Electrophysiological Evidence for the Suppression of Highly Salient Distractors

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ABSTRACT

There has been a longstanding debate as to whether salient stimuli have the power to involuntarily capture attention. As a potential resolution to this debate, the signal suppression hypothesis proposes that salient items generate a bottom-up signal that automatically attracts attention, but that salient items can be suppressed by top-down mechanisms to prevent attentional capture. Despite much support, the signal suppression hypothesis has been challenged on the grounds that many prior studies may have used color singletons with relatively low salience that are too weak to capture attention. The current study addressed this by using previous methods to study suppression but increased the set size to improve the relative salience of the color singletons. To assess whether salient distractors captured attention, electrophysiological markers of attentional allocation (the N2pc component) and suppression (the P_D component) were measured. The results provided no evidence of attentional capture, but instead indicated suppression of the highly salient singleton distractors, as indexed by the P_D component. This suppression occurred even though a computational model of saliency confirmed that the color singleton was highly salient. Altogether, this supports the signal suppression hypothesis and is inconsistent with stimulus-driven models of attentional capture.

Keywords: visual attention, attentional capture, suppression, salience, ERP

ELECTROPHYSIOLOGICAL EVIDENCE FOR THE SUPPRESSION OF HIGHLY SALIENT DISTRACTORS

A vigorously debated question about visual attention has been whether physically salient stimuli can automatically capture attention (Luck et al., 2021). On the one hand, from a phenomenological standpoint, salient stimuli often feel as if they have an inherent power to attract attention. For this reason, salient stimuli such as brightly colored objects are often used as visual warning signals in applied settings, such as a red stop sign or a neon orange construction cone. On the other hand, salient stimuli must be ignored to accomplish everyday visually guided behavior. If attention were captured by every salient stimulus, simple tasks like operating a motor vehicle or shopping for items in the grocery would be nearly impossible. This perplexing puzzle has led to longstanding debate about the nature of attentional control in vision.

As a potential resolution to the attentional capture debate, the signal suppression hypothesis has proposed that salient stimuli automatically compete for attention, but can be proactively suppressed before they capture attention (Gaspelin & Luck, 2018b, 2019). Studies supporting this account have been recently challenged on the grounds that the salient stimuli may have not been highly salient and therefore were easy to suppress (Wang & Theeuwes, 2020; see also Theeuwes, 2004). The current study will therefore evaluate whether highly salient stimuli elicit electrophysiological indices of attentional capture or suppression.

The Attentional Capture Debate

Initial studies of attentional capture supported *stimulus-driven accounts*, which suggest that certain classes of physically salient stimuli have an automatic power to capture visual attention, even when completely task irrelevant (Theeuwes, 1991, 1992; Yantis & Jonides, 1984). For example, Theeuwes (1992) used an *additional singleton paradigm,* in which participants searched for a unique shape target (e.g., a diamond) amongst a homogenous set of distractor shapes (e.g., circles) and reported the orientation of a tilted line inside the target. Importantly, on a subset of trials, one of the nontarget shapes was rendered in a unique color. This *color singleton* was never the target stimulus and therefore should have been ignored. However, manual response times (RTs) were slower when the color singleton was present than when it was absent. This *singleton-presence cost* was interpreted to indicate that the color singleton automatically captured attention, slowing detection of the target when it was present (Theeuwes, 1991, 1992, 2004).

Subsequent studies, however, provided opposing evidence that salient stimuli do not have the ability to automatically capture attention (Bacon & Egeth, 1994; Folk et al., 1992). According to *goal-driven accounts*, physically salient stimuli will only capture attention when they match the attentional control settings of the observer. For example, when participants establish an attentional set for the color red, any red item—including salient red color singletons—could capture attention; whereas, any colored item falling outside of the attentional set, such as a salient blue color singleton, would not (Folk et al., 1992; Folk & Remington, 2010). To explain the aforementioned studies using the additional singleton paradigm (Theeuwes, 1992), goal-driven accounts proposed that participants may have inadvertently been encouraged to establish an attentional set for salience more generally. That is, participants searched for the uniquely shaped target (a shape singleton), and this may have caused observers to search for *any* unique stimulus. This *singleton detection mode* (Pashler, 1988) may have caused the color singleton to capture attention. Later studies modified the additional singleton

paradigm to discourage singleton detection mode by making the non-target shapes heterogeneous, thereby encouraging a more stringent attentional set for the specific target feature (Bacon & Egeth, 1994). This *feature-search mode* completely eliminated the singleton-presence cost, suggesting that the singleton distractor no longer captured attention. This study and others, led to the conclusion that physically salient distractors do not automatically capture attention unless made task relevant (Egeth et al., 2010; Folk et al., 2002; Lamy & Egeth, 2003; Leber & Egeth, 2006; Lien et al., 2008, 2010; Moher et al., 2011).

For decades, the debate between stimulus-driven and goal-driven accounts of the attentional capture remained largely unresolved. This was problematic because stimulus-driven accounts and goal-driven accounts make directly competing predictions about whether salient stimuli can automatically attract attention.

The Signal Suppression Hypothesis

As a potential resolution, a hybrid model of attentional capture was proposed: the *signal suppression hypothesis* (Gaspelin & Luck, 2018b, 2019; Luck et al., 2021). According to this account, physically salient stimuli automatically generate a bottom-up signal that will capture attention. However, salient stimuli can be suppressed via top-down mechanisms to prevent attentional capture. Thus, if a physically salient stimulus is not suppressed, it will automatically capture attention, which is consistent with stimulus-driven accounts. Further, if the physically salient stimulus is successfully suppressed, then there will be no resulting attentional capture, which is consistent with goal-driven accounts.

Support for this account has accumulated through converging evidence from studies of psychophysics (Adam et al., 2021; Chang & Egeth, 2019, 2021; Gaspelin et al., 2015; Won & Geng, 2020), eye movements (Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018a), event-related potentials (Feldmann-Wüstefeld et al., 2020; Gaspar et al., 2016; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Moorselaar et al., 2021; Sawaki & Luck, 2010; Weaver et al., 2017), and single-unit recordings in monkeys (Cosman et al., 2018). Further, an emerging body of literature suggests that observers can learn to suppress salient items based on their locations (Moorselaar & Slagter, 2019; Ruthruff & Gaspelin, 2018; Wang & Theeuwes, 2018a, 2018b), simple features (Adam & Serences, 2021; Cunningham & Egeth, 2016; Gaspelin et al., 2019; Gaspelin & Luck, 2018a; Stilwell et al., 2019; Vatterott & Vecera, 2012), and possibly by learning to anticipate their mere presence more generally (Moher et al., 2011; Moorselaar et al., 2020; Vatterott et al., 2018; Won et al., 2019, 2020).

One line of support for the signal suppression hypothesis has come from the *capture-probe paradigm* (e.g., Gaspelin et al., 2015; Stilwell & Gaspelin, 2021). This task involves intermixing frequent search trials with infrequent probe trials. On search trials, participants search for a target stimulus and attempt to ignore a salient item such as a color singleton. On probe trials, probe letters are briefly superimposed on top of the search items and participants report as many letters as possible in an untimed task. The assumption is that participants should be more likely to report letters at attended locations and less likely to report letters at suppressed locations. The typical finding is that probe report accuracy is lower for letters appearing at the singleton location than for letters appearing at the average nonsingleton location: a *probe suppression effect* (Gaspelin et al., 2015; Stilwell & Gaspelin, 2021). This suggests that singletons are suppressed below baseline levels to prevent attentional capture.

Further evidence for the signal suppression hypothesis has come from ERP studies of the N2 posterior contralateral (N2pc) and distractor positivity (P_D) components. The N2pc component is an index of covert attentional allocation (Eimer, 2014; Eimer & Kiss, 2008; Hickey

et al., 2009; Hillyard et al., 1998; Luck, 2012; Luck & Hillyard, 1994; Woodman & Luck, 2003). It occurs as a negative-going deflection at electrode sites that are contralateral to the attended visual hemifield around 200–300 ms following stimulus presentation. Conversely, the P_D component is a putative index of attentional suppression that appears as a positive-going deflection contralateral to the ignored hemifield (Hickey et al., 2006). The scalp distribution of the P_D component is similar to the N2pc component (Hickey et al., 2009; Sawaki & Luck, 2010). Also, MEG and fMRI studies in humans seem to indicate that source activity underlying the N2pc and P_D components propagates from higher levels of visual cortex such as IT and V4 (Hopf et al., 2006; Luck et al., 1997) to lower levels of visual cortex such as V1 (Donohue et al., 2020; see also Adam & Serences, 2021).

Several studies have demonstrated that task-irrelevant salient stimuli elicit a P_D component, indicating that they are suppressed (Barras & Kerzel, 2016; Berggren & Eimer, 2020; Drisdelle & Eimer, 2021; Feldmann-Wüstefeld et al., 2020; Gaspar et al., 2016; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Henare et al., 2020; Hickey et al., 2009; Jannati et al., 2013; Moorselaar et al., 2021; Sawaki & Luck, 2010). For example, Gaspar and McDonald (2014) found that task-irrelevant color singletons elicited a P_D component, but no corresponding N2pc component, which was taken to suggest that the salient item was proactively inhibited to prevent attentional capture (see also Jannati et al., 2013; Sawaki & Luck, 2010). Additionally, Gaspelin and Luck (2018c) demonstrated that the magnitude of the P_D component was positively correlated with the magnitude of probe suppression effects across participants in the capture-probe paradigm (see also Feldmann-Wüstefeld et al., 2020). Moreover, Weaver et al. (2017) have shown that successful eye movements away from salient distractors are preceded by a P_D component, and this overt suppression depended on the moment the saccade was elicited: When saccades were triggered before the P_D component, there was no evidence for overt suppression (i.e., saccade deviation). Thus, the P_D component seems to reflect covert suppression independent of overt suppression. Collectively, there is an abundance of evidence that salient items can be suppressed, at least under certain circumstances, and that the P_D component indexes this covert suppressive process.

