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Ignoring Salient Distractors Inside and Outside the Attentional Window

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Abstract

There has been much debate about whether salient stimuli have an automatic power to distract us, with many conflicting results. The attentional window account proposes a potential resolution by suggesting that capture depends on the breadth of attentional focus. According to this account, when attention is broadly focused, salient stimuli will fall inside the attentional window and generate a salience signal that captures attention. When attention is narrowly focused, salient stimuli presented outside the window of attention cannot generate a salience signal that attracts attention. If true, this could explain many otherwise-contradictory findings, but this account has not been widely tested. The present study used a shape-discrimination task to manipulate the spread of spatial attention and tested whether salient distractors inside versus outside the attended region capture attention. Attentional capture was assessed by the N2pc component and behavioral measures. Contrary to the predictions of the attentional window account, we found no evidence that capture by salient distractors depended on whether the salient distractor was inside or outside the attended window. Instead, our findings support models of attention which allow feature-based control mechanisms to prevent capture by salient distractors.

Keywords: attention, attentional capture, attentional window, visual search, salience

Ignoring Salient Distractors Inside and Outside the Attentional Window

From neon orange cones on the roadside to brightly colored warnings on consumer products, salient stimuli are often used as warning signals under the assumption that they will capture attention. Here, *salience* refers to how much an object "pops out" from the rest of the display in terms of low-level features (Nothdurft, 1993). For example, a uniquely colored red object amongst many green objects would be considered highly salient (a *color singleton*). Formal research has painted a divided picture on whether salient stimuli automatically capture attention, with many studies suggesting that they do automatically capture attention (Theeuwes, 1991, 1992, 2004; Yantis & Jonides, 1984) and many studies suggesting that top-down control can be used to prevent attentional capture (Folk et al., 1992, 2002; Lien et al., 2008).

Theeuwes (2004, 2023) has attempted to reconcile these diverging results by proposing that the supposed evidence of top-down control to prevent attentional capture is really a side effect of a narrow focusing of spatial attention. According to this *attentional window account*, when attention is broadly focused as in parallel searches, attention will be automatically captured by the most salient object within attentional focus. To prevent capture, observers can narrowly focus their attention by engaging in a serial search, which then attenuates perceptual processing of stimuli outside the window of attention, including stimuli that are highly salient. This account therefore proposes a serious limitation on attentional control: visual distraction can be prevented only by focusing spatial attention away from the location of salient distractors. The present study will critically evaluate this account using event-related potentials (ERPs) to measure capture by salient stimuli when attention is focused on a narrow region or distributed across a broad region. Specifically, we tested whether highly salient color singletons presented within an otherwisehomogeneous ring of task-irrelevant objects will automatically capture attention when attention is distributed broadly across the search display but not when attention is focused narrowly.

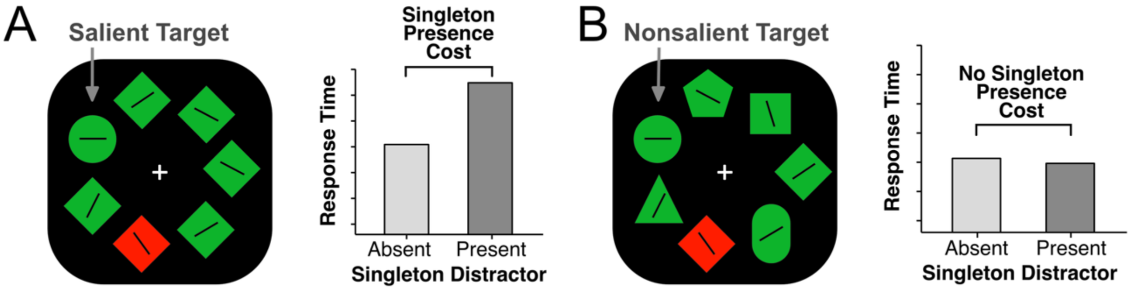
The Attentional Capture Debate

Theories of attentional capture have traditionally been divided into *stimulus-driven* and *goal-driven* accounts. Stimulus-driven accounts suggest that salient stimuli will capture attention, even when task irrelevant (e.g., Theeuwes, 1992; Yantis & Jonides, 1984). These accounts were originally supported by a task in which participants searched for a salient target amongst a homogenous set of shapes (e.g., a circle amongst diamonds) and reported the orientation of a line inside the target (Figure 1A). On half of trials, a randomly chosen distractor was a color singleton. Because this color singleton was never the target, it should have been ignored. However, response times (RTs) were slowed when the color singleton was present than when it was absent. This *singleton-presence cost* was taken as evidence that the color singleton captured attention, slowing detection of the target.

Goal-driven accounts, however, suggest that attentional allocation can be controlled by the observer's top-down goals to prioritize relevant features and avoid irrelevant ones. These accounts propose that observers form an attentional template for target features during search (e.g., green circle) and this template is used to constrain attention to objects with target-matching features, preventing capture by salient stimuli without target-matching features. Importantly, goal-driven accounts suggested that prior studies showing capture by color singletons might have unintentionally made the distractors task-relevant. If the target is defined as a shape singleton (as in Figure 1A), participants might simply search for singletons in general, causing attention to be attracted to the color singleton distractors as well as the shape singleton targets (called *singleton-detection mode*). Here, attentional capture by the singleton would be the result of the top-down

Figure 1

Search Displays and the Typically Observed Result



Note. (A) Stimulus-driven accounts often use a search task with a salient target and this type of task typically leads to a capture effect by the salient distractor (singleton-presence cost). (B) Goal-driven accounts typically use a search array with a nonsalient target to ensure the singleton is task irrelevant and this type of task typically leads to the absence of a capture effect (no singleton-presence cost). The stimuli and results are meant for illustrative purposes and are not based upon actual data.

goals rather than the physical salience of the singleton. Evidence for singleton-detection mode was initially provided by Bacon and Egeth (1994), who used a similar paradigm to Theeuwes (1992) but adapted it to prevent singleton-detection mode by intermixing displays in which the target was not salient (see Figure 1B). This forced participants to search for the specific shape of the target rather than searching for singletons (called *feature-search mode*). Singleton-presence costs were eliminated by this relatively subtle change to the experimental design, suggesting that capture does not occur when singleton-detection mode is prevented.

Later studies provided additional evidence in favor of a singleton-detection mode (e.g., Becker et al., 2019; Lamy et al., 2006; Lamy & Egeth, 2003). For instance, Leber and Egeth (2006) trained participants to adopt either feature-search mode or singleton-detection mode and then later had them search displays in which either strategy was possible. Participants trained in singleton-detection mode showed large singleton-presence costs, whereas those trained in feature-search mode did not. Other support for singleton-detection mode has come from studies of the *signal suppression hypothesis* (see a review by Gaspelin & Luck, 2018c), which is a hybrid model of attentional capture that proposes that salient distractors automatically attract attention in the absence of top-down control but can be inhibited by top-down goals to prevent distraction. Many studies supporting the signal suppression hypothesis have shown that, when the target is nonsalient and can be found via its specific features, color singletons do not produce capture effects and instead appear to be suppressed below baseline levels (Adams et al., 2023; Adams & Gaspelin, 2024; Chang & Egeth, 2019, 2021; Drisdelle & Eimer, 2021, 2023; Gaspelin et al., 2015, 2017; Hamblin-Frohman et al., 2022; Ma & Abrams, 2023a, 2023b, 2023c, 2025; Ramgir & Lamy, 2023; Stilwell et al., 2022, 2023; Stilwell & Gaspelin, 2021; Zhang & Gaspelin, 2024; for a review, see Gaspelin et al., 2025). Many of these same studies also included control experiments demonstrating that attentional capture by the color singleton cannot be prevented when singleton-detection mode is encouraged (e.g., Gaspelin et al., 2015, 2017).

In sum, there has been much debate about whether salient distractors have the ability to capture attention. One important observation is that tasks with salient targets tend to encourage attentional capture and that tasks with nonsalient targets tend to discourage attentional capture. This result is often attributed to differences in search mode (i.e., singleton-detection vs. feature-search mode). As described in the next section, however, a possible alternative explanation has been proposed to explain these findings.

The Attentional Window Account

The attentional window account of Theeuwes (2004, 2023) has offered an alternative explanation for the finding that capture effects depend on whether the target is a salient singleton. When the target is always salient (as in Figure 1A), this account proposes that attention will be broadly distributed across the display in preparation for a parallel search. Feature information from all objects will therefore be available for preattentive processing, allowing the salience of a singleton distractor to be computed and to automatically capture attention. By contrast, if the target is nonsalient (as in Figure 1B), this account proposes that attention will be narrowly focused in preparation for a serial search and that only the features within this narrow window of attention will be fed forward to later processing stages. The singleton will ordinarily fall outside of the focus of attention, so its features will not be processed and it will not produce a salience signal that can capture attention. Thus, the attentional window account predicts that capture will occur under parallel search, but not under serial search. Importantly, it can explain many results that were previously explained by search mode (i.e., the results in Figure 1) by assuming that participants used a narrow window size in the conditions designed to elicit feature-search mode. We would like to stress that the attentional window account is based solely on the spatial distribution of attention, not on other aspects of task relevance.

The idea that attention can be either broadly or narrowly focused is not controversial (Eriksen & St. James, 1986; LaBerge, 1983; Leonard et al., 2013). However, there is no direct evidence that the spatial focus of attention was narrow in prior studies that encouraged feature-search mode. Although there have been some critiques about whether the attentional window account can accurately explain prior results (e.g., Gaspelin, Egeth, et al., 2023; Lien & Ruthruff, 2023), more extensive empirical testing is needed. To test the attentional window account, it is essential to explicitly control the size of the attentional window and manipulate whether salient distractors appear inside or outside the spatial focus of attention.

Some support for the attentional window account has come from a study by Belopolsky and colleagues (2007). In this study, participants searched an array of letters presented in the shape of a triangle for a target letter (E or H). A color singleton could appear at a target or nontarget location. In the diffuse condition, participants used the orientation of the triangular search array (upward or downward) to determine whether to search, which forced them to spread attention across the display before searching. In the focused condition, participants used the shape of the fixation cross (circle or square) to determine whether to search, forcing them to narrowly focus attention before searching. There was a singleton-presence cost in the diffuse condition but not in the focused condition, providing evidence that attentional capture depends on whether attention is narrowly focused or diffusely distributed (see also Belopolsky & Theeuwes, 2010; Kim et al., 2025). This one study provides the main empirical support for the attentional window account's claim that the spatial focus of attention will determine capture and given the importance of this account in theories of attention, additional evidence using different methods is called for.

The Current Study

The present study tested the prediction of the attentional window account that salient objects within the spatial focus of attention will capture attention. To accomplish this, we experimentally manipulated the spatial breadth of attentional allocation and assessed capture inside versus outside the attended region. This allowed us to avoid interpretative ambiguities associated with visual search tasks that manipulate search efficiency. As reviewed above, capture during search for a salient target (i.e., parallel search) could be explained by either a broad window of spatial attention or an attentional set for salient objects. Although capture by salient stimuli is often studied in visual search tasks, stimulus-driven accounts do not limit capture to such contexts. We therefore used a task that eliminates potential ambiguity about how attention was distributed across space, rather than assuming a spatial distribution based upon the efficiency of visual search. This allowed us to pinpoint the specific prediction of the attentional window account that capture should occur when the salient distractor appears inside but not outside of the spatial focus of attention.

