuli were presented using a 24-inch BenQ monitor (1920 × 1080 screen resolution) attached to a SilverStone PC. Participant viewing distance was approximately 80 cm. The experiment was programmed using E-prime 3.0 software (Psychology Software Tools, Pittsburgh, PA). Figure 1 illustrates the experimental setup, including possible target locations (attentional focus; A), the time course of a trial (B), and the different types of visual search displays (C). Participants searched for a predefined target shape among heterogeneous distractor shapes, presented on a black background with a gray fixation cross at the center of the screen (Figure 1c). On each trial, four visual search displays (frames) were presented sequentially (see Figure 1b). Each display contained four items, two on the vertical midline (above and below fixation) and two on the horizontal midline (to the left and right of fixation). The centre of each item was 2° from fixation. The target was a diamond (1.6° × 1.6°), a circle (0.7° in radius) or a hexagon (1.5° × 1.5°; counterbalanced between-subjects), which could either be present or absent in any given search display. A salient distractor (a color singleton square; 1.2° × 1.2°) was present in most search displays (see below for details). For half of the participants, this color singleton was red (CIE coordinates: 0.629/0.333, luminance: 47.2 cd/m<sup>2</sup>) and all other search display items were green (0.306/0.615, 47.3 cd/m<sup>2</sup>). This color assignment was reversed for the other half of participants. In target-absent displays, the color singleton square was always present, and appeared together with two nontarget shapes (e.g., a diamond and a hexagon for participants who searched for circles) and a third shape (a gate stimulus that did not serve as target for any participant; 1.2° × 1.2°). In most target-present displays, the target was presented together with the color singleton square and two randomly selected nontarget shapes. In a minority of target-present displays, the color singleton square was absent, and the target appeared together with the other three nontarget shapes, all in the same color.

Trials began with a fixation cross, which remained present until participants were prompted to respond following the last search display on each trial. After 500 ms, the first of



**FIGURE 1** Illustration of the stimuli and procedure of Experiment 1. (a) Possible target locations in the three blocked attention conditions. (b) Time course of the multiple-frames presentation procedure. On each trial, four successive frames were presented. (c) Spatial configuration of search displays (target: hexagon). Different display included a color singleton distractor and a target (left), a color singleton distractor without the target (middle), or the target without a color singleton distractor (right). Stimuli are not to scale and for visualization purposes only (see Methods for exact dimensions)

the four search displays (frames) appeared. Each frame was presented for 200 ms, with an interframe-interval of 500 ms ( $\pm 100$  ms jitter). After the presentation of the last frame, fixation remained until participants responded. Their task was to report the number of frames with a target (possible responses: 1, 2, 3, or 4 target frames) by pressing the “z”, “x”, “n”, or “m” key on a computer keyboard with their left/right middle/index finger. Participants were informed about the color and shape of the target at the start of the experiment. They were instructed to ignore salient color singleton distractors when present, and to respond as quickly and as accurately as possible at the end of each trial. The next trial was initiated once a response was registered. For incorrect trials in the practice block, a red fixation cross was presented after response execution. In experimental trials, no trial-by-trial feedback was provided, and a gray fixation cross was presented immediately after response execution. Participants received block-by-block feedback on accuracy at the end of all experimental blocks and the practice block.

There were 16 experimental blocks (25 trials in each block), resulting in 400 experimental trials with four frames (1600 frames in total). A practice block (5 trials; 20 frames) was completed by all participants prior to the first experimental block. A target was present in 62.5% of all frames and

absent in the remaining 37.5% frames. Seventy-five percent (75%) of all target-present frames included a color singleton distractor. The color singleton was always present in target-absent frames. Thus, a color singleton distractor was present in 84.4% of all frames ( $[0.75 \times 62.5\%]$  target-present frames + 37.5% target-absent frames). It was presented with equal probability at any nontarget location.

The critical manipulation concerned possible target locations (attentional focus; Figure 1a). In eight successive blocks (200 trials/800 frames), the target could be presented with equal probability in all four possible locations (unfocused attention). In four successive blocks (100 trials/400 frames), it could only appear on the vertical midline (focused attention [midline]), and in the remaining four blocks, only at one of the two lateral positions (focused attention [lateral]). As there were more possible stimuli configurations in the unfocused attention condition, twice as many blocks were included for the focused attention conditions. In the practice block, attention was unfocused.

Frames were randomly sorted into trials, with the restriction that there was an equal overall number of trials with 1, 2, 3, or 4 targets. These four types of trials were then presented in random order within blocks of 25 trials. This was done separately for each attentional focus condition. The order of

the three blocked attentional focus conditions was counter-balanced between-subjects using a Latin square. The order was either (a) unfocused, focused [midline], focused [lateral], (b) focused [midline], focused [lateral], and unfocused, or (c) focused [lateral], unfocused, focused [midline]. The between-subject counterbalancing of color assignment (green target/distractors and red singleton distractor, or vice versa), target shape (diamond, circle, or hexagon), and block order resulted in 18 possible combinations, which were each assigned to one participant.