Can Highly Salient Stimuli Be Suppressed?

The signal suppression hypothesis, however, has been recently challenged on the grounds that the singleton distractor may have been only weakly salient in past studies. According to Theeuwes and colleagues, the search displays used by Gaspelin, Luck, and colleagues were small, typically containing only four to six elements. This small set size may have reduced the salience of the color singleton. To support their argument, Wang and Theeuwes (2020) used the capture-probe paradigm to compare probe suppression effects at low display set sizes of four and six, which have been used previously, and a higher set size of ten, rendering the singleton distractor more salient relative to the nonsingleton distractors. They found probe suppression effects at the lower set size of four, but *probe capture effects* (i.e., higher probe recall for the singleton distractor than nonsingleton distractors) at the higher set size of ten. They concluded that highly salient items cannot be suppressed.

There are a few reasons to be skeptical of the above claim. First, Gaspelin and colleagues ran control experiments which showed that the color singletons in four-item displays were salient enough to capture attention under singleton detection mode (Gaspelin et al., 2015, 2017). Further, Gaspelin and Luck (2018a, Exp. 4) showed their usual suppression effect with displays of size six; after about 20 trials eye movements to the singletons were eliminated. The important point is that during the first 20 trials, these same singletons were sufficiently salient to capture

overt attention. All of these studies suggest that singletons were sufficiently salient to attract attention but that participants could learn to suppress them under conditions that encourage top-down control. Furthermore, Chang et al. (2021) have demonstrated that the color singletons used in these studies seem to be salient as assessed by computational models of saliency.

Additionally, Stilwell and Gaspelin (2021) provided evidence that singletons can even be suppressed at high set sizes, and that the results of Wang and Theeuwes (2020) may have been due, at least in part, to a design flaw whereby increasing the number of probed items caused a type of floor effect. In Stilwell and Gaspelin (2021), participants performed a capture-probe paradigm with large set sizes of ten items which should have rendered the singleton highly salient. Importantly, the number of probe letters were independently manipulated to be either ten or four letters. The four-letter probe displays allowed probe accuracy to remain relatively high, preventing any kind of floor effect that would conceal underlying suppression of the color singleton. Indeed, probe suppression effects were observed in the four-letter displays but were greatly reduced in ten-letter displays, largely because of low overall probe accuracy. This pattern of results is consistent with a floor effect and demonstrates that even highly salient singletons seem to be suppressible, at least under certain conditions.

In summary, some recent studies have suggested that highly salient color singletons cannot be suppressed (Wang & Theeuwes, 2020; see also Theeuwes, 2004). Although there has been some evidence challenging this claim (Chang et al., 2021; Stilwell & Gaspelin, 2021), further evidence is needed to definitively demonstrate that covert attention is not automatically allocated to highly salient color singletons. The current study will use ERPs to assess covert attentional allocation to highly salient color singletons. A benefit of ERP measures is that they provide a continuous measure of visual processing, which allows one to assess whether the salient item was ever covertly attended during an experimental trial. It also allows one to assess whether putative indices of suppression—such as the Pd component—are elicited by highly salient color singletons.

The Current Study

Participants performed a version of the additional singleton task that has previously been shown to produce attentional suppression via the P_D component (Gaspelin & Luck, 2018c), but the task was modified to improve the bottom-up salience of the color singleton. Namely, the search displays were modified to include additional target-colored distractors, which should increase relative bottom-up contrast with the color singleton distractor (Chang et al., 2021; Stilwell & Gaspelin, 2021; Wang & Theeuwes, 2020). We independently verified that this manipulation increased the bottom-up salience of the distractor using a computational model of salience (Hou et al., 2012; Kotseruba et al., 2020). Two separate experiments then assessed whether this highly salient item elicited a P_D component (indicating suppression) or instead an N2pc component (indicating attentional capture). If highly salient items cannot be suppressed as claimed by stimulus-driven accounts, they should elicit an N2pc component.

EXPERIMENT 1

Experiment 1 used an additional singleton paradigm similar to Gaspelin and Luck (2018c) but modified to improve the salience of the color singleton (Figure 1). Participants searched for a specific target shape (e.g., green diamond) amongst a set of heterogeneous distractor shapes (e.g., green triangles, hexagons, ovals, etc.) and made a speeded button press regarding the tilt of an inscribed line (left vs. right). On some trials, a color singleton distractor appeared at a nontarget location. The primary search display consisted of four items, similar to

Gaspelin and Luck (2018c). To improve the salience of the color singleton, an additional 12 target-colored dummy shapes were presented around this search display (see also Stilwell & Gaspelin, 2021). Neither the target nor the singleton ever appeared in this outer ring of dummy shapes, which was only used to improve the salience of the color singleton.

Lateralized ERPs were used to assess attentional allocation. The singleton and target could appear either on the vertical midline or at lateralized location. When an item appears on the vertical midline, the EEG activity elicited by a stimulus should be equal in both visual hemifields, effectively cancelling out any lateralized difference in the ERP waveform. When a stimulus is lateralized, however, an N2pc component should be elicited if it is attended, whereas a P_D component should be elicited if it is suppressed.

Stimulus-driven accounts and the signal suppression hypothesis make competing predictions about ERPs on trials where the singleton distractor is lateralized, and the target appears on the midline (singleton lateral/target midline trials). Stimulus-driven accounts predict that the singleton should automatically capture attention, resulting in an N2pc component (Hickey et al., 2006). Conversely, the signal suppression hypothesis predicts that the singleton should be proactively suppressed, and should therefore result in a P_D component on singleton lateral/target midline trials (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Sawaki & Luck, 2010).

Method

Participants. A sample of 20 participants from State University of New York at Binghamton participated for monetary compensation. In the final sample, 14 were women and six were men (mean age = 18.8 years). Our sample size was determined a priori based on a power analysis of the pooled effect size (Cohen's $d_z = 1.51$) from four recent studies of the P_D component (Sawaki & Luck, 2010, $d_z = 1.44$; Gaspelin & Luck, 2018c, $d_z = 1.83$; Drisdelle & Eimer, 2021, $d_z = 1.42$; Kerzel & Burra, 2020, $d_z = 1.39$). With this effect size, 11 participants would be needed to achieve 99% power. We chose to err on the side of caution and collect a larger sample size.

All participants had normal or corrected-to-normal visual acuity and had normal color vision as indicated by an Ishihara test. All experimental protocols were approved by a university ethics board.

Stimuli & Procedure. Stimuli were presented using PsychToolbox for Matlab (Brainard, 1997) on an Asus VG245H LCD monitor with a black background at a viewing distance of 100 cm. The timing delay of the stimulus presentation system was measured using a photosensor, and event codes were shifted offline to compensate for this delay (12 ms).

As depicted in Figure 1, each search display contained sixteen shapes that were arranged in two concentric rings (Theeuwes, 2004). The inner ring consisted of four shapes arranged equidistantly around a notional circle with a radius of 2.0° and the outer ring consisted of twelve shapes arranged in a notional circle with a radius of 4.0°. The individual shapes were triangles (1.2° by 1.2°), hexagons (1.2° by 1.2°), ovals (1.5° by 0.9°), crosses (1.2° by 1.2°), diamonds (1.2° by 1.2°), and circles (1.2° diameter). The shapes were either red (30.0 cd/m^2, $x = .627$, $y = .330$) or green (30.0 cd/m^2, $x = .292$, $y = .631$) which were photometrically isoluminant. Each shape contained a black line segment (0.4° x 0.1°) tilted either 45° to the left or right, randomly selected. A gray fixation cross (0.5° diameter; 30.0 cd/m^2, $x = .306$, $y = .320$) was continuously visible throughout the trial.

Figure 1
Stimuli and Procedure from Experiment 1
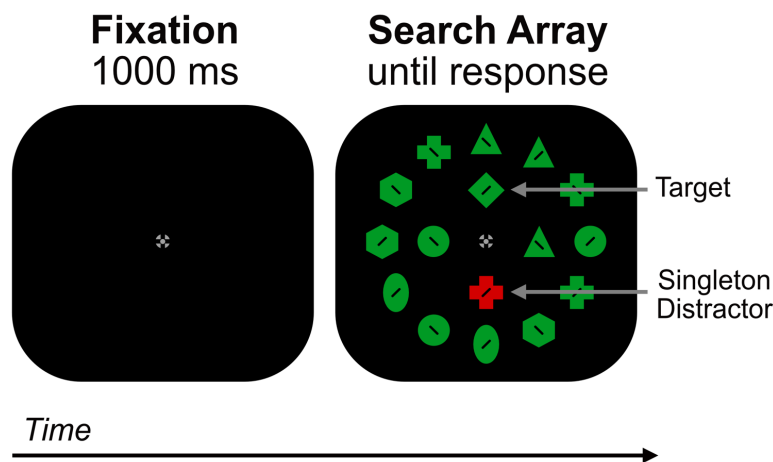
Note. Participants searched an array of 16 shapes for the target (e.g., green diamond) and made a speeded button press indicating the orientation of a black line segment inside (as in Gaspelin & Luck, 2018). Importantly, the target and singleton could only appear in the inner ring. The outer ring was included to boost the salience of the singleton distractor.

