

Salience Effects on Attentional Selection Are Enabled by Task Relevance

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Abstract

Attention is a limited resource that must be carefully controlled to prevent distraction. Much research has demonstrated that distraction can be prevented by proactively suppressing salient stimuli to prevent them from capturing attention. It has been suggested, however, that prior studies showing evidence of suppression may have used stimuli that were not truly salient. This claim has been difficult to test because there are currently no agreed-upon methods to demonstrate that an object is salient. The current study aims to help resolve this by introducing a new technique to test the role of salience in attentional capture. Low- and high-salience singletons were generated via a manipulation of color contrast. An initial experiment then verified the manipulation of salience using a search task where the color singleton was the target and could only be found via its bottom-up popout. High-salience singletons were found much more easily than low-salience singletons, suggesting that salience powerfully influenced attention when task relevant. A following experiment then used the same stimulus displays, but adapted the task so that the singletons were task-irrelevant distractors. Both low- and high-salience singletons were suppressed, suggesting neither was able to capture attention. These results challenge purely stimulus-driven accounts by showing that improving salience only enhances attentional allocation in situations where the object is also task relevant. The results are instead consistent with the signal suppression hypothesis, which predicts that task-irrelevant singletons can be suppressed.

Keywords

Attention
Attentional Capture
Salience
Suppression
Visual Search

INTRODUCTION

Salience Effects on Attentional Selection Are Enabled by Task Relevance

Salient stimuli are commonly used in everyday life to alert people to important information. For example, a bright red light might be used to indicate an emergency exit or a stop signal at a busy traffic intersection.

Although we often assume salient warning signals are effective, research on whether salient stimuli have the power to automatically capture attention has been a topic of much debate. Some studies have shown that salient stimuli can capture attention (e.g., Theeuwes, 1992; Yantis & Jonides, 1984), whereas other studies have shown that salient stimuli can be ignored (e.g., Folk et al., 1992; Bacon & Egeth, 1994). This debate represents a major challenge toward developing a comprehensive model of visual attention.

Many studies have now suggested a resolution to this debate whereby salient stimuli can be proactively suppressed to prevent attentional capture (see review by Luck et al., 2021). However, it was recently claimed that prior studies supporting this account may have used stimuli that were not truly salient (Wang & Theeuwes, 2020). This claim has been difficult to rule out because there is no consensus on a metric to “prove” a manipulation of salience was successful (Bylinskii et al., 2019; Chang et al., 2021; Stilwell et al., 2023). The current study aims to help resolve this by introducing a new technique to test the role of salience in attentional capture. The basic approach involves comparing how improving salience influences attentional allocation in separate tasks where the object is either a task-relevant target or task-irrelevant distractor. As will be seen, we found that improving the salience of an object can massively improve its attention-attracting power, but only when it is also task relevant.

The Attentional Capture Debate

Traditionally, the field of attentional capture was divided into two competing accounts. *Stimulus-driven accounts* claimed that salient stimuli would automatically capture attention, even if task-irrelevant (Theeuwes, 1992; Yantis & Jonides, 1984). For example, Theeuwes (1992) used an *additional singleton paradigm* in which participants were tasked with locating a circle amongst diamonds and reporting the orientation of the line inside of it. On half of trials, one of the distractor items was uniquely colored compared to the other items (*a color singleton*). Response times (RTs) were slower when the singleton was present than when it was absent. This singleton-presence cost was interpreted as evidence that attention was automatically allocated to the singleton distractor, slowing the detection of the target. Later studies provided additional evidence for these accounts by showing that shifts of gaze were biased toward color singletons in a similar task (e.g., Theeuwes et al., 1998).

Goal-driven accounts, however, claimed that salient stimuli have no inherent power to attract attention and that only stimuli with features matching the target are capable of capturing attention (Folk et al., 1992). To explain the aforementioned evidence of stimulus-driven capture in the additional singleton paradigm, Bacon and Egeth (1994) noted that the target was itself a feature singleton in these tasks. This

might encourage participants to adopt a broad attentional set for any feature singleton, making them vulnerable to capture by a color singleton, which they called *singleton-detection mode*. To provide evidence of this, they adapted the task to encourage *feature-search mode* by introducing additional unique forms on some trials to force participants to search for the specific target shape. The results showed that singleton presence costs were eliminated, which was taken to suggest that top-down selectivity can prevent salient stimuli from capturing attention (Becker, 2007; Becker et al., 2010; Cosman & Vecera, 2013; Fukuda & Vogel, 2011; Leber & Egeth, 2006).