### 2.3 | EEG recording and analysis

An electroencephalogram was DC-recorded from 27 scalp electrodes mounted on an elastic cap at the following sites according to the international 10/20 system: Fpz, F7, F8, F3, F4, Fz, FC5, FC6, T7, T8, C3, C4, Cz, CP5, CP6, P9, P10, P7, P8, P3, P4, Pz, PO7, PO8, PO9, PO10, and Oz (Sharbrough, 1991). Data were recorded using Brain Products software and sampled at 500 Hz with an online low-pass filter of 40 Hz. Channels were referenced online to an electrode placed on the left earlobe and re-referenced offline to the average of both earlobes. Data were analysed using BrainVision Analyzer 2 (Brain Products GmbH, Gilching, Germany). The horizontal electrooculogram (HEOG) was calculated offline as the voltage difference between electrodes lateral to the external canthi (placed using the elastic cap) and used to measure horizontal eye movements. Frames were segmented from 100 prestimulus to 500 ms poststimulus (600 ms epochs). Segmentations were then baseline corrected by subtracting the average voltage of the 100 ms prestimulus period from the entire epoch. Frames with activity considered blinks or vertical eye movements (exceeding  $\pm 60 \mu\text{V}$  at Fpz) or horizontal eye movements (exceeding  $\pm 30 \mu\text{V}$  in the HEOG channel) were automatically rejected. To detect any systematic residual eye movements toward lateral targets that remained after automated artifact rejection, lateralized HEOG differences for frames with left or right targets were examined (averaged across all other conditions). Averaged lateralized HEOG deflections remained below  $3 \mu\text{V}$  for all 18 participants included in the sample, indicating that they maintained reasonable fixation. Other artifacts, such as movement related artifacts, were identified and automatically rejected using a cut-off of  $\pm 80 \mu\text{V}$  for all other channels. Trials with incorrect responses were not excluded from EEG analysis, given the overall high accuracy (96%), and because responses were provided only after four visual search frames, which implies that response errors do not indicate a failure to detect any target (e.g., on trials with 4 targets, a “3” response is categorized as error).

Averaged ERP waveforms were computed for different frames, as a function of whether the target (T) or singleton

distractor (D) was presented laterally (L), on the vertical midline (M), or was absent (0). For the unfocused attention condition, ERPs were separately averaged for four different frame types (TM – DL, TL – DM, TL – D0, T0 – DL). For the focused attention [lateral] condition, ERPs were averaged for three frame types (TL – DM, TL – D0, T0 – DL). For the focused attention [midline] condition, ERPs were averaged for two frame types (TM – DL, T0 – DL). ERPs were always computed separately for frames with lateral targets/singleton distractors on the left or right side. No ERPs were computed for frames that could not trigger any lateralized activity (T0 – DM, TM – DM, and TM – D0), and for frames that contained a lateral target and a lateral singleton distractor on opposite sides (TL – DL), because it is difficult to dissociate target- and distractor-induced lateralized activity for these frames. To isolate lateralized activity associated either with the target or salient distractor, ERPs recorded at electrodes PO7/PO8 ipsilateral to the item of interest were subtracted from contralateral ERPs. Lateralized components were quantified using the collapsed localizer method, as described by Luck and Gaspelin (2017). All frames containing either a lateral color singleton or a lateral target were averaged separately. For lateral singletons, a contralateral positivity was observed from 110 to 260 ms and a contralateral negativity from 260 to 330 ms. For lateral targets, no contralateral positivity was observed, but a negativity (N2pc component) was present from 200 to 350 ms.<sup>1</sup>

Analyses of variance (ANOVA) and *t*-tests were used to evaluate ERP results statistically. Reported effect sizes for ANOVA results were determined using partial eta squared ( $\eta_p^2$