Also, rather than relying solely on singleton-presence costs on manual RT to draw inferences about whether the singleton distractors captured attention, we also used the *N2 posterior contralateral (N2pc)* component of the event-related potential (ERP) waveform to assess attention capture (supplemented, in some experiments, by RT measures). The addition of ERP metrics will allow for a more comprehensive assessment of whether attentional capture occurred. There is growing evidence that RT-based capture effects might not directly correspond to the probability of attentional capture (Rigsby et al., 2023). For instance, RT slowing can sometimes occur in the absence of capture (Becker, 2007; Folk & Remington, 1998) and capture can sometimes occur with small RT-based capture effects (Gaspelin et al., 2016; Zivony & Lamy, 2018).

The N2pc is typically observed over lateral occipitotemporal cortex approximately 200–300 ms after the appearance of a search stimulus. It is a negative-going deflection that is larger over the hemisphere that is contralateral to an attended object. There is general agreement that the N2pc component reflects a cognitive process associated with covert attentional allocation to a search target (Hickey et al., 2009; Luck & Ford, 1998; Luck & Hillyard, 1994a; Tan & Wyble, 2015; Woodman & Luck, 2003, 1999; Zivony & Eimer, 2021), although it is still debated what exact mechanism of covert attention is measured by the N2pc (see review by Luck, 2012). The N2pc has been commonly used in prior studies to evaluate whether a salient item captured attention (e.g., Gaspar et al., 2016; Gaspar & McDonald, 2014, 2018; Gaspelin & Luck, 2018a; Hickey et al., 2006; Lien et al., 2008, 2010; McDonald et al., 2013; Stilwell et al., 2022).

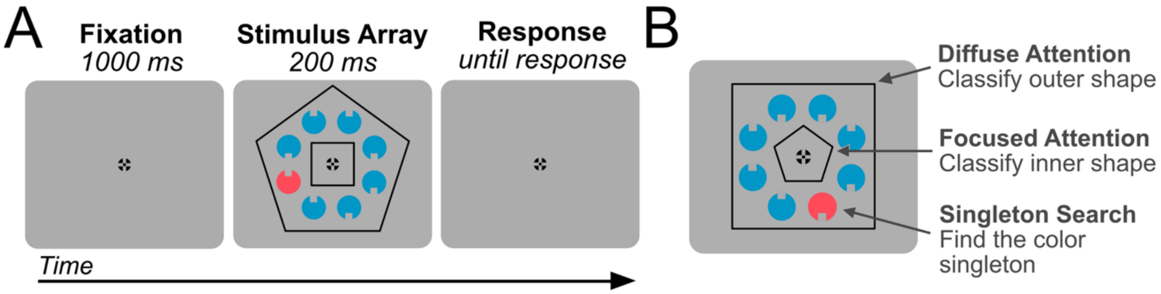
In the following sections, we will present six experiments. Experiments 1 and 2 will introduce our basic paradigm and test whether salient distractors produce any evidence of attentional capture when attention is broadly focused. Experiments 3 and 4 will then increase the overall salience of the distractors to provide a more powerful test of whether attentional capture depends on attentional focus. Experiment 5 will alter our basic paradigm to provide a more powerful manipulation of attentional focus. Experiment 6 serves as a manipulation check, confirming that our experimental paradigm successfully induced the intended spread of attention. To preview the results, all experiments found no evidence of attentional capture when attention was broadly focused, contrary to the prediction of the attentional window account.

Experiment 1: Attentional Window with ERP Measures of Capture

Experiment 1 examined whether it is possible to ignore salient distractors inside versus outside of an attended region. Each display contained two outlined polygons, a large one enclosing a small one (see Figure 2). In addition, each display contained a circular arrangement of eight disks, one of which was a color singleton. This array was outside the inner polygon but inside the outer polygon. The experiment consisted of three conditions meant to manipulate the spread of attention, similar to Belopolsky et al. (2007). In the *diffuse attention* condition, participants classified the outer polygon's shape (pentagon or square), which should force attention to be spread across a large region that included the array of disks. In the *focused attention* condition, participants classified the inner polygon's shape (pentagon or square), which should narrow attention to a region that excluded the array of disks. In the *singleton search* condition, participants searched for the color singleton and made a speeded response to the location of a gap inside the singleton (top or bottom). This control condition was included to evaluate our sensitivity to detect an N2pc to the salient singleton when it was attended.

Figure 2

Stimuli and Task from Experiment 1



Note. (A) A trial progression from the experimental task. (B) Three conditions manipulated the spread of attention to test whether capture depended on the attentional window. In the diffuse and focused attention conditions, participants classified a shape (square or pentagon). The singleton search condition was a control condition that forced participants to attend the color singleton by making it the search target.

If the color singleton captures attention, it should elicit an N2pc component. The attentional window account therefore predicts that the color singleton should elicit an N2pc in the diffuse attention condition, but not the focused attention condition. Alternatively, accounts which predict that top-down control can be used to ignore salient distractors predict that the color singleton will not capture attention in either the diffuse condition or the focused condition because the singleton is task irrelevant (e.g., Bacon & Egeth, 1994; Folk et al., 1992; Gaspelin & Luck, 2018b; Leber & Egeth, 2006). This would result in the absence of an N2pc component regardless of attentional spread.

One possible concern with this design is that participants could focus their attention only on the outer polygon in the diffuse attention condition without also attending to the array of disks inside it (Leonard et al., 2013). Experiment 5 will demonstrate that the same pattern of results generalizes to a different manipulation of spatial attention, and Experiment 6 will demonstrate that the diffuse condition of the present experiment causes attention to spread across the region between the inner and outer shapes.

Method

Participants

Twenty-four students from the University of Missouri participated for payment of $20 per hour. The sample size was determined a priori based upon the N2pc components observed in prior studies of attentional capture. Assuming that the magnitude of the N2pc effect size for singletons is similar to Hickey et al. (2006, $\eta^2_p = .449$), six participants would be needed to achieve 95% power. However, in order to have the power to detect smaller N2pc effects, we chose to err on the side of caution and collect a large sample size.

Four participants were replaced for making excessive eye movements as identified during the artifact rejection process (see details below). In the final sample, the participants were 2 men and 22 women (M_{age} = 23.8 years). All participants had normal or corrected-to-normal visual acuity and normal color vision as measured by the Ishihara color vision test.

Stimuli and Procedure

Stimuli were presented using PsychToolbox for Matlab (Brainard, 1997; Kleiner et al., 2007) on a Linux computer with an Asus VG248QG LED monitor at a viewing distance of 100 cm in a dimly lit room. The timing delay of the stimulus display was measured with a photodiode (7 ms), and event codes were adjusted offline to compensate for this delay. In all displays, an empirically optimized fixation point was continuously visible (Thaler et al., 2013) and stimuli appeared on a gray background (77.0 cd/m^2, $x = .281$, $y = .292$).

The basic task is depicted in Figure 2. Each stimulus display contained an *inner polygon* and an *outer polygon*, which were drawn using black outlines (0.1° in thickness). Each polygon could be a square or a pentagon, randomly and independently chosen. The vertices of a given polygon were 1.1° from the fixation point for the inner polygon and 5.1° from fixation for the outer polygon. Each stimulus display also contained eight colored disks (1.5° diameter), presented on a notional circle between the inner and outer shapes. Each disk was 3.1° from the fixation point. This made the disks equidistant (2.0°) from the inner and outer polygons. Also, prior studies have shown that stimuli at eccentricities 2 to 4° will maximize the magnitude of the N2pc component (Eimer, 1996; Papaioannou & Luck, 2020; Woodman & Luck, 2003). Seven of the disks were homogeneously colored, and one disk was uniquely colored (a color singleton). Each disk had a small gap (0.4° height and width) in the top or bottom.

One of the disks on every trial was a color singleton, which appeared with equal probability at each of the eight locations. For any individual participant, the singleton and nonsingleton colors remained constant across trials, with the color assignments counterbalanced across participants. The colors were selected from photometrically isoluminant values: green (45.0 cd/m^2, x = .254, y = .452), magenta (45.0 cd/m^2, x = .465, y = .271), blue (45.0 cd/m^2, x = .177, y = .203) and red (45.0 cd/m^2, x = .504, y = .297). From these four colors, we created four color pairs that used opposing colors to maximize the salience of the color singleton (blue-red, red-blue, green-magenta, and magenta-green). The location of the gap in each disk was randomly selected on each trial with the constraint that four of the eight circles contained a gap in the top and four contained a gap in the bottom.

The experiment consisted of three conditions, which used the same stimuli but different task instructions. This ensured that any observed differences in the ERPs between conditions were due to differences in attentional allocation, not perceptual differences between stimuli (the *Hillyard principle*; Luck, 2014). In the diffuse attention condition, participants were asked to report the outer shape (pentagon or square). In the focused attention condition, participants were instead asked to report the inner shape (pentagon or square). In the singleton search condition, the color singleton was the search target and participants reported whether the gap was on the top or the bottom of the singleton. This was included as a control condition to demonstrate sensitivity to detect an N2pc from the color singleton.

Each trial began with a fixation display for 1000 ms. This was followed by the stimulus display, which appeared for 200 ms and was then replaced by a response display until a response was generated. Speeded manual responses were collected using a gamepad using the upper-right and lower-right triggers to respond. For the diffuse and focused attention conditions, these buttons were used to report the shape (pentagon or square). In the singleton search condition, these buttons were used to report the location of the gap in the color-singleton target (upper or lower). Participants received immediate feedback following incorrect or slow responses. Incorrect responses followed by an “Error!” feedback message accompanied by a 250-Hz tone for 300 ms. Slow responses (greater than 2000 ms) were followed by a “Too Slow!” message accompanied by the same tone for the same duration. No feedback was provided for correct, timely responses. The response was followed by intertrial interval during which only the fixation point was visible. The duration of this interval was randomly selected between 0 and 500 ms on each trial to prevent entrainment of the EEG waveforms to the stimulus display.

Half of the participants completed the focused attention condition first, followed by the diffuse attention condition, and the remaining participants experienced the opposite order. The singleton search condition was always completed last. This was meant to eliminate any potential carry-over of the attentional template to search for singletons (e.g., see Leber & Egeth, 2006). The experiment consisted of 9 blocks of 128 trials each, resulting in a total of 1,152 trials. Each task condition (diffuse attention, focused attention, and singleton search) consisted of 3 blocks, and the first block of each condition was treated as a practice block. Consequently, 256 trials were available to compute the N2pc component for each task condition.

Electrophysiological Recording and Analysis

The electroencephalogram (EEG) was collected using a 32-channel set of active Ag/AgCl electrodes (Brain Products ActiCHamp) from a set of 27 standard scalp locations (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) and five external electrodes. Two of the external electrodes were used to record voltages from the left and right mastoids, and their average was used to reference the data off-line. In addition, electrooculogram (EOG) electrodes were attached next to the outer canthi of both eyes and below the right eye. This allowed us to detect vertical eye movements and blinks using the vertical EOG and to detect horizontal eye movements using the horizontal EOG. During the experiment, impedances were kept at or below 15 kΩ for all electrodes. Brain Vision Recorder software was used to record the EEG signals with a 500-Hz sampling rate and a cascaded integrator–comb antialiasing filter with a half-power cutoff at 130 Hz, based on the EEG recording protocol (Farrens et al., 2021).