The target shape (circle or diamond) and target color (green or red) were held constant for the entire experimental session, and all four potential combinations were counterbalanced across participants. The inner ring contained a target shape and three distractors. On each trial the three distractors were randomly selected from a pool of the five nontarget shapes without replacement (e.g., triangle, hexagon, oval, cross, or circle in the diamond target condition). The outer ring contained dummy shapes that were meant to boost the relative salience of the singleton distractor (Stilwell & Gaspelin, 2021). These shapes were also randomly selected from the nontarget shapes. To ensure high distractor heterogeneity, no shape could be selected more than three times in the outer ring.

On *singleton-present trials* (75% of trials), a distractor in the inner ring was rendered in a unique color, creating a singleton distractor. On *singleton-absent trials* (25% of trials), all sixteen shapes (in both rings) were the target color. This was meant ensure a high number of trials in which the singleton was present for the primary analysis in this study (singleton lateral/target midline trials). The location of the target shape and location of singleton distractor were selected at random with the exception that that the singleton distractor could not appear at the target location. These two items could appear only in the inner ring of four shapes. This ensured that the singleton distractor and target shape appeared equally distant from fixation to avoid introducing a spatial bias (e.g., see Woodman & Luck, 1999).

To encourage feature-search mode, the distractor shapes were carefully selected to reduce search asymmetries. Specifically, to eliminate any possible use of singleton detection mode, we selected distractor shapes that were both linear and curvilinear to contrast the diamond and circle target shapes, respectively. If only linear shapes were used as distractors, the circle target might "pop out" at high set sizes because it would be a curvilinear singleton, and this could potentially induce singleton detection mode (Bacon & Egeth, 1994).

Trials began with a fixation cross for 1000 ms. Next, the search array appeared, and participants attempted to locate the target shape as quickly as possible. Participants responded to the orientation of the line segment inside the target (left vs. right) via a speeded manual response on a gamepad using the left- and right-shoulder buttons, respectively. If participants were too slow to respond (RT was greater than 2000 ms), a "Too Slow" screen was presented for 500 ms, along with a 200-Hz tone lasting 300 ms. Incorrect responses were followed by the same tone-for the same duration. The interval between trials randomly varied between 0 and 500 ms.

At the beginning of each session, participants were instructed that the singleton distractor would never be the target and should be ignored. Further, participants were instructed that the target would only appear in the inner ring of shapes. Eye movements were discouraged using the online horizontal EOG waveforms; the experimenter reminded participants to maintain fixation throughout the trial whenever eye-movements were detected.

Each session began with one practice block of 192 trials. This was followed by nine regular blocks of 192 trials (1,728 trials in total). This yielded 1,296 singleton-present and 432 singleton-absent trials per participant. The key hypotheses in the current experiment relate to trials where the singleton was presented at a lateral location and the target was on the vertical midline. For each participant, there were approximately 324 of these singleton lateral/target midline trials, which should yield high statistical power to detect any significant effect. Each block was divided into four miniature blocks of 48 trials that were separated by 15-sec breaks to allow participants to blink and/or adjust seating position. At the end of each full block, a 5-minute break was provided. Participants received block-by-block feedback on mean response time (RT) and accuracy.

Electrophysiological Recording and Analysis. The EEG was recorded using active Ag/AgCl electrodes (Brain Products actiCHamp system) from 27 scalp sites (FP1, FP2, F7, F3, Fz, F4, F8, C3, Cz, C4, P9, P7, P5, P3, Pz, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2, according to the modified 10–20 system; American Electroencephalographic Society, 1994) referenced to each mastoid. To detect eye movements and blinks, the EOG was recorded from electrodes placed at the outer canthi of each eye and below the right eye. All signals were recorded in single-ended mode using a customized version of the PyCorder recording software and then referenced offline. The EEG was filtered online with a cascaded integrator–comb antialiasing filter with a half-power cutoff at 130 Hz and then digitized with a 500-Hz sampling rate.

After data acquisition, all analyses were conducted using ERPLAB Toolbox (Lopez-Calderon & Luck, 2014) and EEGLAB Toolbox (Delorme & Makeig, 2004). EEG signals were referenced to the average of the left and right mastoids, and the four EOG signals were averaged for each direction (horizontal and vertical) for each corresponding pair of electrodes. These signals were then filtered offline using a noncausal Butterworth high-pass filter (half-amplitude cutoff: 0.1 Hz, slope: 12 dB/octave). Using a 600-msec epoch, beginning 200 msec before stimulus onset, averaged ERP waveforms were computed. For plotting purposes only, and to maximize temporal precision, a low-pass filter (half-amplitude cutoff: 30 Hz, slope: 12 dB/octave) was applied to the averaged ERPs.

Trials were excluded if an incorrect behavioral result was produced or if manual RT was faster than 200 ms or longer than 1500 ms. Additionally, trials were excluded if a blink or eye movement was detected during the trial in either the horizontal or vertical EOG channels as indexed by step-like voltages in the EEG signal. Blinks were identified as a voltage step exceeding 80 μV between 200 ms to 400 ms in channels FP2 and VEOG. Saccades were

identified as voltage steps exceeding 16 μV for saccades between 100 to 400 ms in the bipolar HEOG channel. To ensure that all eye movements were eliminated, we used an approach similar to Woodman and Luck (2003). Grand averaged bipolar HEOG waveforms were computed for left- and right-target trials. Participants were replaced if bipolar HEOG deviated more than 3.2 μV between 100 and 400 ms poststimulus. Two participants were replaced for this reason. This approach ensures that eye movements did not exceed ± 0.1° in the direction of the target (Lins et al., 1993) during the critical time windows used to assess the N2pc and P_D components (see also Gaspelin & Luck, 2018c). We planned to replace any participant with more than 25% of trials excluded due to any combination of exclusion criteria aforementioned. However, in this experiment, no participants had to be replaced for this reason. In the final set of participants, an average of 6.8% of trials were excluded due to artifacts (range = 0.4–19.5%).

All subsequent EEG analyses were performed using the PO7 and PO8 electrode sites, which were chosen a priori based on previous studies of the P_D component (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Sawaki & Luck, 2010). The N2pc and P_D components were calculated by subtracting the ipsilateral waveform from contralateral waveform to create difference waveforms over time windows chosen a priori based on Sawaki and Luck (2010). That is, the N2pc component was measured as the mean amplitude between 225 ms and 300 ms, and the P_D component amplitude was quantified as the mean amplitude of the difference waveform between 115 ms and 225 ms. This strategy of using an earlier time window for the P_D ERP component than the N2pc component is consistent with several previous studies (Drisdelle & Eimer, 2021; Gaspelin & Luck, 2018c; Sawaki & Luck, 2010; Weaver et al., 2017).

To avoid issues of sphericity, all reported p values in this manuscript were Greenhouse-Geisser corrected for analyses of variances (ANOVAs) with more than two levels of a given factor. When appropriate, we adjusted the partial-eta squared in our reports of effect size for positive bias (Mordkoff, 2019). For within-subject t-tests, Cohen's d_z was used to measure effect size (Lakens, 2013).

Results
Behavioral Results
Figure 2A depicts mean RTs for singleton-present and singleton-absent trials. As can be seen, RTs were significantly faster on singleton-present trials (679 ms) than singleton-absent trials (701 ms), $t(19) = 6.95$, $p < .001$, $d_z = 1.40$. This 22-ms singleton-presence benefit replicates previous studies using displays that encourage feature-search mode (Chang & Egeth, 2019, 2021; Gaspelin et al., 2015; Gaspelin & Luck, 2018c; Stilwell & Gaspelin, 2021; Vatterott & Vecera, 2012). This pattern suggests that the color singleton was proactively suppressed, as if reducing the effective set size of the search display by one search item when it was present. Error rates were not significantly different between singleton-present (3.1%) and singleton-absent (3.3%) trials, $t(19) = 0.62$, $p = .54$, $d_z = 0.14$. Altogether, the behavioral results demonstrate no evidence of attentional capture by the color singleton and instead suggest that it was suppressed.

Figure 2

Manual RT Results for Experiment 1
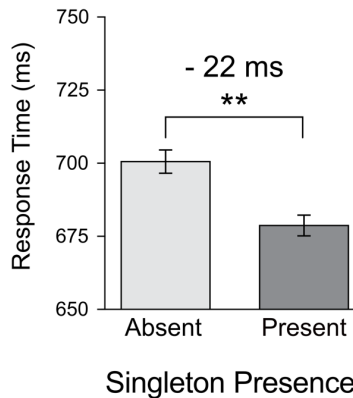
Note. Mean manual response time (RT) as a function of singleton presence for Experiment 1.
Error bars represent within-subject confidence intervals.

Electrophysiological Results

  Figure 3 depicts grand-averaged ERP waveforms for the lateral occipital sites (PO7 and PO8) for targets and singleton distractors. Separate waveforms are shown for electrodes contralateral and ipsilateral relative to the search item of interest. For example, the ipsilateral waveform for the target was the average of the right hemisphere electrode when the target appeared in the right visual field and the left hemisphere electrode when the target appeared in the left visual field. The contralateral waveform was the average of the right hemisphere electrode when the target appeared in the left visual field and the left hemisphere electrode when the target appeared in the right visual field. Trials in which the singleton distractor and target were both lateralized were excluded from the analyses because the lateralized N2pc component to the target and lateralized P_D component to the singleton distractor would summate (e.g., Hickey et al., 2009), preventing a dissociation of target enhancement versus singleton suppression.