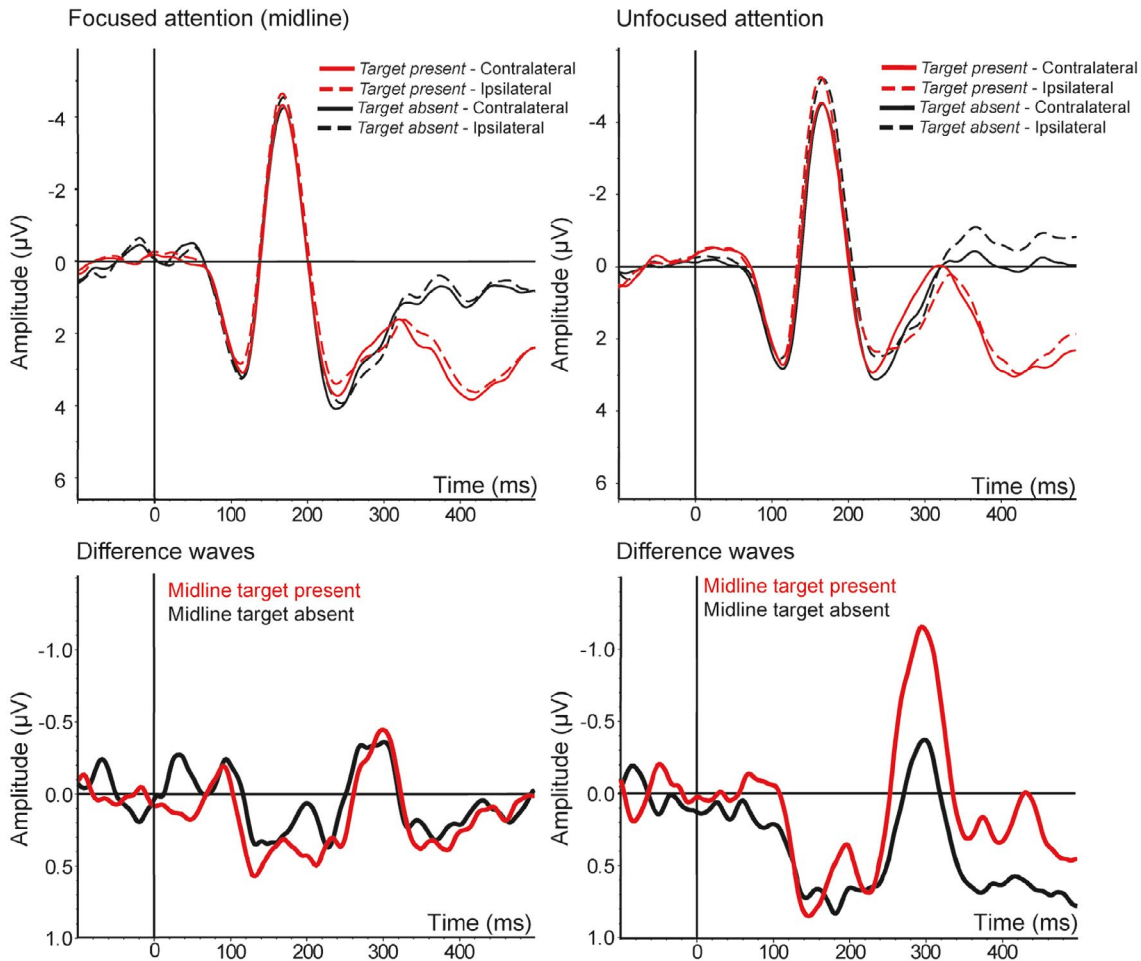
; Keppel, 1991) and for *t*-test results were determined using Cohen's  $d_z$  ( $t/\sqrt{n}$ ; Lakens, 2013; Rosenthal, 1994). As our study focused on lateralized components, only effects containing the laterality factor are reported. Lateralized ERP effects are quantified as contralateral minus ipsilateral differences (C – I  $\Delta$ ).

## 3 | RESULTS

### 3.1 | Behavioral data

Accuracy was very high across all three attention conditions ( $M = 95.9\%$ ,  $SD = 3.1\%$ ), and also within each condition (focused attention [midline]:  $M = 96.3\%$ ,  $SD = 3.1\%$ ; focused

<sup>1</sup>These time windows are consistent with the previous literature. For example, Gaspelin and Luck (2018a) used a 100–300 ms measurement window to quantify the  $P_D$  and a 200–400 ms window to quantify the N2pc (calculated using the technique described in Sawaki et al., 2012). Kerzel and Burra (2020), employed 50 ms measurement windows that were centered at the peak latencies of positive and negative lateralized activity (210 and 290 ms, respectively).



**FIGURE 2** Top panels: Grand-averaged ERPs measured in the focused [midline] and unfocused attention conditions at electrodes PO7/8 contralateral and ipsilateral to a lateral color singleton distractor. ERPs are shown separately for displays with a midline target (red lines) and without a target (black lines). Bottom panels: Corresponding contralateral minus ipsilateral difference waveforms.  $P_D$  components are visible for all conditions, followed by a contralateral negativity that was most pronounced for target-present displays in the unfocused attention condition. Waveforms were low-pass filtered at 15 Hz for visualization purposes

attention [lateral]:  $M = 96.3\%$ ,  $SD = 4.0\%$ ; unfocused attention:  $M = 95.2\%$ ,  $SD = 4.3\%$ ). Although accuracy was numerically higher across the two focused attention conditions relative to the unfocused attention condition, this difference not reliable,  $t(17) = 1.33$ ,  $p = .20$ ,  $d_z = 0.31$ . Because a response was only required following the prompt at the end of each trial and not for individual frames, no response time data are reported.