The EEG data were analyzed offline using EEGLAB Toolbox (Delorme & Makeig, 2004) and ERPLAB Toolbox (Lopez-Calderon & Luck, 2014). All channels were filtered offline using a noncausal Butterworth high-pass filter (half-amplitude cutoff: 0.5 Hz, slope: 12 dB/octave). Averaged ERP waveforms were created from epochs extending from -200 ms to +400 ms relative to stimulus array onset. The EEG signal was baselined using the 200-ms prestimulus period. To facilitate visualization of ERP waveforms, a low-pass filter (half-amplitude cutoff: 20 Hz, slope: 12 dB/octave) was applied to the average ERPs only for plotting (i.e., to preserve temporal resolution, this filter was not used prior to measuring ERP amplitudes).

Trials with incorrect or missing behavioral responses or with outlier RTs (less than 200 or greater than 1,500 ms) were excluded from the ERP analyses (0.3% of trials). Trials with common artifacts (e.g., eye blinks and eye movements) were rejected from the epoched data. We first created bipolar vertical and horizontal EOG channels to help detect eye movement artifacts. Eye blinks were defined as step-like changes in voltages in bipolar vertical EOG that exceeded 80 µV in any 200-ms window during the epoch. Trials were also rejected if the voltage exceeded ±100 µV in any electrode channel during the epoch.

To ensure that the ERPs during the N2pc time window were not contaminated by small-but-consistent eye movements toward the singleton, we applied a two-step saccade rejection method used in prior studies (Luck, 2022; Woodman & Luck, 2003). First, trials were rejected if they contained horizontal eye movements of >1°, defined as a step-like change in voltage that exceeded 16 µV in a 200-ms window in the HEOG channel from 100 to 300 ms post-stimulus. Each participant was screened to ensure that the remaining trials did not contain small (<1°) eye movements in the direction of the singleton. Specifically, we computed separate averaged HEOG waveforms for left- and right-singleton trials to maximize the signal-to-noise ratio for eye movements that were consistently in the direction of the singleton. If the difference between the averaged bipolar HEOG signal for left- and right-singleton averages exceeded 3.2 µV (corresponding to a difference of ±0.1° of eye rotation) for a given participant, the entire process was repeated using a more conservative threshold for rejection of the single trials (i.e., 8 µV). If this was not successful, the participant was replaced. This procedure ensures that, for any included participant, any eye movements triggered by the singleton were extremely small on average and never exceeded 1° on any individual trial.

Finally, if a participant had greater than 25% trials rejected across the entire artifact rejection procedure (averaged across conditions), that participant was replaced. Four participants were replaced for this reason. Among the final sample of participants, an average of 5.2% of trials were excluded due to artifacts. The same subset of trials that met the ERP analysis inclusion criteria in artifact rejection were used to analyze the behavioral data.

To minimize Type I errors, the electrodes and time windows used in the statistical analysis were determined a priori based on previous studies of the N2pc component (Gaspelin & Luck, 2018a; Papaioannou & Luck, 2020; Sawaki & Luck, 2010; Stilwell et al., 2022; Talcott & Gaspelin, 2021). The N2pc component was measured by subtracting the ipsilateral from the contralateral waves at the PO7 and PO8 electrode sites, selected on the basis of the ERP CORE N2pc study (Kappenman et al., 2021). The N2pc component was measured as the mean amplitude from 175 to 275 ms post-stimulus time window. Most prior studies have used N2pc time windows from approximately 200 to 300 ms (see a review by Luck, 2012). We chose a slightly earlier time window than usual (by 25 ms) because several studies have shown that the latency of the N2pc component can be earlier for highly salient stimuli such as the color singletons used in the present study (e.g., Gaspar & McDonald, 2014).

Results

Behavioral Results

The color singleton was always present, preventing us from evaluating singleton-presence costs (which are assessed in Experiment 2). For completeness, mean RTs and error rates were compared in each task condition (diffuse, focused, and singleton search). Planned *t* tests indicated that mean RTs were greater in the singleton search condition (568 ms) than in the diffuse attention condition (489 ms), $t(23) = 6.88$, $p < .001$, $d_z = 1.40$, or in the focused attention condition (476 ms), $t(23) = 8.84$, $p < .001$, $d_z = 1.80$. Mean RTs did not differ significantly between the diffuse attention and focused attention conditions, $t(23) = 1.74$, $p = .10$, $d_z = 0.36$.

The same analysis was conducted for mean error rates. Planned *t* tests indicated that mean error rates were significantly lower in the focused attention condition (1.9%) than in the diffuse attention condition (2.5%), $t(23) = 2.27$, $p = .03$, $d_z = 0.46$, or in the singleton search condition (2.8%), $t(23) = 2.52$, $p = .02$, $d_z = 0.51$. Mean accuracy did not differ between the diffuse attention and the singleton search conditions, $t(23) = 0.92$, $p = .37$, $d_z = 0.19$.

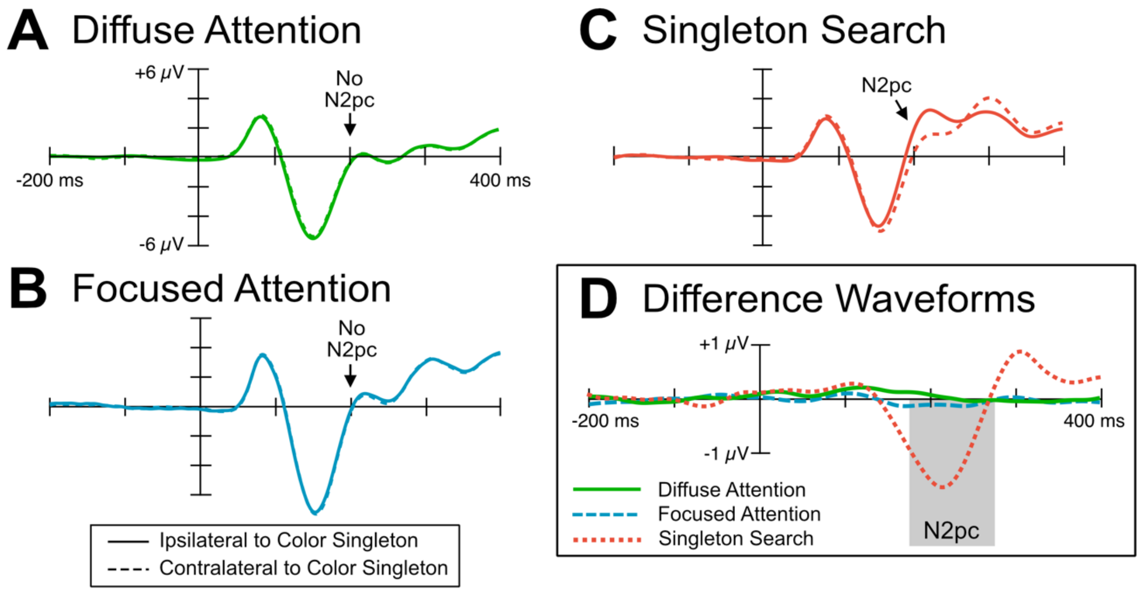
Electrophysiological Analysis of the N2pc Component

Figure 3 depicts grand-averaged ERP waveforms from lateralized occipitotemporal scalp sites (PO7 and PO8) relative to the color singleton. The contralateral and ipsilateral scalp sites are shown in separate waveforms. The contralateral waveform is the average of the left-hemisphere electrode (PO7) when the singleton appeared in the right visual field and the right-hemisphere electrode (PO8) when the singleton appeared in the left visual field. Similarly, the ipsilateral waveform is the average of the left-hemisphere electrode (PO7) when the singleton appeared in the left visual field and the right-hemisphere electrode (PO8) when the singleton appeared in the right visual field. To isolate the N2pc and other lateralized responses from the nonlateralized brain activity, contralateral-minus-ipsilateral difference waveforms were calculated for each task condition (see Figure 3D).

The attentional window account predicts that the color singleton should capture attention in the diffuse attention condition, producing an N2pc component. As can be seen from the waveforms, we found no evidence of this. The N2pc for each task condition was assessed using planned one-sample t-tests to determine whether the voltage from 175-275 ms in the difference wave differed significantly from zero. In the diffuse attention condition, in which the attentional window account predicts that the singleton will capture attention, there no hint of an N2pc (mean = 0.0 μV), $t(23) = 0.45$, $p = .66$, $d_z = 0.09$. In the focused attention condition, there was a small

Figure 3

Results from Experiment 1



Note. (A-C) Parent waveforms for occipital electrode sites (PO7/PO8) that were ipsilateral and contralateral to the color singletons for all task conditions (diffuse attention, focused attention, and singleton search). (D) Contralateral-minus-ipsilateral difference waveforms for each task condition. All ERP waveforms in this paper were low-pass filtered to improve visibility of the effects (Butterworth noncausal filter, half-amplitude cutoff = 20 Hz, slope = 12 dB/octave), but analyses were performed on unfiltered waveforms.

numerical N2pc trend (mean = -0.1 μV) that did not reach significance, $t(23) = 2.01$, $p = .06$, $d_z = 0.41$. Even if this small N2pc was real, this is the condition in which the attentional window account would predict no N2pc. However, the N2pc was robust and significant in the singleton search condition (mean = -1.2 μV), $t(23) = 6.71$, $p < .001$, $d_z = 1.37$, demonstrating that we had the sensitivity to detect an N2pc under conditions in which all theories would predict that attention is directed to the singleton.

The logic of null hypothesis statistical testing does not allow conclusions to be drawn from the absence of a significant effect, so we computed the Bayes factors corresponding to these *t* tests (Rouder et al., 2009), using the default JZS scaling factor of 0.707. The diffuse attention condition N2pc showed $BF_{01} = 4.24$. This indicates that observed data were approximately 4 times more likely to be observed under the null hypothesis than under the alternative hypothesis, providing positive evidence in favor of the null hypothesis. The focused attention condition N2pc showed $BF_{01} = 0.84$, providing no compelling evidence for or against the presence of an N2pc. The singleton search condition showed $BF_{10} > 1000$, indicating strong evidence for the presence of an N2pc component.

We also compared the mean amplitude of the N2pc effects across the three task conditions (diffuse attention, focused attention, and singleton search) using planned paired-samples *t* tests. The N2pc component in the singleton search condition was significantly larger than in the focused attention condition, $t(23) = 6.29$, $p < .001$, $d_z = 1.28$, or in the diffuse attention condition, $t(23) = 7.03$, $p < .001$, $d_z = 1.43$. The N2pc amplitude was slightly but significantly larger in the focused attention condition than in the diffuse attention condition, $t(23) = 2.46$, $p = .02$, $d_z = 0.50$. Note, however, that this small effect was in the opposite direction of the pattern predicted by the attentional window account, which predicts a greater N2pc in the diffuse attention condition.