  When the target was presented at a lateralized location and the singleton was absent (Figure 3A), there was a negative-going deflection in the contralateral waveform compared to the ipsilateral waveform beginning at approximately 200 ms poststimulus: an N2pc component. This N2pc component appeared with approximately the same amplitude and time course when the target was lateralized and the singleton was present (Figure 3B). Conversely, when the singleton distractor was lateralized, and the target appeared on the vertical midline (Figure 3C) during the interval beginning at approximately 130 ms poststimulus, there was an increased positive voltage in the contralateral waveform compared to the ipsilateral waveform: a P_D component. When the target is on the vertical midline, the lateralized activity across hemifields cancels out, isolating the ERP waveform to the singleton distractor. Figure 3D depicts contralateral-minus-ipsilateral difference waveforms for direct comparison of lateralization across conditions. Similar to previous studies (Drisdelle & Eimer, 2021; Gaspelin & Luck, 2018c; Sawaki & Luck, 2010), the positivity elicited by the singleton distractor peaks prior to the negativity elicited by the target, lending further support for the notion that the time window of the P_D component should be earlier than the N2pc component.

Mean Amplitude during the N2pc Time Window. The N2pc components were measured as the mean amplitudes from 225–300 ms post-stimulus in the contralateral-minus-ipsilateral difference waveforms. These mean amplitudes were then analyzed using a one-way within-subject ANOVA comparing the three trial types (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a significant main effect of trial type, $F(2, 38) = 25.50$, $p < .001$, $\eta_p^2 = .551$. Preplanned t tests compared the difference waveforms between trial types. The N2pc component was not significantly different on target lateral/singleton absent trials (-1.1 µV) and target lateral/singleton midline trials (-1.2 µV), $t(19) = 0.76$, $p = .46$, $d_z = 0.17$. This provides preliminary evidence that the singleton distractor did not capture attention. If the singleton had captured attention, target detection should have been impaired on trials where the singleton was present, reducing or perhaps delaying the N2pc component evoked by the lateralized target on singleton present trials compared to singleton absent trials. However, no such pattern was observed. On singleton lateral/target midline trials, the amplitude of the singleton-evoked activity was both positive in polarity (+0.1 µV) and was significantly larger than the amplitude of the target-evoked negativity both on target lateral/singleton midline trials, $t(19) = 5.71$, $p < .001$, $d_z = 1.28$, and target lateral/singleton absent trials, $t(19) = 4.94$, $p < .001$, $d_z = 1.10$.

Planned one-sample t tests compared ipsilateral-minus-contralateral difference waveforms against zero for each trial type (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a significant N2pc component on both target lateral/singleton absent trials (-1.1 µV), $t(19) = 5.35$, $p < .001$, $d_z = 1.20$, and target lateral/singleton midline trials (-1.2 µV), $t(19) = 5.50$, $p < .001$, $d_z = 1.22$. Critically, there was not a significant N2pc component on singleton lateral/target midline trials (+0.1 µV), $t(19) = 0.63$, $p = .54$, $d_z = 0.14$.

Mean Amplitude during the P_D Time Window. The same analyses from the previous section were conducted, but mean amplitudes were calculated between 115–225 ms in the contralateral-minus-ipsilateral difference waveforms to assess the P_D component. These mean amplitudes were analyzed using a one-way within-subject ANOVA comparing the three trial types (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a main effect of trial type, $F(2, 38) = 14.07$, $p < .001$, $\eta_p^2 = .395$. Preplanned t tests compared the contralateral-minus-ipsilateral difference waveforms between trial types. The magnitude of the P_D component to the target stimulus did not differ on target lateral/singleton absent (-0.2 µV) and target lateral/singleton midline trials (-0.3 µV), $t(19) = 1.38$, $p = .19$, $d_z = 0.31$. The P_D component was larger on singleton lateral/target midline trials (+0.4 µV) than target lateral/singleton midline trials, $t(19) = 4.69$, $p < .001$, $d_z = 1.05$, and target lateral/singleton absent trials, $t(19) = 3.41$, $p = .003$, $d_z = 0.76$.

Planned one-sample t tests compared contralateral-minus-ipsilateral difference waveforms against zero for each trial type (singleton lateral/target midline, target lateral/singleton absent, and target lateral/singleton midline). Critically, there was a significant P_D component on singleton lateral/target midline trials (+0.4 µV), $t(19) = 4.36$, $p < .001$, $d_z = 0.98$. No such P_D component was observed on trials where the target was lateralized. If anything, there was a lateralized negativity. On target lateral/singleton midline trials, there was significant negative-going deflection evoked (-0.3 µV), $t(19) = 3.33$, $p = .004$, $d_z = 0.74$. On target lateral/singleton absent trials, there was no statistically reliable positive- or negative-going deflection (-0.2 µV), $t(19) = 1.58$, $p = .13$, $d_z = 0.35$.

Figure 3

Electrophysiological Results for Experiment 1
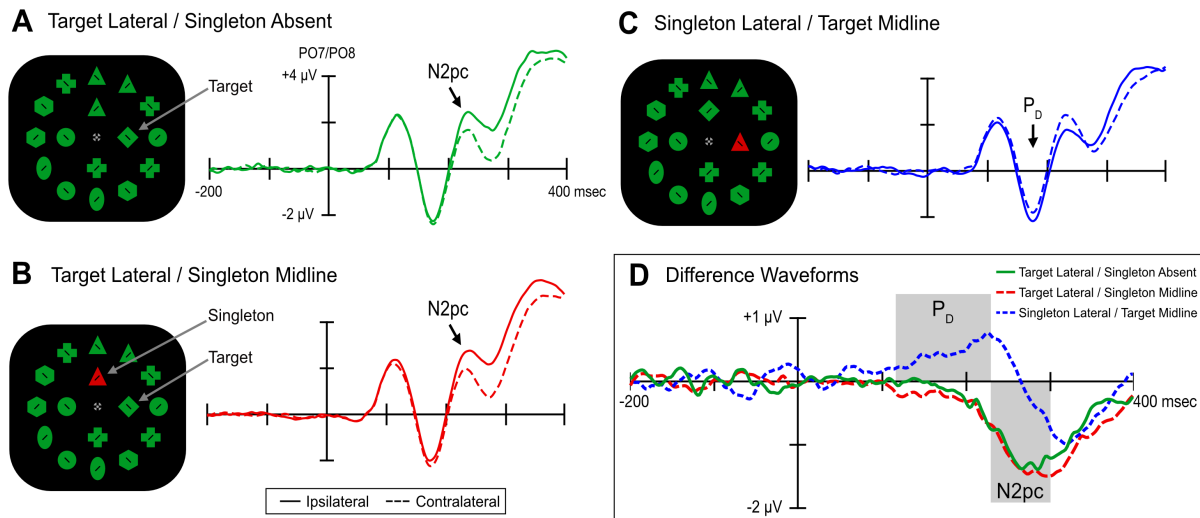
Note. Panels A–C depict ipsilateral and contralateral waveforms for each potential search display configuration. In the schematics of search displays, the target was the green diamond and the singleton distractor was the uniquely colored item. Panel D depicts contra-minus-ipsi difference waveforms for each display configuration. All waveforms in this paper were low-pass filtered to improve the visibility of the effects (Butterworth noncausal filter, half-amplitude cutoff = 30 Hz, slope = 12 dB/octave) but were analyzed using unfiltered waveforms.

Exploratory Analysis: Post-P_D Negativity

      As shown in Figure 3D, on singleton lateral/target midline trials, there is a negative-going deflection that occurred after the P_D component from approximately 275–375 ms. We did not have any specific hypotheses about this post-P_D negativity. It has occurred in some previous studies (Drisdelle & Eimer, 2021; Feldmann-Wüstefeld et al., 2020; Gaspelin & Luck, 2018c, Exp. 3; Kerzel & Burra, 2020b) but not others (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c, Exp. 1; Sawaki & Luck, 2010). The exact cognitive process underlying this post-P_D negativity is currently unknown. Some have proposed that it could reflect attentional capture by the singleton distractor on a small portion of trials or participants, producing a combination of an N2pc and a P_D component in the grand average waveform even though they never occurred on the same trial (Gaspelin & Luck, 2018b). Others have suggested that this negativity may result from a search strategy at low set sizes, whereby the two locations on the horizontal midline are prioritized during visual search. The second negativity could represent either a secondary shift of attention to the singleton (Kerzel & Burra, 2020) or delayed suppression of the nonsingleton distractor opposite of the singleton distractor (Drisdelle & Eimer, 2021).

      We conducted an exploratory analysis to assess the significance of the negativity from 275–375 ms using a one-sample *t* test on the difference waveform on singleton lateral/target midline trials. This indicated the negativity (-0.7 µV) was statistically significant, $t(19) = 5.36$, $p < .001$, $d_z = 1.20$. The post-P_D component did not significantly correlate with the magnitude of the singleton-presence benefit, ($r = 0.29$, $p = .22$). Ultimately, it is currently unknown what

cognitive process the post-P_D negativity reflects but it seems to be unrelated to distractor suppression.

Saliency Maps

Saliency maps were used to independently verify the salience of the color singleton (see Chang et al., 2021; Stilwell & Gaspelin, 2021). A set of 1000 search displays were generated (250 for each counterbalancing condition) using the stimulus code. The resulting images were then processed using the Image Signature Toolbox in Matlab (Hou et al., 2012) to generate saliency maps. This toolbox was chosen because it performs similarly to human observers in its ability to detect singletons in artificial images, unlike many canonical saliency models (Kotseruba et al., 2020). The default settings were used, with the exception of the mapWidth() parameter, which was adjusted to accommodate the image resolution (1920 x 1080). The output was a series of saliency maps that resemble heatmaps depicting the relative distribution of salience across the image (Figure 4). For each saliency map, a circular region of interest (1.8° in diameter) was defined encompassing each of the 16 search items. The mean salience score at each location was calculated by averaging the pixels in the interest area.