## 3.2 | Electrophysiological data

### 3.2.1 | Main analyses

To assess whether a  $P_D$  is elicited by lateral salient distractors that are presented at task-irrelevant locations, and thus outside the focus of attention, we compared lateralized ERP waveforms obtained in response to search displays with a lateral color singleton between the unfocused attention

condition and the focused attention [midline] condition. Figure 2 shows these ERPs, separately for displays where a target was either absent or present on the vertical midline. It suggests a  $P_D$  was elicited by these lateral color singletons, not only with unfocused attention but also in blocks where targets could only appear on the vertical midline.  $P_D$  mean amplitudes (measured from 110 to 260 ms) were submitted to a repeated-measures ANOVA with the factors Attentional focus (unfocused vs. focused [midline]), Midline target (present vs. absent), and Laterality (electrode ipsilateral vs. contralateral to the side of the color singleton).

A main effect of Laterality was present,  $F(1, 17) = 34.5$ ,  $p < .0001$ ,  $\eta_p^2 = 0.67$ , reflecting an enhanced contralateral positivity ( $C - I \Delta = 0.44 \mu V$ ), and indicating that lateral color singletons did indeed elicit a  $P_D$  component. Laterality interacted with Attentional focus,  $F(1, 17) = 7.97$ ,  $p = .01$ ,  $\eta_p^2 = 0.32$ . As can be seen in Figure 2,  $P_D$  components were larger in the unfocused attention condition ( $C - I \Delta = 0.58 \mu V$ ) than

in the focused attention [midline] condition ( $C - I \Delta = 0.31 \mu\text{V}$ ). However, paired  $t$ -tests comparing contralateral and ipsilateral ERPs confirmed that a  $P_D$  component was reliably present not only with unfocused attention ( $t(17) = 6.04, p < .0001, d_z = 1.42$ ), but also, critically, when attention was focused on the vertical midline ( $t(17) = 3.69, p = .002, d_z = 0.87$ ). There was no interaction between Laterality and Midline Target ( $F(1, 17) = 0.24, p = .63, \eta_p^2 = 0.01$ ), indicating that the presence versus absence of a midline target in the same search display did not affect  $P_D$  amplitudes. Finally, there was also no three-way interaction between Laterality, Attentional Focus, and Midline target ( $F(1, 17) = 2.66, p = .12, \eta_p^2 = 0.14$ ).<sup>2</sup>

As can be seen in Figure 2,  $P_D$  components were followed by an enhanced contralateral negativity, which was most pronounced in the unfocused attention condition for displays that contained a midline target. This contralateral negativity (measured from 260 to 330 ms) was analysed in an additional ANOVA with the same three factors described above. There was a main effect of Laterality,  $F(1, 17) = 10.87, p = .004, \eta_p^2 = 0.39$ , reflecting the presence of a negativity contralateral to the color singleton ( $C - I \Delta = -0.4 \mu\text{V}$ ). Laterality interacted with Midline target,  $F(1, 17) = 11.64, p = .003, \eta_p^2 = 0.41$ , and marginally with Attentional focus,  $F(1, 17) = 3.6, p = .07, \eta_p^2 = 0.18$ . Importantly, there was also a reliable three-way interaction between all factors,  $F(1, 17) = 10.37, p = .005, \eta_p^2 = 0.38$ . To decompose this interaction, separate 2-way ANOVAs (Midline target  $\times$  Laterality) were conducted for the unfocused attention and focused attention [midline] conditions. With unfocused attention, a main effect of Laterality,  $F(1, 17) = 12.87, p = .002, \eta_p^2 = 0.43$ , was accompanied by an interaction between Midline target and Laterality,  $F(1, 17) = 27.53, p < .0001, \eta_p^2 = 0.62$ . Paired  $t$ -tests confirmed that a significant contralateral negativity was elicited for displays where a target was present on the midline,  $t(17) = 5.53, p < .0001, d_z = 1.30$ , but not when the target was absent,  $t < 1$ . When attention was focused on the midline, a marginal effect of Laterality,  $F(1, 17) = 4.4, p = .05, \eta_p^2 = 0.21$  was observed, suggesting the presence of a small negativity contralateral to the color singleton distractor ( $C - I \Delta = -0.27 \mu\text{V}$ ). There was no interaction between Laterality and Midline target,  $F < 1$ .