In sum, the results did not support the attentional window account. There was no evidence of an N2pc from the color singleton in the diffuse condition and there was no evidence that the N2pc was greater in the diffuse condition than focused condition.

Exploratory Analysis of the Lateralized Positivity

As shown in Figure 3D, there was a small positive voltage deflection (<0.2 µV) from approximately 100 to 200 ms in the contralateral-minus-ipsilateral difference waves (before the N2pc time window). Given the small magnitude of this activity, it would be problematic to make any strong claims about it. A small positive component in this time range could reflect suppressive mechanism that is applied to color singleton (a P_D *component*; Gaspelin, Lamy, et al., 2023; Gaspelin & Luck, 2018a; Sawaki & Luck, 2010), but it could also reflect differences in low-level sensory processing resulting from presenting a salient stimulus in one hemifield but not the other (a *Ppc component*; Barras & Kerzel, 2016, 2017; Corriveau et al., 2012; McDonald et al., 2023). It could also reflect reduced adaptation of the P1 component for the singleton color relative to the nonsingleton color (Luck & Hillyard, 1994b). In any case, we wanted to analyze this component for completeness.

We conducted an exploratory analysis to assess whether the early positivity from 100–200 ms significantly differed from zero in each condition. One-sample t tests showed that the positivity was significant in the diffuse attention condition (0.17 µV), $t(23) = 2.81$, $p = .01$, $d_z = 0.57$, but was near zero and not significant in the focused attention condition (-0.04 µV), $t(23) = 0.75$, $p = .46$, $d_z = 0.15$. In the singleton search condition, the presence of a large N2pc component beginning at approximately 150 ms caused the voltage during the 100-200 ms time window to be significantly negative (-0.35 µV), $t(23) = 3.67$, $p < .01$, $d_z = 0.75$. Given that salient singleton distractors often elicit a P_D component (Burra & Kerzel, 2014; Gaspelin & Luck, 2018a; Sawaki & Luck, 2010; Stilwell et al., 2022), thought to reflect suppression of the distractor (Gaspelin, Lamy, et al., 2023), it may seem surprising that we did not observe a robust positive-going deflection in the diffuse and focused attention conditions. We will return to this issue in the General Discussion.

Discussion

Experiment 1 manipulated the spread of attention to test the prediction of the attentional window account that capture will occur when a salient item is inside the attended region but will not when it is outside the attended region. We found no evidence in line with this prediction. In the diffuse attention condition, the salient singleton distractor was inside the attended region, but it produced no N2pc component. Note that Experiment 6 will demonstrate that the diffuse attention does, in fact, cause attention to be spread throughout the region containing the salient singleton. Note also that the lack of an N2pc in this condition was not due to lack of sensitivity, because the singleton produced a robust N2pc when it was the target (in the singleton-search condition). These results challenge the prediction of the attentional window account that salient distractors should capture attention when inside of the spatial focus of attention. The next experiment will provide converging evidence using a behavioral measure of capture.

Experiment 2: Attentional Window with Behavioral Measures of Capture

As reviewed in the introduction, attentional capture by salient distractors typically leads to slower RTs on singleton-present trials than on singleton-absent trials (a singleton-presence cost; Theeuwes, 1992, 1994). This singleton-presence cost could not be analyzed in Experiment 1 because the singleton appeared on every trial. Experiment 2 was therefore conducted as a behavioral follow-up. Participants completed the same basic diffuse and focused attention tasks from Experiment 1, but singleton-absent trials were included so that singleton-presence costs on manual RT could be assessed. According to the attentional window account, we should observe a singleton-presence cost in the diffuse attention condition but not in the focused attention condition.

Method

All methods were identical to Experiment 1, except as follows. A new sample of 24 participants were recruited for course credit (8 men, 16 women, M_{age} = 21.0 years). The EEG was not recorded. Only the focused attention and diffuse attention conditions were included, and the order of conditions was counterbalanced across participants. A singleton was present on a random 50% of the trials within each condition (*singleton-present trials*). On the remaining trials, all the eight disks had the same color (*singleton-absent trials*). Because there was no singleton search condition, the gaps were removed from the eight disks. Additionally, the search array was visible until a response was made, which is more common in behavioral tasks of attentional capture (e.g., Gaspelin et al., 2015; Ma & Abrams, 2023c, 2025; Stilwell & Gaspelin, 2021; Theeuwes, 1992, 1994).

Participants completed 10 blocks of 64 trials (640 trials total), with 5 blocks of each condition. The first block for each condition was considered a practice block and was removed from analysis. Trials with RTs less than 200 ms or greater than 1,500 ms were excluded from analysis (0.5% of trials). In addition, trials with inaccurate responses were excluded from the RT analysis.

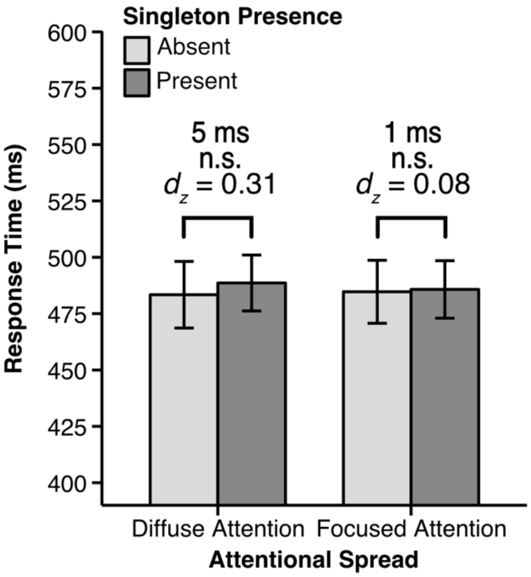
Results

Figure 4 shows RT as a function of singleton presence in the focused and diffuse attention conditions. If the singleton captured attention, there should be a singleton-presence cost, a slowing of RT on singleton-present trials, but there was no evidence of this in either condition. Planned *t* tests comparing singleton-present and singleton-absent trials showed that there was no singleton-presence cost for the focused attention condition (1 ms), $t(23) = 0.39$, $p = .70$, $d_z = 0.08$, or the diffuse attention condition (5 ms), $t(23) = 1.50$, $p = .15$, $d_z = 0.31$. There was also no significant difference in the magnitude of the singleton-presence cost between the focused and diffuse attention conditions, $t(23) = .97$, $p = .34$, $d_z = .20$.

We also computed Bayes factors corresponding to these *t* tests. In the focused attention condition, the data were substantially more consistent with the absence of a singleton-presence cost than with the presence of a cost ($BF_{01} = 4.35$). In the diffuse attention condition, the data were slightly more consistent with the absence of a cost than with the presence of a cost ($BF_{01} =$

Figure 4

Results from Experiment 2



Note. Response times for each task condition. All error bars in this paper represent within-subject 95% confidence intervals (Morey, 2008).

1.74). There was also moderate evidence for no difference between the size of the singleton-presence cost between the two conditions ($BF_{01} = 3.04$). Thus, there was no real evidence of capture by the singleton in either condition.

The same analysis was conducted on error rates and produced similar results. There was no singleton-presence cost for the focused attention (-0.4%), $t(23) = 1.21$, $p = .24$, $d_z = 0.35$, $BF_{01} = 2.43$, or diffuse attention (0.1%), $t(23) = 0.21$, $p = .84$, $d_z = 0.04$, $BF_{01} = 4.57$. The size of the singleton-presence cost also did not differ between the two conditions, $t(23) = 1.03$, $p = .31$, $d_z = 0.21$, $BF_{01} = 2.89$.

Discussion

Experiment 2 used the same basic task as Experiment 1 but adapted to measure RT costs associated with attentional capture. We found no evidence that salient singleton distractors automatically capture attention whether they occurred inside or outside the window of attention.

This pattern of results replicates the basic findings of Experiment 1, but with RTs instead of the N2pc component.

Experiment 3: Increased Salience Combined with ERP Measures of Capture

Experiments 1 and 2 showed that a color singleton did not capture attention when it appeared within the attentional window, counter to the predictions of the attentional window account. A potential explanation for the lack of the capture effect is that the singleton might have not been salient enough to capture attention (Wang & Theeuwes, 2020; but see Stilwell et al., 2022, 2023, 2024; Stilwell & Gaspelin, 2021; Zhang & Gaspelin, 2024). This might occur, for example, due to the relatively low contrast between the colored disks against the isoluminant gray background or if the number of disks was not sufficiently large to induce popout on the color dimensions.

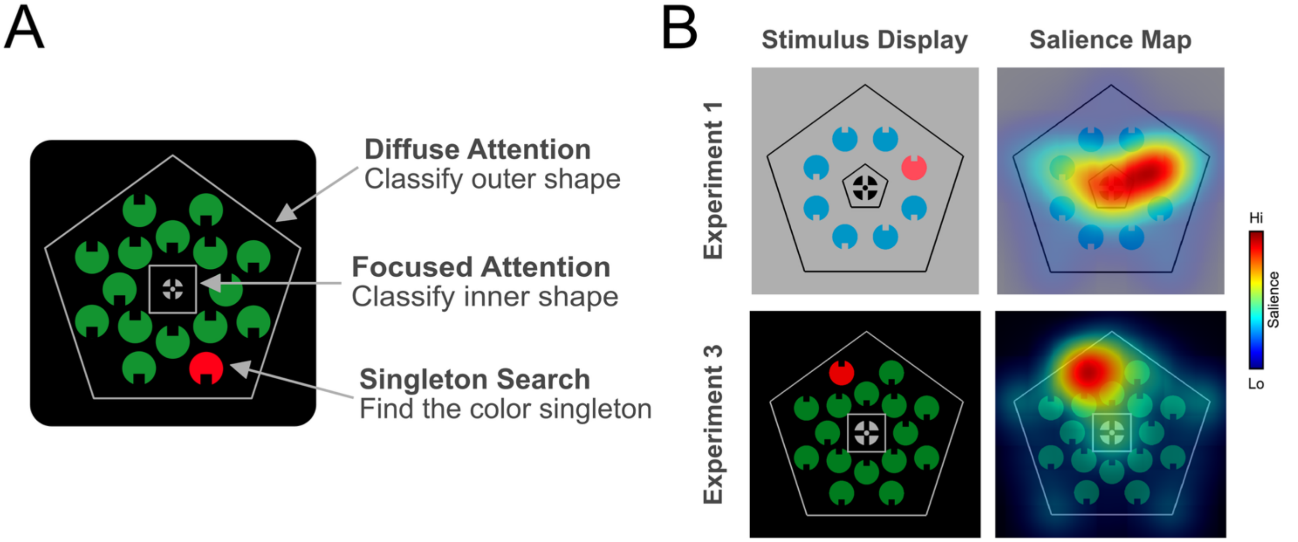
Experiment 3 therefore used the same design as Experiment 1 but with an even more salient singleton distractor (see Figure 5A). To increase salience, we increased the number of disks from 8 to 16, thereby increasing the number of homogenously colored objects that contrast with the color singleton. We also changed the background from gray to black to improve the color contrast (e.g., as in Theeuwes, 1992). As in Experiment 1, the attentional window account predicts that the color singleton should elicit a robust N2pc in the diffuse attention condition but little or no N2pc in the focused condition. The singleton-search condition again serves to assess our sensitivity to detect an N2pc component when all theories predict that the singleton should be attended.