Mean salience scores were used to calculate two metrics of salience: the *global saliency index* (GSI) and the *singleton win rate*. First, the global saliency index was computed as the mean salience score at the singleton distractor minus the mean salience score at the average of all nonsingleton locations (Kotseruba et al., 2020). The difference score was normalized by dividing by the sum of the salience scores of all search items. The GSI is a continuous metric ranging from -1 to 1. A positive value indicates that the singleton is more salient than the average nonsingleton item, whereas negative values indicates that the singleton is less salient than the average nonsingleton item. A value of zero indicates that the singleton is as salient as the average of all of the other items. The average GSI across all images was 0.81 (SE = 0.003), $t(999) = 320.67$, $p < .001$, $d_z = 10.14$, indicating the singleton had an average salience score that was much higher than the other search items. The second metric to assess salience was the *singleton win rate*, which is the percentage of images in which the singleton had the highest salience score of all items in the saliency map. The singleton win rate was 100%. This means that the singleton distractor was selected as the most salient item in the display in every singleton simulation image.

We also compared singleton salience in sixteen-item displays of the current study with four-item displays (resembling Gaspelin & Luck, 2018c). The basic goal was to ascertain whether increasing the set size actually increased the salience of the color singleton compared to previous studies. Four-item displays were created by removing the outer ring of dummy shapes. Four-item displays produced an average GSI of 0.47 (SE = 0.005) which was significantly lower than the GSI of 0.81 (SE = 0.003) produced in the current study, $t(999) = 59.72$, $p < .001$, $d_z = 1.89$. However, the singleton win rate was still 100% of trials, even in the four-item displays. These results suggest that the singletons in the current study were more salient than the four-item displays of Gaspelin and Luck (2018c). However, it is important to highlight that even the displays of Gaspelin and Luck (2018c) seem to suggest that the singletons used were highly salient: the GSI of 0.47 was significantly above 0, $t(999) = 93.99$, $p < .001$, $d_z = 2.97$, and the singleton win rate was 100%.

Figure 4
Saliency Map Results for Both Experiments
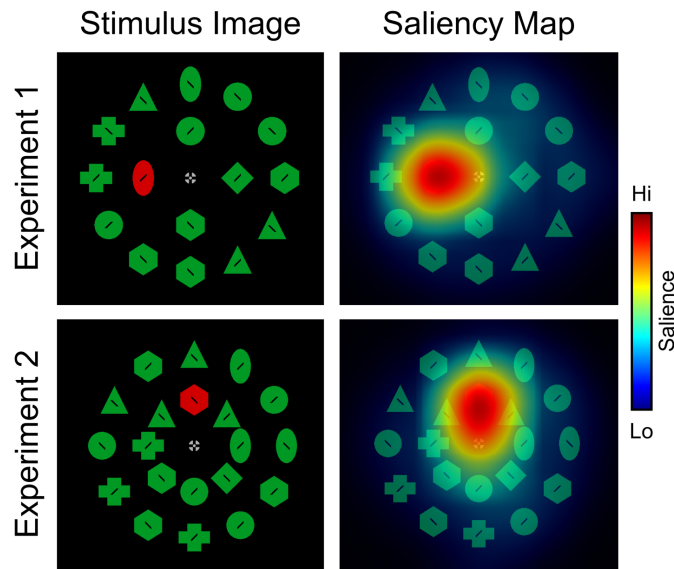
Note. Stimulus images (*N = 1,000 for each Experiment) were analyzed using the Image Signature Toolbox (Hou et al., 2012) for each Experiment to determine if the singleton was truly salient. In this example, the saliency map indicated a high salience score at the location of the color singleton.*

Discussion

Experiment 1 tested whether highly salient color singletons can be suppressed or instead capture attention. To improve the salience of the color singleton, we increased the set size compared to previous studies from four items to sixteen items (Stilwell & Gaspelin, 2021; Wang & Theeuwes, 2020). Indeed, computational models of salience suggested that increasing the display set size improved the salience of the color singleton. Despite increasing the salience of the singleton distractor, the singleton did not capture attention. First, manual RTs were significantly faster when the singleton was present than absent, suggesting suppression of the singleton. Second, there was a significant P_D component on singleton lateral/target midline trials, reflecting suppression of the salient singleton. Altogether, these results suggest that the salient singleton distractor was proactively suppressed, supporting the signal suppression hypothesis and refuting stimulus-driven accounts.

EXPERIMENT 2

In Experiment 1, the color singleton elicited a P_D component which, along with the behavioral results, would seem to indicate that the color singleton was suppressed. It is possible, however, that adding an outer ring of dummy shapes may have encouraged participants to restrict visual processing to only the inner ring of shapes. If the saliency computations between the singleton and nonsingleton distractors were somehow restricted to the inner ring of shapes, the singleton would be no more salient than previous demonstrations using four-item search arrays (such as in Gaspelin & Luck, 2018c).

Experiment 2 was therefore designed to increase the salience of the singleton distractor by increasing the number of items at task-relevant locations. The search displays were similar to

Experiment 1 but had an inner ring of eight items rather than four items (see Figure 5). This manipulation guarantees that the singleton would be more salient than in Experiment 1. The theoretical predictions are identical to Experiment 1. According to the signal suppression hypothesis, the singleton distractor should be suppressed, resulting in a P_D component when it is lateralized. According to the stimulus-driven account, however, the singleton distractor should capture attention, resulting in an N2pc component when it is lateralized. Additionally, the increased set size of the inner ring of shapes also allows us to test a recent alternative account of the P_D component (see the "Idiosyncratic Search Hypothesis: P_D Horizontal Midline Analysis" in the Results; Kerzel & Burra, 2020).

Method
　　　Participants. A new sample of 20 participants from State University of New York at Binghamton (16 women and 4 men; mean age = 21.5 years) participated for monetary compensation. The sample size was determined a priori to match Experiment 1. A power analysis of the effect size observed for the P_D component in Experiment 1 ($d_z = 0.98$) suggested this sample size would yield 99% power to detect a significant effect.
　　　Stimuli & Procedure. The experimental task was identical to Experiment 1, except that four nonsingleton distractor shapes were added to the inner ring (see Figure 5). These shapes appeared at the four diagonal positions between the four cardinal positions used in Experiment 1. All search items in the inner ring were equidistant from central fixation. On each trial, the target shape was equally likely to appear at each inner ring location. The remaining five distractor shapes were randomly selected to appear in the remaining inner ring and outer ring positions with the constraint that a given distractor shape could only be used at most two times in the inner ring or three times in the outer ring. This was meant to maximize heterogeneity of distractors and encourage feature-search mode.
　　　In ERP studies, it is important to ensure that there are enough trials per condition to prevent statistical noise that could lead to a Type I error (Luck & Gaspelin, 2017). By adding four items to inner ring of the search display, this reduced the number of trials in which a search items appeared on the vertical or horizontal midline. To improve statistical power, the three lateralized locations on either side of the vertical midline were collapsed to form a single lateralized condition for each hemifield. For example, singleton lateral/target midline trials included any trial in which the singleton appeared at one of the three lateralized locations. Similar approaches have been used in previous studies that use high set sizes (e.g., Feldmann-Wüstefeld et al., 2021; Gaspar et al., 2016; Gaspar & McDonald, 2014, 2014). This approach did not significantly alter the results: the results of these full-display analyses were similar to the results of Experiment 1 and the partial-display analyses (i.e., restricting analyses to items appearing on the vertical and horizontal midlines) of Experiment 2, albeit noisier. Also, for the key ERP component (singleton lateral/target midline), we analyzed separate waveforms for when the singleton was and was not on the horizontal midline which allows for a direct comparison with Experiment 1 (see "Idiosyncratic Search Hypothesis: P_D Horizontal Midline Analysis" and Figure 8).

Figure 5

Example Search Array from Experiment 2
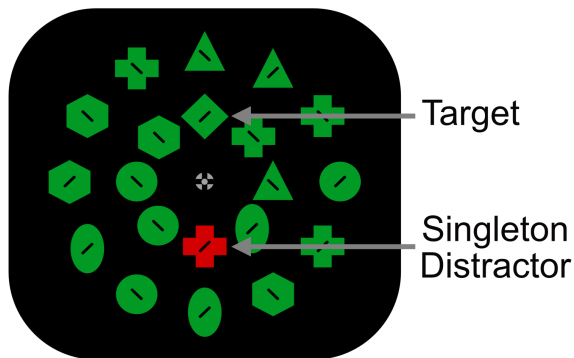
Note. The search displays in Experiment 2 were identical to Experiment 1 except for the addition of four distractors in the inner ring, raising the set size of the inner ring from four to eight items. The overall display contained four more distractors, rendering the color singleton distractor even more salient than Experiment 1.
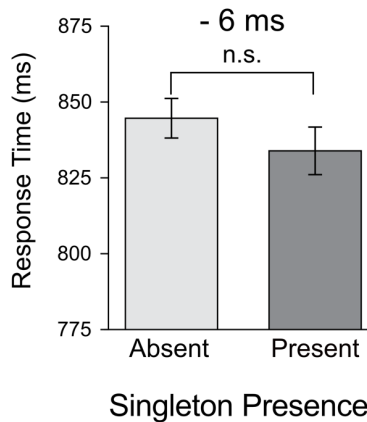
Results

      To summarize, the basic results are similar to Experiment 1. There was no singleton-presence cost on mean RT. In addition, lateralized color singletons elicited a P_D component. Importantly, this P_D component occurred at all lateralized positions supporting the signal suppression hypothesis.