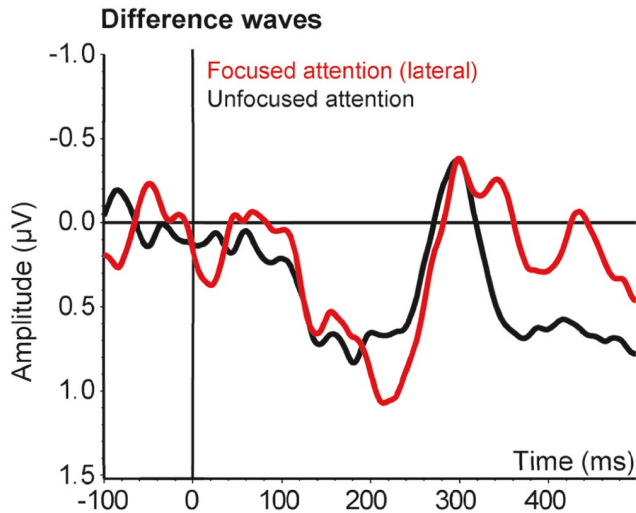
<sup>2</sup>Mixed-model ANOVAs including color assignment (2 levels) and block order (3 levels) as between-subject factors were also conducted. For the  $P_D$ , color interacted with laterality, where a larger  $P_D$  was observed when the color singleton was red compared with green, as previously reported (see Fortier-Gauthier et al., 2013),  $F(1, 12) = 5.62, p = .04, \eta_p^2 = 0.32$ . For the N2pc, a 3-way interaction between block order, attentional focus, and laterality was observed,  $F(2, 12) = 7.35, p = .008, \eta_p^2 = 0.55$ .

### 3.2.2 | Additional analyses

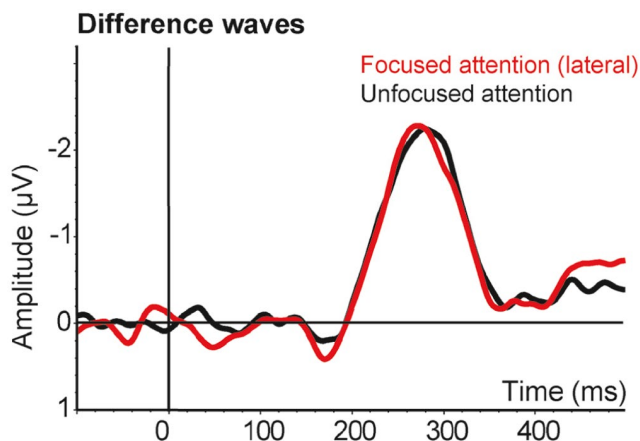
Our main analyses showed that although a  $P_D$  component to lateral color singleton distractors was reliably present when attention was focused on the midline, this component was larger with unfocused attention. This difference may be a result of the fact that lateral locations were task-relevant in unfocused attention blocks but not in focused attention [midline] blocks. Alternatively, it could be due to the difference in the total number of attended locations between unfocused and focused attention conditions (four vs. two). To disentangle these two possibilities, we compared  $P_D$  components elicited by lateral color singleton distractors in the unfocused attention condition and in the focused attention [lateral] condition. In both conditions, distractors now appeared at task-relevant locations, but the number of attended task-relevant locations still differed. If  $P_D$  amplitudes were sensitive to this factor, they should again be smaller with two attended locations in the focused attention [lateral] condition than with four attended locations in the unfocused attention condition. If the  $P_D$  amplitude difference between focused and unfocused [midline] blocks was due to the task-relevance of singleton distractor locations, no such difference should be observed. Figure 3 shows contralateral—ipsilateral difference waves for target-absent displays with lateral color singletons in these two conditions.  $P_D$  mean amplitudes (measured from 110 to 260 ms) were submitted to an ANOVA with the factors Laterality and Attentional focus (unfocused vs. focused [lateral]). There was a main effect of Laterality,  $F(1, 17) = 33.56, p < .0001, \eta_p^2 = 0.66$ , reflecting an enhanced contralateral positivity indicative of the  $P_D$  component ( $C - I \Delta = 0.68 \mu\text{V}$ ). Critically, there was no interaction between Laterality and Attentional focus,  $F < 1$ , indicating that despite the difference between attended task-relevant locations, this component was similar in size in both attention conditions.

Because the absence of a significant effect does not constitute as evidence for the null hypothesis, the nonsignificant interaction between Laterality and Attentional focus was supplemented by the calculation of a Bayes Factor in favor of the null hypothesis ( $BF_{01}$ ) using JASP (0.14.0). For simplicity, we first calculated the difference between contralateral and ipsilateral activity (Laterality difference) to isolate activity associated with the  $P_D$  component. A paired  $t$ -test comparing both attention conditions (unfocused vs. focused [lateral]) for the Laterality difference was conducted. Because we had no a priori expectation, a default prior was used (Cauchy scale of 0.707). The Bayes factor provided strong support for the null ( $BF_{01} = 3.78$ ).