Method

All methods were identical to those of Experiment 1, except as follows. A new sample of 24 participants was recruited (6 men, 18 women, M_{age} = 26.5 years). The disk colors were

Figure 5

Stimuli from Experiment 3 and Comparison of Salience Between Experiments 1 and 3



Note. (A) Experiment 3 was identical to Experiment 1, but the displays were adapted to improve the salience of the color singleton by using opposing colors on a black background and increasing the number of disks. (B) An example of salience heatmaps of stimulus displays in Experiments 1 and 3 generated by a computational model of salience. As can be seen in this example, the color singleton was better identified in heatmaps of salience in Experiment 3, suggesting its salience was truly improved.

changed to red (29.6 cd/m^2, x = .639, y = .325) and green (30.2cd/m^2, x = .272, y = .614) against a black background. These colors are more common in the attentional capture literature, and we assumed that these opponent colors on a dark background would boost salience (e.g., Gaspelin et al., 2015; Stilwell et al., 2023). The central fixation point and the polygons were drawn in gray (77.0 cd/m^2, x = .281, y = .292) rather than black. We also increased the set size from 8 to 16 disks to improve overall salience by increasing the number of objects that contrast with the color singleton. This was accomplished by using two concentric circular arrays of disks (radiuses of 2.3 ° and 3.9°). The color singleton appeared with equal probability at any of the 16 locations.

A final change was made to further encourage spreading attention in the diffuse condition. In Experiment 1, the rotational angle of the pentagon and square were fixed (always upright). A participant could, in theory, have performed the task by attempting to attend a single position to see if a straight or angled line appeared at that position (denoting a square or pentagon). Experiment 3 prevented this strategy by rotating the orientation of the pentagon randomly across trials by 0°, 90°, 180°, or 270°, which allowed the vertices of the pentagon to equally often align with one of the four vertices of the square contour.

Participants completed a total of 9 blocks of 128 trials each, split into 3 blocks for each task condition (focused attention, diffuse attention, and singleton search) with the first block of each task being a practice block. Trials with incorrect or missing behavioral responses or with outlier RTs (less than 200 or greater than 1,500 ms) were excluded from analysis (0.4%). In addition, we used the same artifact rejection procedures to detect large artifactual voltages, eye blinks, and eye movements. All participants had residual eye movements lower than 3.2 µV in the HEOG bipolar channel for the difference between left- and right-target trials and also had fewer than 25% of total trials removed during artifact rejection. Therefore, all 24 participants were included in the analysis. Among them, an average of 3.2% of trials were excluded due to artifacts.

Computational Model of Salience

We verified that the salience manipulation was successful using a computational model of salience (Figure 5B). We created 200 display images from Experiments 1 and 3. These display images were then analyzed using the Image Signature Toolbox (Hou et al., 2012) in Matlab to generate saliency maps. This toolbox has been previously shown to be sensitive to feature singletons in artificial laboratory displays (Kotseruba et al., 2020) and has been used by previous studies to verify the salience of color singletons (Stilwell et al., 2022, 2024; Stilwell & Gaspelin, 2021). The default settings of the toolbox were used, except that the mapWidth() parameter was adjusted to accommodate the image resolution (1920 x 1080). The output images are heatmaps distinguishing regions that have high and low salience (right column of Figure 5B). As can be seen, the singleton is better identified in the new displays (Experiment 3) than in the old displays (Experiment 1), suggesting saliency was improved.

To quantify salience, we calculated a measure of salience called the *global saliency index* (GSI; Stilwell & Gaspelin, 2021). The GSI was computed as the mean salience score at the singleton disk location minus the grand average of the salience scores across all the non-singleton disk locations. This difference score was then normalized by dividing by the sum of the salience scores of all array items. This results in a value ranging from -1 to +1, with a positive value indicating the singleton was more salient than the average display item and a negative value indicates that the singleton was less salient than the average display item. A GSI of zero suggests equal salience between the singleton and nonsingletons. Color singletons in Experiment 3 produced an average GSI of +0.89 [95% CI: +0.877, +0.893], whereas the singletons in Experiment 1 produced an average GSI of +0.77 [95% CI: +0.760, +0.777]. An independent-samples *t* test confirmed that the GSI was significantly greater in Experiment 3 than Experiment 1, $t(368) = 19.83$, $p < .001$, $d_z = 1.98$. Altogether, these analyses provide evidence that the singletons in both experiments were quite salient (>75% of the maximum possible GSI value) and that, as intended, the singletons in Experiment 2 were even more salient than the singletons in Experiment 1.

Results

Behavioral Results

The color singleton was always present in this experiment, so we could not evaluate singleton-presence costs on RTs (but see Experiment 4). For completeness, mean RT and error rates were compared across conditions. Planned *t* tests indicated that mean RTs were greater in the singleton search condition (564 ms) than in either the diffuse attention condition (489 ms), $t(23) = 6.46$, $p < .001$, $d_z = 1.32$, or the focused attention condition (487 ms), $t(23) = 5.61$, $p < .001$, $d_z = 1.14$. Mean RTs did not differ significantly between the diffuse attention and the focused attention conditions, $t(23) = 0.20$, $p = .84$, $d_z = 0.04$.

The same analysis was conducted on mean error rates. Planned *t* tests indicated that mean error rates were higher in the singleton search condition (3.4%) than in either the diffuse attention condition (2.2%), $t(23) = 2.29$, $p = .03$, $d_z = 0.47$, or the focused attention condition (1.8%), $t(23) = 2.91$, $p = .01$, $d_z = 0.59$, indicating that the search task was more difficult than the shape-discrimination tasks. Mean error rate did not differ significantly between the diffuse attention and focused attention conditions, $t(23) = 1.72$, $p = .10$, $d_z = 0.35$.

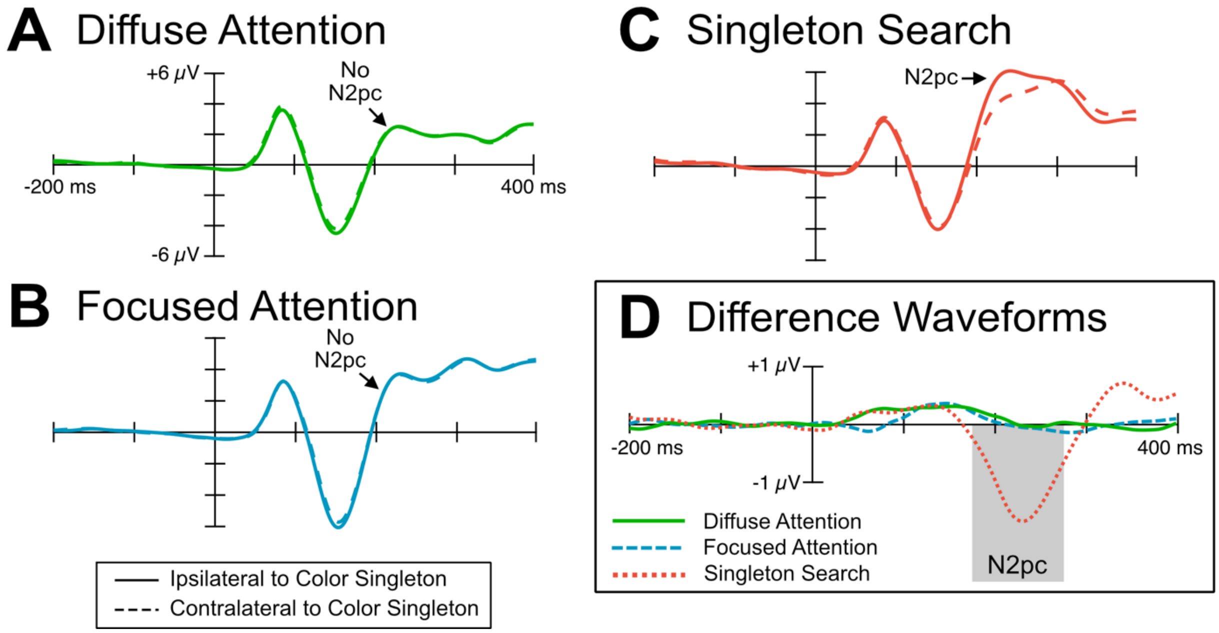
Analysis of the N2pc Component

Figure 6 depicts grand-averaged waveforms from the contralateral and ipsilateral occipital scalp sites (PO7 and PO8) relative to the color singleton. The attentional window account predicts that the color singleton should capture attention in the diffuse attention condition but not the focused attention condition. We found no evidence of this: There was no N2pc in either the diffuse or focused attention conditions.

One-sample *t* tests examined whether the N2pc significantly differed from zero in each condition. N2pc amplitude was significantly different from zero in the singleton search condition (-1.2 μV), $t(23) = 4.29$, $p < .001$, $d_z = 0.88$, but not in the diffuse attention condition (0.1 μV), $t(23) = 0.88$, $p = .39$, $d_z = 0.18$, or the focused attention condition (0.0 μV), $t(23) = 0.36$, $p = .72$, $d_z = 0.07$. The logic of null hypothesis statistical testing does not allow conclusions to be drawn from the absence of a significant effect, so we computed the Bayes factors corresponding to these *t* tests. The diffuse attention condition N2pc showed $BF_{01} = 3.28$ and the focused attention

Figure 6

Results from Experiment 3



Note. (A-C) Parent waveforms for occipital electrode sites (PO7/PO8) that were ipsilateral and contralateral to the color singletons for all task conditions (diffuse attention, focused attention, and singleton search). (D) Contralateral-minus-ipsilateral difference waveforms for each task condition.

condition N2pc showed $BF_{01} = 4.40$. These indicate that the data were 3 to 4 times more likely to occur under the null hypothesis than under the alternative hypothesis, providing positive evidence for the absence of an N2pc in the diffuse and focused attention conditions. The singleton search condition showed $BF_{10} > 100$, indicating strong evidence for the presence of an N2pc component, as expected.

N2pc amplitudes were compared across the three task conditions (diffuse attention, focused attention, and singleton search) using a one-way repeated measures ANOVA on the contralateral-minus-ipsilateral difference scores. There was a significant main effect of task condition, $F(2,46) = 17.23$, $p < .001$, $\eta_p^2 = 0.43$. Paired-samples t tests compared the N2pc mean amplitude between pairs of conditions. The N2pc component was larger in the singleton search condition than in either the focused attention condition, $t(23) = 4.00$, $p < .001$, $d_z = 0.81$, or the diffuse attention condition, $t(23) = 4.50$, $p < .001$, $d_z = 0.92$. However, N2pc amplitude did not differ between the focused attention condition and the diffuse attention condition, $t(23) = 0.94$, $p = .36$, $d_z = 0.19$.

In sum, we observed no evidence supporting the key prediction of the attentional window account, namely the presence of an N2pc in the diffuse attention condition. The results suggest that the singleton was effectively ignored despite its high level of salience, even when it occurred inside the attended region.