Behavioral Results

      Mean RTs for Experiment 2 are depicted in Figure 6. Overall RTs were slower in Experiment 2 (840 ms) than Experiment 1 (690 ms), $t(38) = 5.90$, $p < .001$, $d_z = 1.86$, suggesting that search was more difficult in Experiment 2 due to the higher set size (e.g., Wolfe, 2021; Wolfe & Horowitz, 2017) and/or increased visual crowding (Whitney & Levi, 2011).

      In Experiment 2, mean RTs were numerically faster on singleton-present trials (837 ms) than singleton-absent trials (843 ms) but this difference was nonsignificant, $t(19) = 1.64$, $p = .12$, $d_z = 0.37$. This lack of a singleton presence cost suggests that the color singleton did not capture attention. It is interesting to note that the singleton-presence benefit was smaller in Experiment 2 (-6 ms) than Experiment 1 (-22 ms), $t(38) = 3.43$, $p = .001$, $d_z = 1.08$. This is consistent with the notion that that suppressing the singleton is akin to reducing the set size by an item. The net benefit of this suppression would thereby be weaker in Experiment 2 (reducing the relevant set size from 8 to 7 items) than Experiment 1 (reducing the relevant set size from 4 to 3 items). Error rates were not significantly different between singleton-present (2.9%) and singleton-absent (2.6%) trials, $t(19) = 1.60$, $p = .13$, $d_z = 0.36$.

Figure 6
*Manual RT Results for Experiment 2*

Note. *Mean manual response time (RT) as a function of singleton presence for Experiment 2. Error bars represent within-subject confidence intervals.*

Electrophysiological Results

The same exclusion criteria (i.e., artifact rejection and participant replacement) from Experiment 1 were used in Experiment 2. In the final set of participants (six participants were replaced due to eye movements), an average of 5.8% of trials were excluded due to artifacts (range = 0.0–20.8%).

Figure 7 depicts grand-averaged ERP waveforms for the lateral occipital sites (PO7 and PO8) for targets and singleton distractors. When the target was presented at a lateralized location, there was an N2pc component starting at approximately 200 ms poststimulus, which was similar in magnitude when the singleton was present or absent (Figure 7A and 7B). Conversely, when the singleton distractor was presented at a lateralized location and the target appeared on the vertical midline, there was a P_D component beginning at 130 ms with no corresponding N2pc component (Figure 7C).

Mean Amplitude during the N2pc Time Window. Mean amplitudes from 225–300 ms were analyzed using a one-way within-subject ANOVA comparing the three trial types (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a significant main effect of trial type, $F(2, 38) = 6.23$, $p = .005$, $\eta_p^2 = .207$. Preplanned t tests compared the contralateral-minus-ipsilateral difference waveforms between trial types. Importantly, the N2pc component evoked by the lateralized target did not differ significantly based upon whether a singleton appeared on the midline (i.e., target lateral/singleton absent and target lateral/singleton midline conditions, -0.4 µV for both), $t(19) = 0.31$, $p = .76$, $d_z = 0.07$. On singleton lateral/target midline trials, there was a negative-going deflection (-0.1 µV) that was significantly smaller than the N2pc component on both target lateral/singleton midline trials (-0.4 µV), $t(19) = 3.48$, $p = .003$, $d_z = 0.78$, and target lateral/singleton absent trials (-0.4 µV), $t(19) = 2.46$, $p = .024$, $d_z = 0.55$.

Figure 7

Electrophysiological Results for Experiment 2
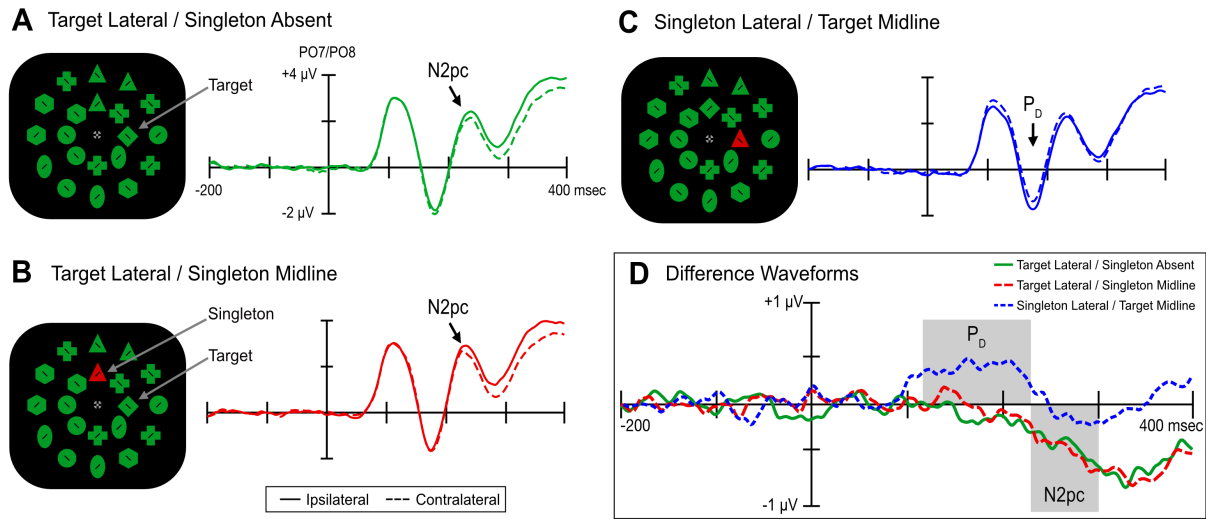
Note. Panels A–C depict ipsilateral and contralateral waveforms for each potential search display configuration. In the schematics of search displays, the target was the green diamond and the singleton distractor was the uniquely colored item. Panel D depicts contra-minus-ipsi difference waveforms for each display configuration.

Planned one-sample *t* tests compared ipsilateral-minus-contralateral difference waveforms against zero for each trial type (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a significant N2pc component on both target lateral/singleton absent trials (-0.4 µV), $t(19) = 3.79$, $p = .001$, $d_z = 0.85$, and target lateral/singleton midline trials (-0.4 µV, $t(19) = 4.64$, $p < .001$, $d_z = 1.04$. Critically, there was not a significant N2pc component on singleton lateral/target midline trials (-0.1 µV), $t(19) = 0.73$, $p = .47$, $d_z = 0.16$.

Mean Amplitude during the P_D Time Window. Mean amplitudes were calculated between 115–225 ms in the contralateral-minus-ipsilateral difference waveforms to assess the P_D component. These mean amplitudes were analyzed using a one-way within-subject ANOVA comparing the three trial types (target lateral/singleton absent, target lateral/singleton midline, and singleton lateral/target midline). There was a main effect of trial type, $F(2, 38) = 12.57$, $p < .001$, $\eta_p^2 = .367$. Preplanned *t* tests compared the contralateral-minus-ipsilateral difference waveforms between trial types. The magnitude of the P_D component to the target stimulus did not differ significantly between the two singleton conditions (i.e., target lateral/singleton absent, -0.1 µV, and target lateral/singleton midline conditions, 0.0 µV), $t(19) = 0.65$, $p = .52$, $d_z = 0.15$. The P_D component was larger on singleton lateral/target midline trials (+0.4 µV) than target lateral/singleton midline trials (-0.1 µV), $t(19) = 4.20$, $p < .001$, $d_z = 0.94$, and target lateral/singleton absent trials (0.0 µV), $t(19) = 4.99$, $p < .001$, $d_z = 1.12$.

Planned one-sample *t* tests compared contralateral-minus-ipsilateral difference waveforms against zero for each trial type (singleton lateral/target midline, target lateral/singleton absent, and target lateral/singleton midline). Critically, there was a significant P_D component on singleton lateral/target midline trials (+0.4 µV), $t(19) = 5.37$, $p < .001$, $d_z =$

1.20. As in Experiment 1, no such P_D component was observed on trials where the target was lateralized. If anything, there was a lateralized negativity. On target lateral/singleton absent trials, there was a nonsignificant negative-going deflection evoked (-0.1 µV), $t(19) = 1.48$, $p = .16$, $d_z = 0.33$. On target lateral/singleton midline trials, there was no statistically significant positive- or negative-going deflection (0.0 µV), $t(19) = 0.31$, $p = .76$, $d_z = 0.07$.

Experiment 1 vs. Experiment 2. As can be seen in Figures 3D and 7D, there was a decrease in the magnitude of the target-elicited N2pc components from Experiment 1 to Experiment 2. This suggests that the target was more difficult to locate in Experiment 2, due to the higher set size (e.g., Wolfe, 2021; Wolfe & Horowitz, 2017) and/or increased visual crowding of search items (Whitney & Levi, 2011). This difficulty in locating the target would cause nontarget items to be initially attended more frequently than in Experiment 1, decreasing the magnitude of the N2pc component. This interpretation is also consistent with the increased mean RT from Experiment 1 to Experiment 2.

To formally assess this, the mean amplitudes of the contra-minus-ipsi difference waveforms were compared during the N2pc time window for trials with lateralized targets (i.e., target lateral/singleton absent and target lateral/singleton midline) between each experiment using independent-samples *t* tests. On target lateral/singleton absent trials, the mean amplitude of the N2pc component was reduced from Experiment 1 (-1.1 µV) to Experiment 2 (-0.4 µV), $t(38) = 3.10$, $p = .004$, $d_z = 0.98$. Similarly, on target lateral/singleton midline trials, the mean amplitude of the N2pc component was reduced from Experiment 1 (-1.2 µV) to Experiment 2 (-0.4 µV), $t(38) = 3.25$, $p = .002$, $d_z = 1.03$.