In the final analysis, we examined whether N2pc components to lateral targets were affected by the number of attended task-relevant locations in unfocused and focused



**FIGURE 3** Difference waveforms obtained by subtracting ERPs at electrodes PO7/8 ipsilateral to a color singleton distractor from contralateral ERPs in response to target-absent displays in the focused [lateral] and unfocused attention conditions.  $P_D$  components of similar size were present in both conditions. Waveforms were low-pass filtered at 15 Hz for visualization purposes



**FIGURE 4** Difference waveforms obtained by subtracting ERPs at electrodes PO7/8 ipsilateral to a lateral target from the corresponding contralateral ERPs in response to target-present displays in the focused [lateral] and unfocused attention conditions (collapsed across displays with and without a singleton distractor on the vertical midline). Target N2pc components did not differ between these two conditions. Waveforms were low-pass filtered at 15 Hz for visualization purposes

[lateral] blocks. More efficient attentional guidance with fewer possible target locations could result in larger and/or earlier target N2pc components with focused attention. Figure 4 shows N2pc components based on contralateral-ipsilateral difference waves for unfocused and focused [lateral] conditions (averaged across displays where a midline singleton distractor was either present or absent). No clear N2pc differences between these conditions were apparent.

An ANOVA of N2pc mean amplitudes (measured from 200 to 350 ms post-stimulus) with the factors Laterality and Attentional focus (unfocused vs. focused [lateral]) revealed a main effect of Laterality,  $F(1, 17) = 32.24$ ,  $p < .0001$ ,  $\eta_p^2 = 0.66$ , confirming the existence of target N2pc components ( $C - I \Delta = -1.45 \mu V$ ). However, there was no interaction between Laterality and Attentional focus,  $F < 1$ , suggesting that target N2pc amplitudes did not differ between the two attention conditions. Likewise, a comparison of N2pc onset latencies based on the jackknife-based method described by Miller and colleagues (Miller et al., 1998) found no evidence for any target N2pc onset difference between focused and unfocused attention,  $F < 1$ .

## 4 | DISCUSSION

The question whether salient but task-irrelevant signals capture attention reflexively or can be actively suppressed is a central topic in current debates about the scope of top-down attentional control. One key piece of evidence supporting the signal suppression hypothesis is that salient distractors in visual search elicit  $P_D$  components assumed to be associated with active inhibition (Gaspelin & Luck, 2018a). However, this interpretation has recently been challenged by Kerzel and Burra (2020), who claimed that the distractor  $P_D$  observed by Gaspelin and Luck (2018a) was actually an N2pc in response to a lateral context item in the opposite visual field as a result of observers employing a lateral-first serial search strategy.

We tested this alternative account proposed by Kerzel and Burra (2020) by measuring  $P_D$  components in a visual search task where attention was initially unfocused because targets could be presented at any of four display locations, and in a task where targets could only appear on the vertical midline but never at lateral positions. If the  $P_D$  observed with unfocused attention was in fact an N2pc associated with the attentional selection of lateral context objects, it should not be found in this focused attention [midline] task, because participants had no reason to allocate attention to these objects. The critical finding of this study was that  $P_D$  components to search displays with a lateral color singleton were not only observed in unfocused attention blocks, but were also reliably present in focused attention blocks where lateral locations were completely task-irrelevant, thus removing any incentive for participants to actively scan (i.e., allocate attention to) these locations. The presence of a  $P_D$  to color singletons at irrelevant locations does show that these distractors were preattentively registered and presumably triggered an attend-to-me signal (Sawaki & Luck, 2010), but were then proactively suppressed, thereby preventing attentional capture. It is also notable that the onset of the  $P_D$  to a lateral color singleton (Figure 2) was much earlier than the onset



of the N2pc component to a lateral target (Figure 4), indicating that the suppression of the color singleton occurs prior to any allocation of attention. This is inconsistent with the alternative serial scanning account (Kerzel & Burra, 2020), since it is unclear why attention should be allocated earlier to a context item opposite to the color singleton than to the search target. Overall, these results are incompatible with the proposal by Kerzel and Burra (2020) but are fully in line with the original hypothesis by Gaspelin and Luck (2018a) that the  $P_D$  is a marker of active distractor suppression. They are also in line with previous work demonstrating the presence of  $P_D$  components to salient distractors in search displays with larger set sizes (e.g., Gaspar & McDonald, 2014; Sawaki & Luck, 2010), where it is unlikely that participants would adopt a lateral-first serial scanning strategy (see also Gaspelin et al., 2017, for evidence of oculomotor suppression in such displays).

Notably, the  $P_D$  to a lateral color singleton was reduced in size in blocks where attention was focused on the midline relative to unfocused attention blocks, suggesting that inhibition was stronger when color singletons appeared at potential task-relevant locations. Alternatively, this  $P_D$  amplitude difference could be linked to the total number of attended task-relevant locations in these two task conditions (two vs. four). Our additional observation that  $P_D$  amplitudes in response to search displays with lateral color singleton did not differ between the unfocused and the focused attention [lateral] condition rules out this alternative interpretation. Thus, active distractor inhibition, as reflected by the  $P_D$  component, appears to be scaled with the potential task relevance of distractor locations, presumably because distractors at relevant and thus attended locations are likely to interfere more strongly with target processing. The observation that the magnitude of the  $P_D$  and the magnitude of behavioral suppression are correlated (Gaspelin & Luck, 2018a) is also in line with this suggestion.