The Signal Suppression Hypothesis

The *signal suppression hypothesis* attempts to resolve this debate by proposing that salient stimuli have an automatic power to attract attention, consistent with stimulus-driven models; but that this capture can be prevented via a top-down inhibitory mechanism, consistent with goal-driven models (Gaspelin & Luck, 2018a, 2019; Sawaki & Luck, 2010). Thus, the signal suppression hypothesis is a hybrid account with components of both stimulus-driven and goal-driven accounts.

One line of evidence for the signal suppression hypothesis has come from studies of shifts of gaze (Gaspelin et al., 2017). In an initial control experiment, participants searched for a target that was a shaped singleton in a homogeneous array of distractors (e.g., a diamond amongst many circles), encouraging singleton-detection mode. Shifts of gaze were directed to singleton distractors above baseline levels, indicating they captured attention. Importantly, when the task was adapted to prevent singleton-detection mode by having participants search for a specific target shape amongst heterogeneously shaped distractors (e.g., a diamond amongst circles, squares, and hexagons), shifts of gaze were directed to the singleton distractor below the baseline level of nonsingleton distractors. This *oculomotor suppression effect* was taken to suggest that salient distractors could be suppressed as long as they were task irrelevant (see also Gaspelin & Luck, 2018b, 2019; Hamblin-Frohman et al., 2022; Stilwell et al., 2023).

The signal suppression hypothesis has been further supported in many other ways. For example, many studies using event-related potentials (ERPs) have indicated that color singletons elicit a P₀ component and no corresponding N2pc component,

which suggests they can be suppressed to prevent capture (see review by Gaspelin et al., 2023; Drisdelle & Eimer, 2023; Gaspar & McDonald, 2014; Sawaki & Luck, 2010; Stilwell et al., 2022; Tam et al., 2022). Other studies provided psychophysical evidence using probe techniques to show the information at singleton distractor locations is recalled below the baseline level of other objects in the display (Chang & Egeth, 2019, 2021; Gaspelin et al., 2015; Ma & Abrams, 2023b). More recent evidence has suggested that participants learn how to suppress singleton distractors by gaining experience with their specific locations and/or features (Adam et al., 2021; Gaspelin & Luck, 2018b; Lien et al., 2022; Stilwell et al., 2019; Vatterott & Vecera, 2012; Wang & Theeuwes, 2018). Distractor suppression also seems to occur, at least under certain circumstances, by learning to anticipate the general presence of salient distractors irrespective of their features or locations (Ma & Abrams, 2023a; Won, 2021; Won & Geng, 2020).

The Low-Salience Account of Suppression

Although there has been much evidence for the signal suppression hypothesis, this account has been recently criticized on the grounds that prior studies may have relied on salient distractors that were not truly salient (Theeuwes, 2004; Wang & Theeuwes, 2020). According to this low-salience account, prior studies of signal suppression used relatively small display sizes (e.g., four items), and this may have rendered color singletons that were relatively weak in salience. If the salience of the distractor is improved, according to this account, the salient distractor might be able to overpower suppression and capture attention. As evidence for this, Wang and Theeuwes (2020) used a letter-probe task that was similar to prior studies of signal suppression (e.g., Gaspelin et al., 2015), but manipulated the display size from four to ten items. At display-size four, the singleton was successfully suppressed. At display-size ten, however, this effect was (slightly) reversed, suggesting that singleton distractor (weakly) captured attention. This was taken as evidence that, if singleton is strongly salient, it will automatically capture attention, aligning with stimulus-driven accounts.