Interestingly, the magnitude of the singleton-elicited P_D component was unaffected by the increase in set size between experiments. The mean amplitude of the P_D components on singleton lateral/target midline trials were similar in Experiment 1 (+0.4 µV) and Experiment 2 (+0.4 µV), $t(38) = 0.37$, $p = .716$, $d_z = 0.12$. This is consistent with the notion that the singleton was suppressed in both experiments: It was quickly detected on a preattentive feature map and suppressed before the first shift of covert attention to prevent any attentional orienting to that item.

Idiosyncratic Search Hypothesis: P_D Horizontal Midline Analysis

The increased set size of items in the inner display also allowed us to test an alternative account of the P_D component (see Figure 8A). Recently, Kerzel and Burra (2020) proposed the *idiosyncratic search hypothesis* in which low set sizes encourage an unusual search strategy of prioritizing search items on the horizontal midline. This bias toward the two items on the horizontal midline causes an issue on trials where the singleton distractor appears on the horizontal midline. The nonsingleton distractor at the opposite location will automatically attract attention because it matches the target color, yielding an N2pc component. This N2pc component (a negative-going deflection) could easily be confused with a P_D component (i.e., a positive-going deflection) to the singleton distractor on the opposite side. Thus, by this account, the "P_D" component to the singleton distractor in Gaspelin and Luck (2018c) is actually an N2pc component to the nonsingleton distractor opposite to the singleton distractor on the horizontal midline.

Figure 8
P_D Horizontal Midline Analysis for Experiment 2
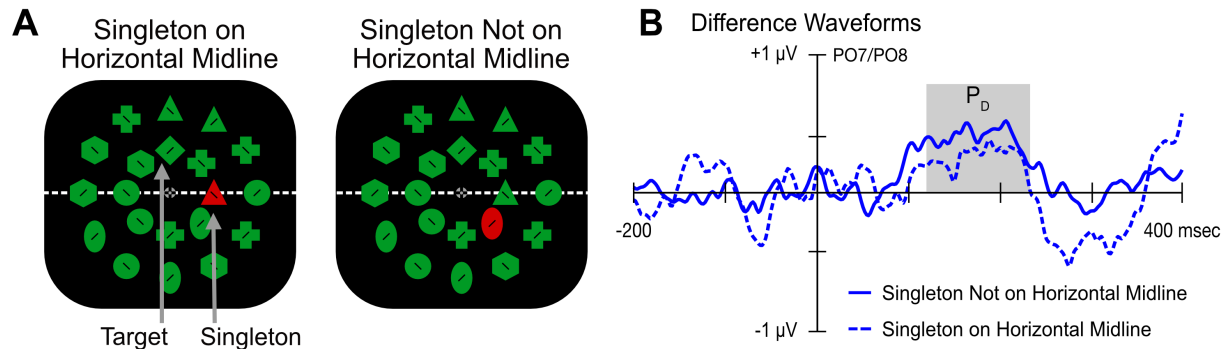
Note. (A) The singleton distractor could appear either on a location that is on the horizontal midline or that is not on the horizontal midline. The white dashed line shows the horizontal midline for illustrative purposes and was not included in the actual experiment. (B) The contra-minus-ipsi difference waveforms on singleton lateral/target midline trials as a function of whether the singleton appeared on the horizontal midline.

The idiosyncratic search hypothesis makes an important prediction in Experiment 2: This problem should be eliminated on trials where the singleton is not on the horizontal midline. On these trials, the two locations on the horizontal midline are occupied by nonsingleton distractors, and they should have, on average, an equal attentional priority. As a result, there should be no bias of an N2pc component to one lateralized search item on the horizontal midline. Thus, according to this hypothesis, the P_D component—which is purportedly an N2pc component to a nonsingleton distractor on the horizontal midline—should be eliminated on trials where the singleton distractor is not on the horizontal midline.

As can be observed in Figure 8B, a P_D component was evoked by the singleton distractor regardless of whether or not it appeared on the horizontal midline. One-sample t tests comparing the mean amplitude (115–225 ms) of each P_D component to zero were performed. There was a significant P_D component evoked by the singleton distractor both when the singleton appeared on the horizontal midline (+0.3 µV), $t(19) = 2.48$, $p = .023$, $d_z = 0.56$, and critically, when it did not (+0.4 µV), $t(19) = 5.44$, $p < .001$, $d_z = 1.22$. Interestingly, the mean amplitude of the P_D component was numerically larger when the singleton was not on the midline than when it was, however there was no significant difference between the magnitude of these two P_D components, $t(19) = 1.31$, $p = .21$, $d_z = 0.29$. These results are inconsistent with the idiosyncratic search hypothesis, and instead support the signal suppression hypothesis.

Exploratory Analysis: Post-P_D Negativity
In Experiment 1, there was a negative-going deflection after the initial P_D component on singleton lateral/target midline trials, which has been observed in some previous studies. This post-P_D negativity was not apparent in Experiment 2 (Figure 7D). An exploratory analysis was conducted to assess the significance of the negativity from 275–375 ms using a one-sample t test on the difference waveforms. This analysis indicated the late negativity (-0.1 µV) was nonsignificant, $t(19) = 0.69$, $p = .50$, $d_z = 0.15$. This late negativity was significantly smaller in mean amplitude than Experiment 1, $t(38) = 4.04$, $p < .001$, $d_z = 1.28$. Its magnitude did not

correlate with the magnitude of the singleton-presence benefit (r = -0.21, p = .37). Altogether, these results indicate that the post-P_D negativity did not appear consistently in our two experiments (see also Gaspelin & Luck, 2018c) and seems to be unrelated to distractor suppression.

Saliency Maps

　　As depicted in Figure 4, saliency maps were again used to independently assess the salience of the color singleton (see Chang et al., 2021; Stilwell & Gaspelin, 2021). We generated 1000 search arrays, and the resulting images were processed using the Image Signature Toolbox in Matlab (Hou et al., 2012). We calculated two saliency metrics: the GSI and the singleton win rate. The average GSI across all images from Experiment 2 was 0.82 (SE = 0.002), indicating the singleton had an average salience score that was much higher than the other search items. This GSI was significantly higher than a four-item display, $t(1998)$ = 62.64, p < .001, d_z = 2.80. It was also slightly larger than Experiment 1 (GSI = 0.81, SE = 0.003), $t(1998)$ = 3.68, p < .001, d_z = 0.16. The singleton win rate in Experiment 2 was 100%, which is equivalent to Experiment 1 and the four-item displays matching Gaspelin and Luck (2018c). Together, these saliency map results suggest that the singleton was highly salient, and if anything, the singleton was more salient in Experiment 2 than in Experiment 1 and previous studies using four-item displays (Gaspelin & Luck, 2018c).

Discussion

　　To boost the salience of the singleton distractor, Experiment 2 increased the number of items in the inner (task-relevant) ring to test between two competing models: the stimulus-driven account, and the signal suppression hypothesis. Despite the increased salience of the singleton distractor, there was no evidence of a singleton presence cost in the manual RTs. There was also no evidence of attentional capture in the ERPs. The N2pc component to lateralized target was unaffected by the presence of a singleton on the midline. In addition, the singleton distractor evoked a P_D component, which has been previously established to indicate suppression. All of these results are inconsistent with a stimulus-driven account, which would directly predict that the singleton distractor capture attention and interfere with search.

　　It is worth noting that the increased set size in Experiment 2 seemed to impact target processing independent of suppression of the salient singleton. Manual RTs were slower in Experiment 2 than Experiment 1, and the N2pc components elicited by the lateralized target were reduced in mean amplitude from Experiment 1 to 2. However, the mean amplitude of the P_D component elicited by the salient singleton distractor was unaffected by the increased set size between experiments. Together, these results suggest that increasing the number of task relevant items in Experiment 2 rendered the target more difficult to localize than in Experiment 1, but this set size manipulation did not impact suppression of the singleton distractor. This pattern is consistent with the signal suppression hypothesis which predicts that the singleton distractor was proactively suppressed. Furthermore, this pattern of results adds to a growing literature suggesting that distractor processing is independent of target processing (Adam & Serences, 2021; Chang & Egeth, 2019; Stilwell & Vecera, 2020)

GENERAL DISCUSSION

According to the signal suppression hypothesis, salient stimuli generate a bottom-up salience signal that automatically competes for attentional allocation, but this salience signal can be proactively suppressed to prevent attentional capture. Previous evidence in support of the signal suppression hypothesis (e.g., Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018c) has been challenged on the grounds that the small set sizes used in these studies may have yielded color singletons that were insufficiently salient to capture attention (Theeuwes in Luck et al., 2021; Wang & Theeuwes, 2020). Although there has been some evidence refuting such an interpretation (Chang et al., 2021; Stilwell & Gaspelin, 2021), further evidence is needed to definitively determine whether highly salient distractors can be suppressed. The current study therefore assessed whether highly salient color singletons elicit electrophysiological indices of attentional capture (the N2pc component) or attentional suppression (the P_D component).