Kerzel and Burra (2020) reported additional behavioral evidence for their proposed lateral-first serial search strategy, as RTs in their study tended to be faster for lateral relative to midline targets. Here, we assumed that when observers knew that targets could only appear on the vertical midline, they should not adopt such a strategy, and would allocate attention only to the two midline locations. However, it remains theoretically possible that even under these conditions, they would still always attend to lateral items first. Because our ERP study used a multiple-frames procedure where no responses to individual search displays were required, this possibility could not be ruled out with behavioral data. We therefore ran an additional behavioral control experiment with 18 participants, using the same search display types and attentional focus conditions as our ERP experiment, except that trials with and without a color singleton distractor were equiprobable, and a speeded response was required after each search

display. Participants' task was to localize the position of a dot within the target shape (similar to Gaspelin & Luck, 2018a; Kerzel & Burra, 2020). If participants were prioritizing midline locations in the focused attention [midline] condition, RTs to midline targets should be faster for this condition relative to the unfocused attention task. If lateral locations are always scanned first, even when they are task-irrelevant, no such RT difference should be found. As predicted, responses to midline targets were indeed substantially faster when attention was focused on the midline than in the unfocused attention condition (focused [midline]:  $M = 509$  ms,  $SE = 17$  ms; unfocused [midline]:  $M = 581$  ms,  $SE = 20$  ms;  $t(17) = 6.36$ ,  $p < .0001$ ,  $d_z = 1.5$ ), indicating that irrelevant lateral locations were not prioritized.

This result leaves open the possibility that when targets can appear at any of four possible locations, observers adopt a lateral-first serial search strategy, as suggested by Kerzel and Burra (2020). To assess this, we compared RTs to lateral targets obtained in the same control experiment in blocks where attention was either unfocused or focused on the two lateral locations. RTs for lateral targets with focused lateral attention ( $M = 536$  ms,  $SE = 18$  ms) were faster than with unfocused attention ( $M = 578$  ms,  $SE = 20$  ms;  $t(17) = 2.99$ ,  $p = .008$ ,  $d_z = 0.70$ ), which is not in line with the hypothesis that attention is by default always directed to lateral locations first. It should be noted that both sets of comparisons are between tasks where either two or all four display locations could contain the target, and that slower RTs in the unfocused attention task could in part reflect this difference in effective search set size. This factor should have little effect if participants were scanning lateral locations first on all or on a large majority of trials regardless of task instructions (as suggested by Kerzel & Burra, 2020), but would become relevant if this strategy was adopted only on some trials.

Faster RTs to lateral targets with focused lateral relative to unfocused attention in this control experiment may appear inconsistent with the observation that N2pc components to these targets measured in our ERP experiment did not differ in amplitude or onset latency between these two task conditions (Figure 4). This was indeed unexpected, as attentional target selection, as reflected by N2pc components, should presumably have been more efficient with focused attention. The absence of any N2pc differences suggests that when search displays contain only four items and a shape-defined target is therefore relatively easy to locate, the initial rapid deployment of attention is not affected by information about possible target location. In this case, the RT difference observed in our control experiment was likely to be produced by processes that follow this initial deployment, such as target identification and response selection.

While the presence of a  $P_D$  component in the focused attention [midline] condition strongly suggests that this

component is associated with distractor suppression, one other aspect of our ERP results may seem difficult to reconcile with this interpretation. Similar to Kerzel and Burra (2020), we also found that the  $P_D$  in response to search displays with lateral color singletons was followed by a contralateral negativity. This negativity was most pronounced for target-present displays in the unfocused attention condition, but was also nearly significant in the focused attention [midline] condition. If this contralateral negativity was an N2pc reflecting attentional capture by the color singleton, as suggested by Kerzel and Burra (2020), this would call into question the link between the  $P_D$  and distractor suppression, since suppression should presumably prevent attentional capture. One possible explanation is that successful distractor suppression and attentional capture occur on different trials, with capture the result of incomplete or failed inhibition. Averaging across trials with effective and ineffective suppression could result in a pattern of a  $P_D$  followed by an N2pc component (see also Gaspar & McDonald, 2014, for similar suggestions). While this possibility cannot be ruled out entirely on the basis of the current results, it is unlikely for two reasons. First, if the color singleton had captured attention on a substantial number of trials, this should result in overall performance costs, with slower target RTs for search displays where this singleton was present relative to displays when it was absent. In fact, both Kerzel and Burra (2020) and Gaspelin and Luck (2018a) observed the opposite effect, with RTs actually being faster for singleton-present displays. This was confirmed in the unfocused attention task of our behavioral control experiment, where responses were also faster when a singleton was present in a search display (present:  $M = 573$  ms,  $SE = 19$  ms; absent:  $M = 592$  ms,  $SE = 22$  ms;  $t(17) = 4.04$ ,  $p = .0008$ ,  $d_z = 0.95$ ), suggesting that instead of inducing attentional capture, the presence of the singleton reduced effective display set size. Second, the hypothesis that the singleton captured attention on a proportion of trials also cannot account for our observation that the contralateral negativity in the unfocused attention was much larger when search displays contained a midline target than when the target was absent (Figure 2). It is unclear why the presence of a target should increase rather than decrease the ability of a color singleton distractor to capture attention.