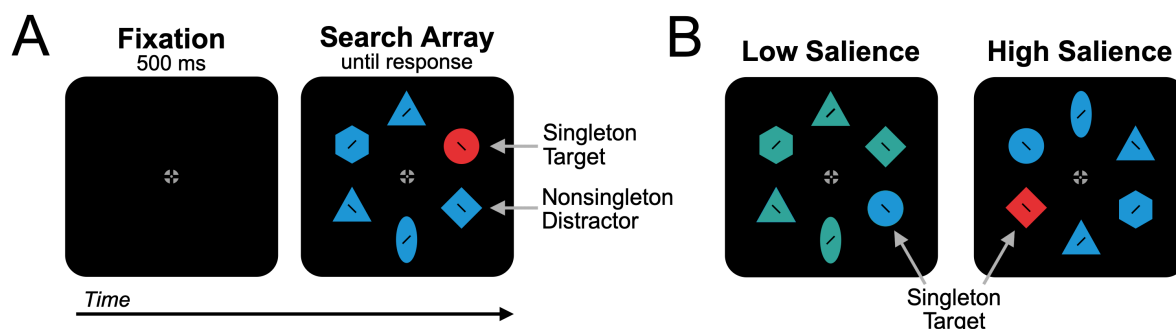
There are many reasons to doubt the low-salience

account. First, Stilwell and Gaspelin (2021) showed that the results of Wang and Theeuwes (2020) were likely due to a kind of design flaw that encouraged a floor effect on the probe report. When corrected by limiting the number of probed items, suppression was observed even at exceptionally high display sizes. Additionally, there has been evidence from ERPs showing that color singletons produce a PD component even at high display sizes, suggesting they can be suppressed (Gaspar & McDonald, 2014; Sawaki & Luck, 2010; Stilwell et al., 2022). Nonetheless, the study of Wang and Theeuwes has sparked much recent debate about the role that salience plays in suppression and there have been many different perspectives in the issue (e.g., Chen et al., 2023; Constant & Liesefeld, 2021; Drisdelle & Eimer, 2023; Lien et al., 2022; Moher et al., 2015; Ramgir & Lamy, 2022; Stilwell & Gaspelin, 2021; Zhang et al., 2024).

An important limitation of prior studies on this topic is that most included no measure of salience or any verification that the manipulation of salience was successful. This makes it challenging to definitively test the predictions of the low-salience account. Any time that capture is not observed by a salient distractor, proponents of the low-salience account could simply argue that the distractor was not salient enough. Furthermore, without a measure of salience, it is impossible to know how potent a manipulation of salience was or how the salience of stimuli in one study compares to those used in another. This will make understanding the role of salience in suppression difficult, if not impossible, to resolve.

We recently introduced a new psychophysical technique to compare the salience of stimuli (Stilwell et al., 2023).¹ Low- and high-salience color singletons were generated via manipulation of color contrast with other objects in the display. For example, a high-salience singleton might be a red singleton amongst blue items, whereas a low-salience singleton might be a teal singleton amongst blue items. To verify the manipulation of salience was successful, we used an *oddball detection task* in which participants attempted to detect a color singleton in briefly presented displays that were immediately masked. The color of the singleton randomly alternated so that it had to be detected based upon its bottom-up popout alone. A staircasing procedure was used to adjust the duration

¹ This technique was originally suggested by Jan Theeuwes in Wöstmann et al. (2022) as a method to empirically demonstrate that a distractor is salient (see Rule #1).

Figure 1*Task and Stimuli for Experiment 1*

(A) Participants searched for a target that was a color target. Because the shape and color of the singleton target were unpredictable, the target had to be found solely based upon its color popout (i.e., its bottom-up salience). (B) Low- and high-salience singletons were created by manipulating the color contrast between the singleton and other display items.

of the displays to estimate the minimum duration at which a singleton could be reliably detected (*an exposure threshold*). The underlying logic was that, as a singleton becomes more salient, it should be more easily detected, resulting in a lower exposure threshold. Indeed, exposure thresholds were lower for high-salience singletons than low-salience singletons, suggesting that the high-salience popout was more easily detected. Critically, when the same displays were then used in a task where the salient stimuli were distractors that needed to be ignored (similar to Gaspelin et al., 2017), high-salience distractors were easier to ignore than low-salience distractors. This provided evidence against the low-salience account of suppression by showing that an empirically validated improvement of salience did not necessarily lead to attentional capture.