Exploratory Analysis of the Lateralized Positivity

As depicted in Figure 6D, there was a relatively small lateralized positive voltage (<0.3 μV) from approximately 100 to 200 ms, prior to the N2pc time window. As in Experiment 1, we cannot make any strong claims about this small lateralized positivity. Some studies have found that positivities such as this can elicited by distractors as a result of sensory adaptation, as a response to salience, or as a result of suppression, and we have no way of distinguishing among these causes in the present experiment. For the sake of completeness, however, we conducted an exploratory analysis using one-sample *t* tests on the contralateral-minus-ipsilateral voltage in the 100–200 ms time window. We found that the positivity was significant in both the diffuse attention condition (0.27 μV), $t(23) = 4.25$, $p < .001$, $d_z = 0.87$, and the focused attention (0.26 μV), $t(23) = 4.96$, $p < .001$, $d_z = 1.01$, but not in the singleton search condition (0.07 μV), $t(23) = 0.54$, $p = .59$, $d_z = 0.11$. We will revisit this lateralized positivity in the General Discussion.

Discussion

Experiment 3 replicated the key results of Experiment 1 with changes to the display that made the color singleton more salient. Despite being highly salient, the color singleton did not capture attention regardless of appearing inside or outside the attentional window, as evidenced by the absence of an N2pc component. Bayesian analyses provided positive evidence for the lack of an N2pc in both the diffuse and focused attention conditions. By contrast, the singleton search task again produced a robust N2pc, demonstrating our sensitivity to detect an N2pc under conditions in which all theories would predict one. Thus, even with a very highly salient color singleton, we found no evidence for the attentional window account.

Experiment 4: Improved Salience with Behavioral Measures of Capture

Experiment 4 was designed to provide converging behavioral evidence about the presence or absence of capture using the very high salience singleton displays of Experiment 3. Like Experiment 2, we included singleton-absent trials that allowed us to evaluate singleton-presence costs, but we did not measure ERPs or include the singleton-search condition. The attentional window account predicts that capture should occur in the diffuse attention condition, resulting in a singleton-presence cost on RT, but not in the focused attention condition.

Method

All methods were identical to those of Experiment 3, except as follows. A new sample of 24 participants was recruited (15 men, 9 women, M_{age} =18.8 years). The experiment only included the focused attention and diffuse attention conditions, the order of which was counterbalanced across participants. For half of trials, the singleton was absent, and for the other half, the singleton was present. Because there was no singleton search condition, the gaps were removed from the eight circles. The search array was visible until a response was made.

Participants completed 12 blocks of 64 trials, resulting in 768 trials in total. The experiment was divided into two halves, with 6 blocks of the focused attention condition and diffuse attention condition. The first block of each half was considered a practice block and was eliminated from the final analysis. This yielded a total of 320 trials in each task, with 160 singleton-present trials and 160 singleton-absent trials for each condition. Trials with RTs less than 200 ms or greater than 1,500 ms were excluded from analysis (0.3% of trials). In addition, trials with incorrect responses were excluded from the RT analysis.

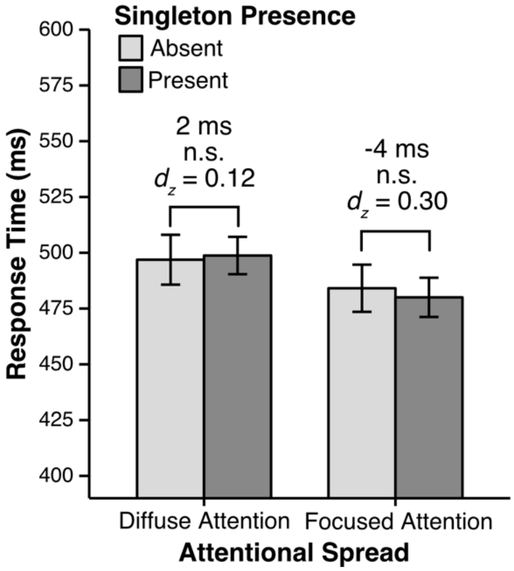
Results

Figure 7 shows mean RT as a function of singleton presence in the focused and diffuse attention conditions. If the singleton captured attention, it should have produced slower RTs on singleton-present than singleton-absent trials. As can be seen, there was no evidence of such a singleton-presence cost in either condition. In planned *t* tests comparing singleton-present and singleton-absent trials, we obtained no singleton-presence cost for either the focused attention condition (-4 ms), $t(23) = 1.48$, $p = .15$, $d_z = 0.30$, or the diffuse attention condition (2 ms), $t(23) = 0.60$, $p = .55$, $d_z = 0.12$. We also computed Bayes factors corresponding to these *t* tests: focused attention condition, $BF_{01} = 1.79$, and diffuse attention condition, $BF_{01} = 3.95$. The latter result indicates that, in the diffuse condition, the data were almost four times more likely under the null hypothesis than under the alternative hypothesis. In addition, the singleton-presence cost was not significantly greater in the diffuse attention condition than in the focused attention condition, $t(23) = 1.54$, $p = .14$, $d_z = .31$, $BF_{01} = 1.65$.

The same analyses were repeated for error rates. There was no significant singleton-presence cost on error rates for either the focused attention (0.5%), $t(23) = 1.36$, $p = .19$, $d_z = 0.28$, $BF_{01} = 2.05$, or the diffuse attention condition (-0.2%), $t(23) = 0.43$, $p = .67$, $d_z = 0.09$, $BF_{01} = 4.28$. The size of the singleton-presence cost also did not differ between the two conditions, $t(23) = 1.11$, $p = .28$, $d_z = 0.23$, $BF_{01} = 2.68$.

Figure 7

Results from Experiment 4



Note. Response times for each task condition. Error bars represent within-subject 95% confidence intervals (Morey, 2008).

Discussion

Experiment 4 was conducted as a behavioral follow-up to Experiment 3, aiming to check for any singleton-presence cost from the color singleton. We observed no evidence of a singleton-presence cost in either mean RT or error rate. Thus, Experiment 4 provided converging evidence that highly salient singletons do not capture attention even when they are inside the attended region. These findings match the findings of Experiments 1–3 and directly contradict the fundamental prediction of the attentional window account, namely that color singletons should automatically capture attention when they occur inside the window of attention.

Experiment 5: An Even Stronger Method for Spreading Attention Diffusely

In Experiments 1–4, participants were required to selectively attend to the outer polygon in the diffuse attention condition. A possible concern with this design, however, is that it might have been possible for participants to spatially filter the region inside the polygons, including the colored disks. Indeed, some previous research has shown that such filtering could apply to visual stimuli that are highly discriminable from the target or spatially segregated from the target location (Folk & Remington, 1998; Kahneman et al., 1983; Leonard et al., 2013; Treisman et al., 1983).

To rule out this possibility, Experiment 5 adapted the task to force participants to spread attention across both the inner and outer shapes simultaneously (Figure 8). The same stimuli were used as in Experiment 1, but participants were instructed to report whether the two polygons had the same shape or different shapes. Given the brief presentation time (200 ms), this comparison would require attention to be spread across both contours simultaneously. Thus, the attentional window must encompass the region that contained the salient distractor to perform the task. ERP and behavioral indices of attentional capture were both measured. The attentional window account predicts that the salient distractor should capture attention because it is inside the focus of attention during the shape comparison task. If this occurs, the salient distractor should yield an N2pc component in ERPs and a singleton-presence cost on mean RT.

Method

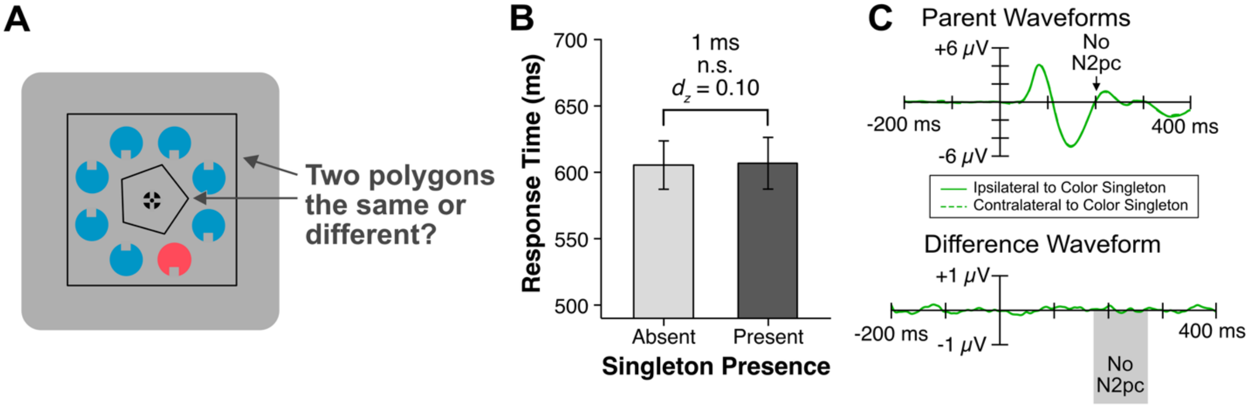
All methods were identical to Experiment 1, except as follows. A new sample of 24 participants were recruited (7 men, 17 women, M_{age} = 24.4 years).

As illustrated in Figure 8A, we used only a single task in which participants were asked to report whether the inner and outer polygons were the same shape or different shapes. Each polygon shape (square or pentagon) was randomly and independently selected on every trial. Consequently, the inner and outer shapes were same on half of the trials and different on the other half. Additionally, the polygons were rotated randomly by 0°, 90°, 180°, or 270° on each trial to prevent participants from selectively attending a specific region of space. Another significant change was that the singleton was absent on half of trials, allowing measurement of behavioral capture effects (singleton-presence costs). Each participant completed a total of 4 blocks of 128 trials each, with the first block being a practice block.

The EEG recording and analysis methods were the same as in Experiments 1 and 3. Trials with incorrect or missing behavioral responses or with outlier RTs (less than 200 ms or greater than 1,500 ms) were excluded from the EEG analysis (0.2% of trials). All participants had residual eye movements of less than 3.2 µV in the bipolar HEOG channel for the difference between left- and right-target trials, and all participants had fewer than 25% of total trials removed during artifact rejection. Therefore, all 24 participants were included in the analysis. Among them, an average of 3.0% of trials were excluded due to artifacts.

Figure 8

Task and Results for Experiment 5



Note. (A) Participants made a speeded response to denote whether the inner and outer shape contours were the same or different as one another. Given the brief duration of the stimulus display (200 ms), this forced participants to spread attention across the display. (B) Response times for singleton-present and -absent trials. (C) ERP waveforms from for occipital electrode sites (PO7/PO8). Difference waveforms were calculated as contralateral minus ipsilateral.

Results

Behavioral Results

Figure 8B shows mean RT as a function of singleton presence. If the singleton captured attention, this should have slowed target discrimination on singleton-present trials, leading to a singleton-presence cost on RT. As can be seen, there was no evidence of this in the data. In a planned t test comparing singleton-present and singleton-absent RTs, there was no significant singleton-presence cost (1 ms), $t(23) = 0.50$, $p = .62$, $d_z = 0.10$. The corresponding Bayes factor was $BF_{01} = 4.16$, indicating that the data were four times more likely to occur under the null hypothesis than under the alternative hypothesis, providing positive evidence for the lack of a singleton-presence cost.