For these reasons, we propose an alternative account of this contralateral negativity. We suggest that this negativity is not an N2pc associated with attentional capture by lateral color singletons, but instead a  $P_D$  that is elicited as a result of inhibiting the nonsalient context element on the opposite side. Previous research on lateralized ERP components elicited during target selection in visual search displays has shown that lateral distractor objects elicit a contralateral positivity linked to inhibition that can be triggered simultaneously with a contralateral negativity to targets (Hickey et al., 2009; see also Gaspar & McDonald, 2014, for related results).

Importantly, this contralateral positivity is triggered by lateral distractors in a search display even when these are not more salient than other display items (Hickey et al., 2009). In the four-item search displays used in the present study (as well as by Kerzel & Burra, 2020), search displays that triggered a contralateral positivity followed by a negativity always included a lateral color singleton and a nonsingleton distractor on the opposite side. Because this distractor was the only other lateralized item apart from the singleton, its inhibition should trigger a  $P_D$  component, whereas any parallel inhibition of nonlateralized vertical distractors would not elicit any lateralized activity. In other words, we propose that the temporal pattern of a positivity followed by a negativity contralateral to the color singleton reflects two successive distractor inhibition processes reflected by two successive  $P_D$  components. Due to its salience, the color singleton is registered (without being attended) and suppressed first, followed by the suppression of all nonsalient distractors in the search display.

This alternative account can explain why the contralateral negativity (nonsingleton distractor  $P_D$ ) was larger for target-present displays in the unfocused attention condition, because registering the presence of the target should trigger stronger distractor suppression in order to facilitate target selection. It can also explain why this contralateral negativity was smaller and only marginally significant when lateral locations never contained a target and thus could be ignored. As stated earlier, distractor inhibition may generally be less pronounced for task-irrelevant locations. Moreover, this interpretation can also account for the puzzling fact that Gaspelin and Luck (2018a) only found a positivity but no subsequent negativity contralateral to a color singleton distractor in their first two experiments where search and probe trials were interleaved. In contrast, both lateralized components were clearly present in Experiment 3 where no probe trials were included. Because all four display locations were task-relevant on probe trials, the inclusion of these trials is likely to have prevented the active suppression of locations occupied by nonsalient distractors, as reflected by the absence of  $P_D$  components triggered by these distractors. Our account of the two successive lateralized components as reflecting two successive distractor suppression processes provides a consistent and theoretically plausible explanation of the current results as well as of the findings of Kerzel and Burra (2020) and Gaspelin and Luck (2018a). However, it remains a conjecture at present, and thus requires confirmation in future studies.

It is also important to note that the pattern of distractor suppression effects observed in these studies may be specific to search displays that contain relatively few objects. For example, Wang and Theeuwes (2020) showed that behavioral probe suppression effects can only be found with small display set sizes, but not for search displays with 10 items, and no  $P_D$  to singleton distractors was found when search displays contained eight instead of four items (Barras & Kerzel, 2016).

There is also evidence that suppression may be modulated by the proximity of singleton distractors and targets (Gaspar & McDonald, 2014). Understanding the role of active distractor suppression processes in visual search will require further work to elucidate more systematically how these processes are affected by factors such as display set size, spatial parameters, and the task-relevance of distractor locations.

## 4.1 | Conclusion

We demonstrated that  $P_D$  components were elicited by lateral color singleton distractors even when these distractors appear at known task-irrelevant locations. These results support the signal suppression hypothesis (Gaspelin & Luck, 2018a) by confirming that the  $P_D$  is indeed associated with active distractor inhibition, but are inconsistent with the alternative lateral-first serial scanning strategy account proposed by Kerzel and Burra (2020).

## CONFLICTS OF INTEREST

There are no conflicts of interest to report.

## AUTHOR CONTRIBUTIONS

**Brandi Lee Drisdelle:** Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Visualization; Writing-original draft. **Martin Eimer:** Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Software; Supervision; Visualization; Writing-review & editing.

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