The Current Study

As reviewed above, the oddball detection task is a new psychophysical technique that can be used to compare the salience of feature singletons. The present study will build upon this prior work by further testing the low-salience account with a new technique that relies on oculomotor behavior, rather than detection thresholds, to assess the role of salience in attentional capture. Although the oddball detection task of Stilwell et al. demonstrated that a manipulation of salience influenced the detectability of a singleton, it did not demonstrate that a manipulation of salience led to

differences in attentional guidance, per se. The current study will therefore use oculomotor measures to show that the same manipulations of salience can also influence overt attentional guidance. Specifically, we will show that improving salience does increase attentional selection of a task-relevant target; but that this does not improve attentional capture by that same object in a separate task where it is task irrelevant. In addition, the oculomotor measures provide fine-grained information about the time course of guidance.

Color singletons were generated with two levels of salience manipulated via color contrast (Figure 1B), similar to Stilwell and colleagues (2023). The task relevance of the color singleton was manipulated across two experiments. Experiment 1 tested whether increasing the salience of the singleton would improve its ability to be found in a search display when it served as the target. If the manipulation of salience was successful, the high-contrast targets should be easier to find than low-contrast targets, which should lead to a higher percentage of initial shifts of gaze being directed to the target. Analogous approaches have been used by some previous studies to investigate the role of salience in target detection (e.g., Becker & Ansorge, 2013; Rangelov et al., 2017; Zehetleitner et al., 2013). Experiment 2 then used the same stimuli to test how color singletons could be ignored in a task where they were an irrelevant distractor. This allowed us to test whether the previous manipulation of salience would influence involuntary attentional capture. As will be seen, although we found that

salience powerfully influenced the ability to find target stimulus, the same exact salience manipulation did not make singletons more difficult to ignore when they were task-relevant distractors.

EXPERIMENT 1

Experiment 1 was a control experiment to demonstrate that the salience manipulation was successful at improving target detection. Participants searched for a target that was defined solely by its status as a color singleton while shifts of gaze were recorded (Figure 1A). Importantly, the color and shape of the target randomly alternated on each trial, meaning the target had to be found based upon its bottom-up popout, and could not be found by using top-down goals for a specific color or shape. Salience was varied by manipulating the color contrast between the singleton target and other display items (Figure 1B). Low-salience singletons were generated by using two colors that were nearby in color space (e.g., teal, and blue). High-salience singletons were generated by using two colors that were far in color space (e.g., blue, and red).

If the manipulation of salience was successful, the high-salience targets should be easier to find than the low-salience targets. This should result in faster manual RTs for high-salience targets than low-salience targets. Furthermore, initial shifts of gaze should be more likely to be directed to high-salience targets than low-salience targets. Specifically, we will compare how much more likely shifts of gaze are to be directed to the target than other search items in the displays (*a target enhancement effect*) as a function of salience.

Method

Participants Twenty-four students from the University of Missouri participated for payment of \$12 per hour (9 men and 15 women, $M_{\text{age}} = 18.7$ years). The sample size was determined a priori based upon a previous study using a similar paradigm and salience manipulation (Stillwell et al., 2023). Assuming the target enhancement effects are similar in strength to the exposure thresholds ($d_z = 1.71$), seven participants would be needed to obtain 95% power to detect a difference between salience conditions. We collected more participants to err on the side of caution and match the sample sizes of previously published studies using similar oculomotor search tasks (e.g., Adams et al., 2023; Adams & Gaspelin, 2021; Gaspelin et al.,

2017, 2019; Gaspelin & Luck, 2018b; Talcott & Gaspelin, 2020).

All participants had normal color vision as indicated by an Ishihara test and had normal or corrected-to-normal visual acuity as evaluated by a Snellen chart. The current study had a target population of local undergraduates from the University of Missouri. Demographic information beyond age and gender was not collected. It is therefore possible that the current results may not apply to all populations. The research protocol was approved by the local ethics board at the University of Missouri.