The same analysis was conducted on error rates. Error rates were not significantly higher on singleton-present trials (3.6%) than singleton-absent trials (3.3%), $t(23) = 0.77$, $p = .45$, $d_z = 0.16$, $BF_{01} = 3.58$.

Electrophysiological Analysis of the N2pc

Figure 8C depicts grand-average contralateral and ipsilateral parent waveforms along with contralateral-minus-ipsilateral difference waveforms. The attentional window account predicts that the color singleton should capture attention in this shape comparison task, which would produce an N2pc component, but we observed no evidence of an N2pc. A one-sample t test comparing the contralateral-minus-ipsilateral amplitude to zero was not significant (0.0 μV), $t(23) = 0.36$, $p = .72$, $d_z = 0.07$. The corresponding Bayes factor was $BF_{01} = 4.39$, indicating that the data were approximately four times more likely under the null hypothesis than under the alternative hypothesis.

Exploratory Analysis of the Lateralized Positivity

As in the prior ERP experiments, we conducted an exploratory analysis to assess the presence of a lateralized positivity in the time window from 100–200 ms. Interestingly, a one-sample *t* test indicated that there was no significant lateralized positivity in this time range (0.07 µV), $t(23) = 0.89$, $p = .38$, $d_z = 0.18$. The absence of a positive deflection here and the weakly positive voltages in Experiments 1 and 3 will be discussed in the General Discussion.

Discussion

Experiment 5 used a task that was designed to provide greater certainty that attention would be spread over the region containing the salient distractor. Still, the singleton did not capture attention, as evidenced by the absence of an N2pc component and by the absence of a singleton-presence cost on behavior. These findings replicate and extend the previous experiments by providing additional converging evidence that salient singletons do not automatically capture attention when they appear inside the window of spatial attention. These findings challenge the attentional window account, which predicts that capture should mandatorily occur when attention is spread diffusely.

Experiment 6: Validating the Attentional Spread Manipulation

Experiments 1–4 manipulated the size of the attentional window by having participants classify an inner or outer shape. Experiment 6 aimed to confirm that this manipulation invoked spreading of attention as intended. That is, we aimed to verify that the diffuse and focused conditions actually caused attention to be broadly and narrowly focused, respectively. This is especially important given that the two conditions did not cause any difference in attentional capture by salient distractors in Experiments 1–4.

This experiment used a letter-probe technique adapted to measure the spread of attention (Gaspelin et al., 2015; Gaspelin & Luck, 2018a). As depicted in Figure 9A, on most trials, participants performed the same shape-discrimination task as prior experiments. They made a speeded buttonpress to classify the shape of the polygon in a focused or diffuse condition. On small subset of trials, letter probes were briefly presented either inside the inner polygon (inner probes) or in the intermediate region between both polygons (outer probes). Participants were asked to report as many letters as possible. Based on the location of the correctly reported letters, it can be inferred how broadly attention was spread. If our attentional window manipulation was effective, the diffuse condition should lead to higher probe report rates of the outer probes compared to the focused condition. This would indicate that participants truly were spreading attention to encompass the region occupied by the salient distractor.

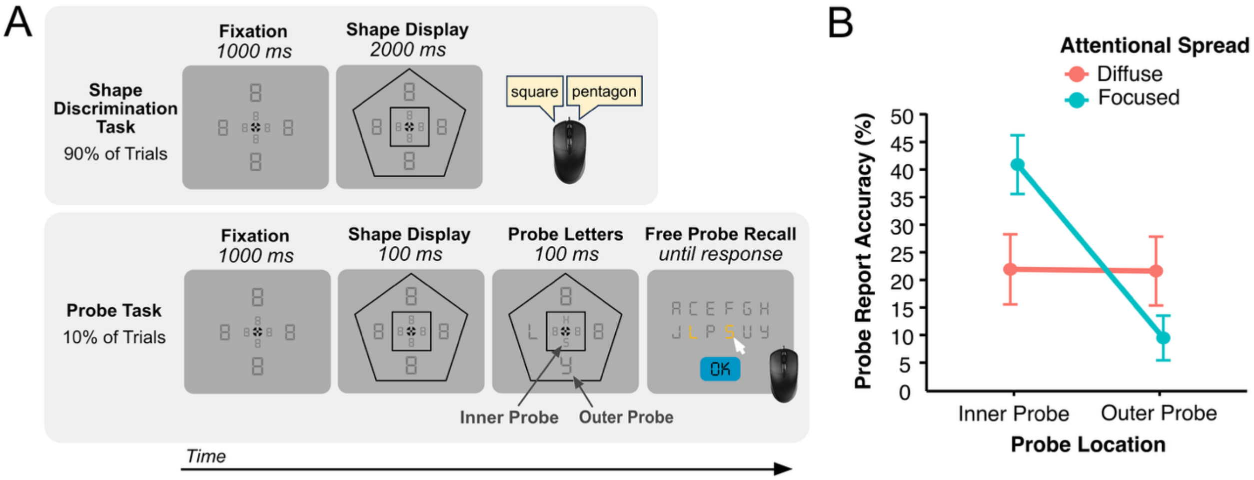
Method

All methods were identical to Experiment 2, except as follows. A new sample of 24 participants were recruited (15 men, 9 women, M_{age} = 19.5 years).

As illustrated in Figure 9A, participants performed the same shape-discrimination task as in Experiments 1–4. On these 90% of the trials, two shapes appeared on the screen and participants made a speeded buttonpress classifying whether either the inner (focused) or outer (diffuse) shapes were a square or pentagon. Unlike previous experiments, no disk array was presented. Instead, eight placeholders in the shape of digit ‘8’ appeared in a digital-clock typeface (DS-Digital font) that were dark gray color (20.1 cd/m^2, x = .283, y = .287). Four placeholders were inside the inner polygon (*inner probe*, eccentricity: 0.6°), and the other four were in the intermediate region between the two polygons (*outer probe*; eccentricity: 3.1°). These placeholders were continuously visible throughout shape-discrimination trials (and will come into play on probe trials).

Figure 9

Stimuli and Task from Experiment 6



Note. (A) Trial progression of the shape-discrimination and letter probe tasks, which were intermixed and presented in random order. (B) Probe report performance: The focused condition led to near-exclusive reporting of the inner probes, while the diffuse condition led to equal reporting of the inner and outer probes.

A random subset of trials were probe trials. On these 10% of trials, the shape display appeared briefly for 100 ms and then four of the digit 8 placeholders had segments offset to reveal letters for 100 ms and then disappeared. Participants were then asked to use a mouse to select as many letters as they remembered in an untimed response. A set of 12 letters (A, C, E, F, G, H, J, L, P, S, U, and Y) were used, from which four probe letters were randomly drawn without replacement on each trial. Two of the letters appeared in inside the inner shape (*inner probes*) and two of the letters appeared in the intermediate region between the two shapes (*outer probes*). The location of the two probe letters in each layer was randomly selected on each trial. The letters (and placeholders) were scaled for cortical magnification and ensure equal competition between letters at different eccentricities. Larger letters were used for the outer probe letters (2.0° vertically; 1.6° horizontally) compared to the inner probe letters (1.1°

vertically; 1.0° horizontally; computed based on methods in Virsu & Rovamo, 1979). Probe trials and shape-discrimination trials were presented in random order.

It is important to highlight two aspects of the probe task. First, the outer probes appeared in the same region occupied by the color singleton in Experiments 1–5. Thus, any enhanced probe report of the outer probes suggests the enhanced attention to the region occupied by the singleton in prior experiments. Second, the probe letters were designed to minimize dynamic transients that might capture attention (Yantis & Jonides, 1984, Adams, Ruthruff, & Gaspelin, 2022). Because of the digital clock font, letters were formed solely by subtracting segments from the digit '8'. As a result, transforming the placeholder into any of these letters involved only the offset of existing visual elements, without the onset of new ones, which should minimize attentional capture by the probe letters.

The experiment was divided into two halves for each attentional spread condition (diffuse vs. focused) and the order of halves was counterbalanced across participants. Each half of the experiment began with a practice block (20 trials) of the shape-discrimination task alone, followed by a practice block (50 trials) of intermixed shape-discrimination and probe tasks. The main experiment consisted of 8 blocks of 80 trials each, resulting in 320 trials for each attentional spread condition. As a result, each attentional spread condition had approximately 256 shape-discrimination trials and 64 probe trials.

Trials with RTs less than 200 ms or greater than 1,500 ms on the shape-discrimination task were excluded from analysis (0.8% of trials). In addition, trials with incorrect responses on the shape-discrimination task were excluded from the RT analysis.

Results

Shape-Discrimination Trials

We had no a priori predictions about performance on shape-discrimination trials but analyzed them for the sake of completeness. Paired-samples *t* tests were used to compare the focused and diffuse conditions in RT and accuracy. Participants were significantly faster to classify the polygons in the focused (498 ms) than the diffuse condition (530 ms), $t(23) = 3.04$, $p = .006$, $d_z = 0.62$. The two conditions did not differ in accuracy (focused: 96.6%; diffuse: 97.0%), $t(23) = 1.63$, $p = .116$, $d_z = 0.33$.

Probe Trials

Participants reported an average of 1.7 letters on each trial of the probe task with a hit rate of 55%, similar to previous studies using the letter-probe technique (Gaspelin et al., 2015).

Figure 9B shows mean probe report accuracy as a function of probe letter location (inner probe vs. outer probe) and attentional spread condition (diffuse vs. focused). If our manipulation of attentional spread was successful, the focused condition should have improved probe report accuracy for the inner probes than the outer probes, whereas the diffuse condition should lead to similar accuracy for probes in both layers. As can be seen, this prediction was perfectly matched by the results.

We conducted a two-way repeated measures ANOVA with the factors of attentional spread (focus vs. diffuse) X probe location (inner vs. outer). There was a main effect of probe location, $F(1,23) = 17.38$, $p < .001$, $\eta_p^2= 0.43$, indicating the inner probes were reported at a higher frequency than outer probes. There was also a nonsignificant trend of a main effect of attentional spread, $F(1,23) = 4.14$, $p = .054$, $\eta_p^2= 0.15$, with the focused condition having a slightly higher accuracy than the diffuse condition. Crucially, there was a significant interaction of attentional spread and probe location, $F(1,23) = 54.78$, $p < .001$, $\eta_p^2 = 0.70$. The focused condition had a much higher report rate for the inner probes (40.9%) compared to the outer probes (9.5%), $t(23) = 8.78$, $p < .001$, $d_z = 1.79$, $BF_{10} > 1000$. In contrast, the diffuse condition had approximately equal report rates of the inner (21.9%) and outer (21.6%) probes, $t(23) = 0.06$, $p = .951$, $d_z = 0.01$, $BF_{01} = 4.65$. This result demonstrates that the shape-discrimination task powerfully influenced the spread of attention, as was assumed in Experiments 1–5.

Discussion

Experiment 6 used the letter-probe task to verify the attentional spread manipulation used in Experiments 1–4. In the focused condition, there was near-exclusive detection of inner probes near fixation. In the diffuse condition, there was equal report of inner probes near fixation and outer probes in the intermediate region between shapes. This finding effectively validates the intended manipulation of attentional window size between the focused and diffuse conditions by showing that the diffuse condition did increase attentional allocation to the intermediate region where the color singleton appeared in Experiments 1–5.