Experiment 1 used an additional singleton paradigm similar to Gaspelin and Luck (2018c), which previously produced electrophysiological evidence of distractor suppression, but modified the task to make the singleton distractor more salient by increasing the set size. This higher set size should increase the relative contrast of the singleton distractor with other search items. The results indicated that the singleton distractor was suppressed and did not capture attention. Manual RTs were, if anything, faster when the singleton distractor was present than when it was absent: a singleton-presence benefit. The ERP data also indicated that singleton distractors were suppressed. First, lateralized singleton distractors elicited a P_D component, indicative of proactive distractor suppression (Drisdelle & Eimer, 2021; Feldmann-Wüstefeld et al., 2020; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Hickey et al., 2009; McDonald et al., 2013; Moorselaar et al., 2021; Sawaki et al., 2012). Second, lateralized targets elicited N2pc components that did not differ as a function of singleton distractor presence. If the singleton distractor mandatorily captured attention, this should have disrupted target processing and delayed and/or reduced the magnitude of the N2pc component. Altogether, the results suggest that the singleton distractor was suppressed and did not interfere with search for the target, consistent with the signal suppression hypothesis.

Experiment 2 provided a more stringent test of whether increasing salience of the singleton distractor would lead to attentional capture. In Experiment 1, the set size was increased—compared to prior studies that used four-item displays (e.g., Gaspelin & Luck, 2018c)—by surrounding the central search array with a ring of dummy shapes to boost the low-level feature contrast between the singleton and nonsingleton items (i.e., distractor-distractor dissimilarity, see Duncan & Humphreys, 1989). However, due to the outer ring's task-irrelevance, visual processing may have been restricted to the inner ring of shapes. Experiment 2 therefore also increased the number of task-relevant items in the inner ring (from four to eight items). The results largely replicated those of Experiment 1. Lateralized salient distractors elicited a P_D component, indicating suppression. Lateralized targets elicited N2pc components that were unaffected by the presence of a singleton distractor. These results suggest that the singleton was suppressed to prevent attentional capture, which is inconsistent with a stimulus-driven account but consistent with a signal suppression account.

The current results fits nicely with prior studies demonstrating suppression of salient singleton distractors. Singleton distractors did not evoke an N2pc component but instead evoked P_D components, consistent with the previous literature on distractor suppression (Drisdelle & Eimer, 2021; Feldmann-Wüstefeld et al., 2020; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c; Hickey et al., 2009; McDonald et al., 2013; Moorselaar et al., 2021; Moorselaar &

Slagter, 2019; Sawaki et al., 2012). Further, both the current ERP results and the results of studies using the capture-probe paradigm (Chang & Egeth, 2019, 2021; Gaspelin et al., 2015; Stilwell & Gaspelin, 2021), converge to suggest that salient singleton distractors are proactively suppressed. Moreover, the current study adds to a growing body of literature aimed at uncovering the nature of saliency and its role in models of attentional capture (Chang et al., 2021; Egeth et al., 2010; Luck et al., 2021).

It is interesting to note that the mean amplitude of the singleton-elicited P_D component was unchanged by the set size manipulations in the current study. The mean amplitude of the P_D component was equivalent at the set size 16 of Experiment 1 (+0.4 µV) and the set size 20 of Experiment 2 (+0.4 µV). This may be because both experiments used relatively large set sizes that maximized the salience of the color singleton. We therefore also compared the magnitude of the P_D component to a previous study (e.g., Gaspelin & Luck, 2018c; Exp. 1), which was nearly identical to the current study but used a much smaller set size of 4 items. The mean amplitude of the singleton-elicited P_D component was quite similar (+0.5 µV) to the current experiments. At face value, this suggests that increasing the salience of the singleton does not necessarily impact suppression. However, future studies may be needed to more directly manipulate the salience of the singleton distractor systematically and test whether suppression is modulated by degrees of salience.

In both experiments, we provide independent support for the notion that the singleton distractor was indeed salient using a computational model of salience (Chang et al., 2021; Hou et al., 2012; Kotseruba et al., 2020). The global saliency index (GSI = 0.81 in Exp. 1 and GSI = 0.82 in Exp. 2) and the singleton win rate (100% in both Exp. 1 and 2) indicated that the singleton had a high salience score in all of the images. We additionally compared the salience scores to displays of set size four, similar to Gaspelin and Luck (2018c). The results indicated that the singleton was actually more salient in the current experiments than in past experiments using a set size of four (GSI = 0.47). Together, these analyses lend further support to the claim that these singleton distractors were highly salient in the current study and were more salient than previous studies of distractor suppression (e.g., Gaspelin & luck, 2018c). A shortcoming of this approach is that it depends on the validity of the computational model of salience (see Jeck et al., 2019). Therefore, future research may be needed to establish new metrics to measure bottom-up saliency based upon human performance and/or electrophysiological measures.

The increased the number of task-relevant items in Experiment 2 allowed us to test an alternative account of the P_D component: the idiosyncratic search hypothesis (Kerzel & Burra, 2020). According to this account, the low set sizes used in previous studies cause the locations on the horizontal midline to be searched first and the P_D component does not reflect suppression of the salient item, but rather an N2pc enhancement of the nonsingleton distractor on the horizontal midline. However, this account seems unlikely for a few reasons. First, Experiment 2 found that the singleton distractor elicited a reliable P_D component even when it was not on the horizontal midline. Second, perhaps more directly, Drisdelle & Eimer (2021) used a similar design to the current study but compared conditions where the target could appear at horizontal locations to conditions where the target could only appear at vertical locations, which should discourage a horizontal search bias. They still found that the P_D components elicited by the singleton distractors were the same across conditions. Last, the idiosyncratic search hypothesis fails to account for the data from higher set size displays where the incentive to attend to items on the horizontal midline should be reduced (e.g., Gaspar & McDonald, 2014). Altogether, there

might be an attentional bias to search items on the horizontal midline at low set sizes, but the evidence that this could unambiguously account for the P_D component seems relatively weak.

It has been recently claimed that displays of heterogeneous shapes—as used in the current study—may render the target stimulus nonsalient. As a result, participants may stop using the attentional priority map to locate the target and instead adopt an approach of randomly searching items (clump scanning; Liesefeld et al., 2021a, 2021b). This, in turn, causes items with high attentional priority due to bottom-up salience to fail to capture attention. Although interesting, there are some major shortcomings of this model. First, the target is enhanced above baseline levels in heterogeneous displays as indicated by measures of probe report (Gaspelin et al., 2015; Stilwell & Gaspelin, 2021) and eye movements (Gaspelin et al., 2017, 2019). If participants were not using the priority map, these target enhancement effects should not occur: search should be effectively "unguided" and therefore random. Second, this account cannot explain how attentional allocation is guided *away* from color singletons. If participants were not using a priority map, then attention should behave randomly and would not be biased toward or away from any kind of stimulus feature. Ultimately, the clump scanning hypothesis needs to be tested more directly, but without a direct measure of the attentional priority map and whether participants are using it, this account will be difficult to falsify.

An interesting finding of the current study and prior investigations is the late negativity appearing approximately 275–375 ms post stimulus on trials containing a lateralized singleton distractor. This post-P_D negativity seems inconsistent: Some studies have found it (Drisdelle & Eimer, 2021; Feldmann-Wüstefeld et al., 2020; Gaspelin & Luck, 2018c, Exp. 3; Kerzel & Burra, 2020b) while others have not (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c, Exp. 1; Sawaki & Luck, 2010). In this study, it occurred in Experiment 1 but not Experiment 2. It is currently unknown exactly what this lateralized negativity reflects. Some have suggested that the lateralized singleton distractor is suppressed on the majority of trials, but on the trials when the singleton captures attention, the waveforms blend together producing a later negativity (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018c). Another possibility is that the late negativity reflects a second P_D component to the nonsingleton distractor opposite the singleton distractor (Drisdelle & Eimer, 2021). The current study does not offer definitive evidence for either explanation; therefore, future studies will likely be needed to test more directly what this ERP component reflects.

The signal suppression hypothesis claims the singleton distractor is *proactively* suppressed to prevent attentional capture. It is important to note that the terminology "proactive suppression" could indicate one of two mechanisms. Proactive suppression could mean that suppression is implemented before any stimulus is presented, effectively suppressing a specific location or feature before the presentation of the search array. For example, Eimer and Grubert (2014) demonstrated that feature-based attentional templates are activated in anticipation of the search array. Alternatively, proactive suppression could mean that salient stimuli are suppressed after the stimuli onset, but prior to the initial shift of covert attention. The present study was not designed to distinguish between these two forms of proactive suppression, which would require some measurement of the attentional template before the search array appears. Therefore, further studies will be needed to distinguish between these models.

It is important to highlight that the current study does contrast with forms of reactive inhibition (e.g., Moher & Egeth, 2012) whereby distractors must first be attended before they can be ignored (e.g., the "search-and-destroy model) or rapidly disengaged from following attentional capture (e.g., Theeuwes, 2010). If the singleton was attended before it was inhibited,

this should have resulted in some indication of attentional allocation, such as an N2pc component, before suppression was observed. As demonstrated by Weaver et al., (2017), covert suppression can function prior to and independent of overt behavioral measures such as overt eye movements. The current study isolated covert shifts of attention by preventing overt attentional shifts (i.e., requiring participants to maintain central fixation) and found no evidence that the salient distractors were covertly attended. These results, and others, suggest that reactive inhibition is not the sole mechanism for suppression of salient distractors. Importantly, it should be highlighted that reactive and proactive inhibition are not mutually exclusive mechanisms (for review see Geng, 2014).

       In summary, the current study clearly demonstrates that highly salient color singleton distractors are proactively suppressed, as indexed by the P_D component. Furthermore, the current study provides converging evidence in support of the signal suppression hypothesis, helping steer the field towards a potential resolution to the decades-long debate on attentional capture, and highlights the importance of addressing physical salience in models of attentional control.

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