Apparatus Stimuli were presented using PsychToolbox for Linux (Brainard, 1997). An Asus VG248QG LED monitor presented stimuli against a black background at a viewing distance of 100 cm in a dimly lit room. A photosensor was used to measure the timing delay of the video system (12 ms), and this delay was subtracted from all latency values in the paper. An SR Research Eye Link 1000+ desk-mounted eye tracker measured gaze position from the right eye at 500 Hz. The Eye Link Toolbox was used to interface the stimulus presentation and eye-tracking systems (Cornelissen et al., 2002).

Stimuli Twenty The search stimuli were based on Stillwell and colleagues (2023). As shown in Figure 1A, each search display comprised six shapes arranged in a notional circle at an eccentricity of 4.3° from the center of the screen, the shapes contained one diamond ($1.7^\circ \times 1.7^\circ$) and one circle (1.7° diameter). The remaining items could be hexagons ($1.7^\circ \times 1.7^\circ$), triangles (1.7° height and 1.7° base width), and ovals ($2.0^\circ \times 1.4^\circ$), and their shapes were randomly selected with the exception that no more than two instances of a given shape could be present in a given search display. The shapes were colored red (30.2 cd/m^2 , $x = .613$, $y = .312$), blue (30.2 cd/m^2 , $x = .190$, $y = .211$), pink (30.0 cd/m^2 , $x = .579$, $y = .293$), or teal (30.2 cd/m^2 , $x = .219$, $y = .317$). Each shape featured a small black line (0.2° long and 0.1° in thickness) tilted to a 45° angle. Each search display included an empirically optimized fixation cross positioned at the screen's center (Thaler et al., 2013), which consisted of a gray circle (30.2 cd/m^2 , $x = .290$, $y = .294$) with a diameter of 0.5° that contained a black crosshair with a gray dot measuring 0.1° in diameter.

The singleton target could be high- or low-salience (Figure 1B). These conditions were created by generating an isoluminant color wheel from CIE color

space ($L = 30.0$, radius = 90). Low-salience singletons were created by selecting a color that was 27° in color space from the nonsingleton color. This created four potential low-salience color singletons: a blue singleton amongst teal items, a teal singleton amongst blue items, a pink singleton amongst red items, or a red singleton amongst pink items. High-salience singletons were created by selecting a color that was 180° in color space from the nonsingleton color. This created four potential high-salience color singletons: a red singleton amongst blue items, a blue singleton amongst red items, a teal singleton amongst pink items, or a pink singleton amongst teal items.

Procedure The present experiment aimed to verify that the manipulation of salience was successful using a task where the color singleton was the target. Participants searched for a target that was defined solely by its status as a color singleton. Because the color and shape of the target were unpredictable, the target had to be found solely based upon the salience of its color pop-out. If it is more salient in one condition than another, the target should be easier to locate.

The shape of the target varied randomly on each trial and could be any of the potential shapes in the search display. Similarly, the color of the target varied randomly from any of the colors. The salience of the target (low or high) also varied randomly on each trial. The orientation of each line (left- or right-tilt) was randomly selected.

Each trial began with the fixation cross. To initiate the trial, participants had to maintain gaze within a circular region of 1.5° centered around the center of the screen for 500 ms. Once the fixation requirement was met, participants were asked to search for the singleton target (e.g., red hexagon) and report the orientation of the line (left or right tilted) inside the target via a speeded button press on a gamepad (i.e., left- and right- shoulder buttons respectively). The search array appeared until a response was made or until a 2,000 ms timeout. If the participants responded inaccurately or a timeout occurred, a 200-Hz tone sound and a prompt message showing “Wrong!” or “Too Slow!” were displayed for 300 ms before moving on to the subsequent trial. Feedback on mean accuracy and RT was provided at the end of each block. These block breaks also warned participants if their accuracy fell below 90%.

The experiment comprised 64 practice trials and 512 formal trials, organized into 9 blocks. Between each block, there was a break during which

participants were given feedback on response accuracy and speed. The eye tracker was recalibrated using a nine-point calibration before the start of a new block. During the task, the eye tracker was also recalibrated if a participant struggled to initiate a trial via a central fixation for more than 8 seconds.