General Discussion

Prior research has produced conflicting results about whether salient distractors capture attention. A common pattern of results is that salient stimuli capture attention when the target is salient but not when the target is nonsalient. Different theories have been proposed to explain this finding. Goal-driven accounts proposed that salient targets encourage participants to search broadly for any salient object, which enables capture by salient distractors (Bacon & Egeth, 1994). The attentional window account proposes an alternative explanation: this pattern of results is due to the spread of attentional focus (Theeuwes, 2004, 2023). According to this account, top-down control to ignore salient objects can *only* be achieved by narrowing the spatial focus of attention so that the salient objects are excluded from the attentional window. This is a fundamental issue, because it has implications for whether attention is captured by salient stimuli in an automatic fashion or as a result of interactions between task goals and the sensory input.

The present study tested the specific prediction of the attentional window account that salient objects within the spatial focus of attention will capture attention. A shape-discrimination task manipulated the focus of spatial attention by requiring participants to attend an inner polygon (focused attention) or an outer polygon (diffuse attention). An array of disks appeared in the intermediate regions between the two polygons that contained a color singleton. This task allowed us to avoid potential pitfalls from prior studies which have used the difficulty of visual search to infer attentional spread (see Figure 1). Specifically, the diffuse condition spread the focus of spatial attention independently of search difficulty, which allowed the attentional window account and goal-driven accounts to make separate predictions.

Experiments 1 and 2 served as initial tests of the attentional window account using the shape-discrimination task described above. The color singleton did not elicit an N2pc component or singleton-presence costs on manual RT, even when attention was broadly focused. Experiments 3 and 4 used the same task but increased the salience of the color singleton to improve its likelihood of capturing attention. These experiments replicated the previous results with no ERP or behavioral evidence of capture in either attentional spread condition. Experiment 5 used the same stimuli but adapted the task to improve the likelihood that attention was spread diffusely. Still, there was no evidence of an N2pc component or a singleton-presence cost. Experiment 6 verified that the shape-discrimination task induced the spread of spatial attention using a probe task. The results showed that the diffuse condition did improve probe detection in the intermediate zone where the color singleton appeared in Experiments 1–5.

Altogether, the current findings are inconsistent with the prediction of attentional window account that salient stimuli within the spatial focus of attention will capture attention. Five experiments provided converging evidence from ERPs and behavior that salient distractors did not capture attention even when attention was diffusely spread across the display. Importantly, this study included several control conditions meant to ensure a fair and thorough evaluation of the attentional window account. For instance, control conditions were included in which the color singleton was a target to ensure an N2pc could be detected. Additionally, Experiments 5 and 6 were included to ensure that attention was actually spread diffusely. Also, rather than just assuming that the color singletons were salient, we used a computational model of salience and showed that the singletons were 77% of the maximum possible salience in Experiments 1, 2 and 5, and 89% of the maximum possible salience in Experiments 3 and 4.

Additional Evidence Against the Attentional Window Account

The current findings fit previous studies providing evidence against the attentional window account. Famously, Leber and Egeth (2006) challenged the attentional window account by providing evidence that attentional capture in the additional singleton paradigm is due to search mode rather than the breadth of attentional focus. They had two groups of participants separately train on tasks that required different search modes. One group searched for a salient target whose identity changed from trial-to-trial, invoking a singleton-detection mode. The other group searched for a non-salient target shape, invoking a feature-search mode. After this training, both groups performed a test phase that involved a version of the task that allowed either search mode. The group that had previously used singleton detection mode showed large capture effects, whereas the group that had previously used feature-search mode did not. Importantly, the search slopes in the test phase were flat (< 2 ms per item) in both groups, suggesting a parallel search in both conditions.

Many other studies have also manipulated search seriality via manipulating target-distractor similarity and have tested how this influences capture (Gaspelin et al., 2016; Kerzel & Huynh Cong, 2024; Ruthruff et al., 2020). These studies found that, counter to the predictions of the attentional window account, parallel search does not necessarily enable capture. Although these studies provided evidence against the attentional window account, their manipulation of search mode was not as obviously related to attentional window size. While the actual size of the attentional window cannot be measured, many researchers have used the slopes of RT as a function of set size as an index to assess search seriality (e.g., Jonides & Yantis, 1988; Pashler, 1987; Theeuwes, 2004), while others have argued against that interpretation (e.g., Liesefeld & Müller, 2019; Michaelsen et al., 2024; Palmer, 1995; Townsend, 1971). The present study avoided this ambiguity by directly manipulating the spread of attention with a shape-discrimination task, without altering search difficulty (see also Tay et al., 2022).

As discussed earlier, Belopolsky and colleagues (2007) did provide some evidence that manipulating the spread of attention could influence attentional capture. They had participants evaluate the orientation of a triangle, that was either the global configuration of the array (diffuse condition) or the central fixation (focused condition), to determine whether to proceed with a search within the global array. The search array was composed of homogeneously colored letters and a uniquely colored letter, each of which was equally likely the search target. It was found that the when the target letter was uniquely colored, it was reported significantly faster than when it was nonuniquely colored in the diffuse condition, implying capture by the salient letter. Yet this difference was eliminated in the focused condition. The design of Belopolsky et al.

(2007) contained some elements that might explain why they found evidence of attentional capture. First, the color singleton was a part of the task-relevant shape for the go/no-go task in their diffuse condition, but not their focused condition. This confound makes it plausible that the singleton captured attention in their diffuse condition because of an interaction with task goals, not simply because it was salient.

A second problem with the design of Belopolsky et al. (2007) was that the color singleton was the target on some trials. Consequently, participants might have learned to associate singleton status with the target, especially on trials immediately following a singleton-target trial. In addition, because the singleton could be the target, participants might have started their search at the singleton location not because they could not suppress it, but because they needed to start somewhere and the singleton was as good a starting point as any. Almost all studies designed to examine automatic capture by salient singletons are designed so that the target is never the singleton (e.g., Theeuwes, 1992, 2004; Theeuwes & Burger, 1998; Wang & Theeuwes, 2020), avoiding these problems.

Given these shortcomings of the evidence in favor of the attentional window account, the previous evidence against this account, and the present results, the preponderance of evidence is strongly against this account, and instead favors the idea that salient singletons do not automatically and inevitably capture attention when they occur inside the window of attention.

Potential Limitations

A potential limitation of the present study is that the salient distractor was located at a task-irrelevant location between the inner and outer shapes. Thus, the salient distractor was located within the attended spatial region but not within the functionally relevant portion of the display. This is different from prior studies supporting the attentional window account (e.g., Theeuwes, 1992, 2004), where the salient distractor was both spatially and functionally tied to the attentional window. However, Theeuwes's attentional window account does not distinguish between spatial locations and functional relevance, so the present results are inconsistent with this account in its current form. Thus, at the very least, a major revision to the window account would be needed to explain the current findings.

The present study used the N2pc component to index attentional capture by the salient distractor in some experiments. The N2pc has been commonly used to evaluate whether a salient item captured attention (e.g., Gaspar et al., 2016; Gaspar & McDonald, 2014, 2018; Gaspelin & Luck, 2018a; Hickey et al., 2006; Lien et al., 2008, 2010; McDonald et al., 2013; Stilwell et al., 2022), but may not be a definitive measure of all forms of attentional allocation. Some studies have suggested that N2pc instead represents an attentional engagement process rather than directly measuring orienting (Goller et al., 2020; Mazza & Caramazza, 2011; Tan & Wyble, 2015; Zivony et al., 2018). In the present study, conclusions on attentional capture were thus never drawn based on the N2pc alone but were always supplemented with behavioral evidence. Control conditions also confirmed that an N2pc could be detected when the salient stimulus was a search target. Future research might focus on additional indices of attentional capture, such as eye movements, to provide converging evidence for the claims made here.

The P_D Component

Our ERP experiments were designed to use the N2pc component to determine whether attention was focused on the color singletons. However, in many cases, the absence of attentional capture by color singletons is the result of a process that suppresses the singletons (Gaspelin et al., 2015, 2017; Ma & Abrams, 2025; Stilwell & Gaspelin, 2021), and this suppressive process typically elicits a distractor positivity (P_D) component (Gaspar & McDonald, 2014b; Gaspelin, Lamy, et al., 2023; Gaspelin & Luck, 2018a; Hickey et al., 2009; Jannati et al., 2013; Sawaki & Luck, 2010). We therefore conducted exploratory analyses of the present data to assess the magnitude of any contralateral positivity during the period prior to the N2pc component.

Experiments 1 and 3 showed small contralateral positive voltages and Experiment 5 showed no positive deflection between 100–200 ms. Due to the small and inconsistent effects, it seems unwarranted to conclude that they reflect suppressive signals of salient distractors. Similar kinds of contralateral positivities following stimulus onset have also been interpreted as reduced adaptation of the P1 component for the singleton color (Luck & Hillyard, 1994b) or the presence of salience signals due to stimulus imbalance between hemifields (Barras & Kerzel, 2016, 2017; Corriveau et al., 2012; McDonald et al., 2023). A unique attribute of the P_D that distinguishes it from the other explanations is that it is only observed when the salient stimulus was the to-be-ignored distractor, but not when it was the target (e.g., as in Gaspelin & Luck, 2018a, Experiment 3). However, in our Experiments 1 and 3, the singleton-search condition also showed an early positivity between 50–100 ms, similar in magnitude to the diffuse or focused attention conditions, which was gradually attenuated between 100–200 ms influenced by the subsequent N2pc. Therefore, it seems unlikely that the early positivity in the current study reflects suppression, per se.

Why might suppression be absent in the current task? This might be explained by the differences between our shape-discrimination task and typical visual search tasks. First, unlike the present study, prior studies showing significant P_D components typically used visual search tasks that allowed free allocation of attention to subsets of the display, rather than forced spreading of attention across all items (e.g., Gaspelin & Luck, 2018a; Sawaki & Luck, 2010). The lack of a need to shift attention away from salient distractors might explain the absence of

P_D components in the present experiments. Second, search tasks typically involve maintaining a feature-based target template (e.g., the color green), which facilitates suppression of distractors defined by opposing features (e.g., red). In contrast, our shape-discrimination task does not require the formation of such a template, potentially weakening feature-based suppression mechanisms. In any case, the current study still provides a direct test of the attentional window account, which predicts that bottom-up capture by salient distractors is involuntary in nature and should be enabled by diffusely spreading attention.

Conclusion

Previous studies on attentional capture led to a debate about whether cases in which salient items fail to capture attention can be explained by control processes or by a small attentional window. The present study tested the predictions of the attentional window account by directly manipulating the breadth of attention and testing how this influenced capture by salient distractors. By measuring ERP and behavioral indices of capture, we found no capture by the salient distractor regardless of whether it appeared inside the attentional window. The findings provide evidence against the attentional window account and instead suggest that control signals can be used to avoid capture by salient-but-irrelevant stimuli.

Author Contribution Statement

XM: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, visualization, writing-original draft preparation, writing-review & editing

SJL: Conceptualization, methodology, validation, writing-review & editing

NG: Conceptualization, formal analysis, funding acquisition, investigation, methodology, resources, supervision, validation, writing-original draft preparation, writing-review & editing

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