First saccades were measured using methods that are similar to previous eye-tracking studies conducted in our lab (Adams et al., 2023; Adams & Gaspelin, 2021; Gaspelin et al., 2017, 2019; Stilwell et al., 2023; Talcott & Gaspelin, 2020). The onset of a saccade was determined by a minimum acceleration threshold of $9500^\circ/\text{sec}^2$ and a minimal eye velocity threshold of 30° per second. To categorize the destination of the first saccade on each trial, an annulus was defined, centered on the fixation cross, with an inner radius of 1.5° from fixation and an outer radius of 7.5° from fixation. The first eye movement landing within the annulus was identified as the first saccade and the nearest search item was then selected as the first saccade destination. This effectively creates wedge-shaped interest areas around each search (Gaspelin et al., 2017; Leonard & Luck, 2011). Saccadic latency was measured as the start time of the first saccade that landed within the annulus.

The first block was excluded from analysis as practice. Trials with RTs less than 200 ms or greater than 2000 ms were removed from analysis (0.3% of trials). Trials in which participants did not move their eyes from central fixation (0.2%) and trials with abnormal saccade latencies (less than 50 ms or greater than 1,000 ms, comprising 1.6% of trials) were also removed. Trials with incorrect responses (1.9%) were omitted from analyses. In total, 3.9% of trials were excluded. In all analyses of variance (ANOVAs) reported in this article, we report the Greenhouse–Geisser corrected p-value. All Cohen’s d for within-subjects t -tests are reported as d_z (Lakens, 2013).

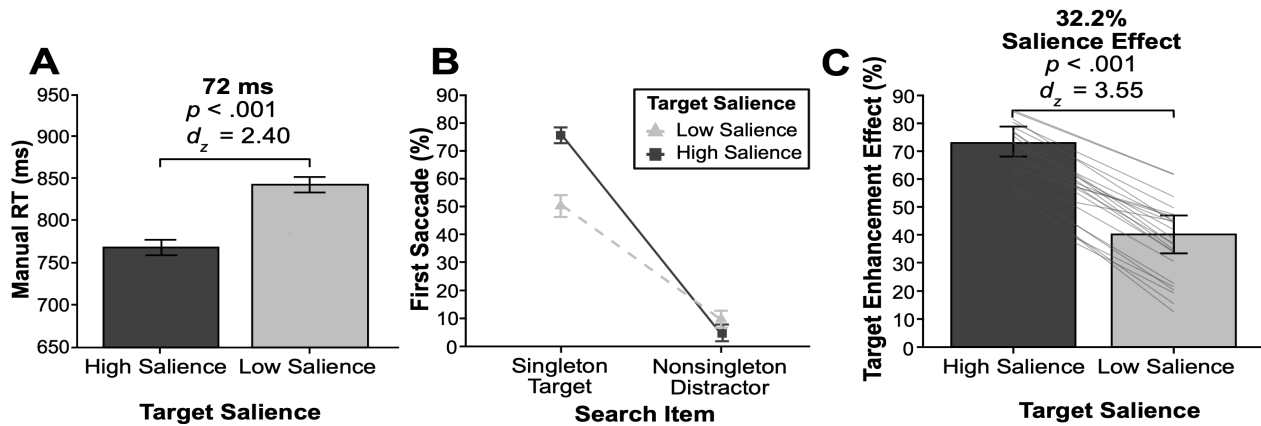
Transparency and Openness All data and stimulus presentation programs are available on the Open Science Framework (OSF.io) at <https://osf.io/kgs9v/>. This study was not preregistered and the data was collected in 2023.

Results

Manual Responses

Manual RTs were much faster when the target was a high-salience singleton (769 ms) than a low-salience singleton (841 ms), $t(23) = 11.74$, $p < .001$, $d_z = 2.40$

Figure 2
Results from Experiment 1



(A) Manual RT as a function of target salience. (B) The percentage of first saccades to each search item as a function of target salience. (C) Target enhancement effects for each level of target salience, which were calculated as difference score between the percentage of first saccades to the singleton target minus the nonsingleton distractor. For all panels, error bars represent within-subject 95% confidence intervals. The gray lines depict individual participants in panel C.

(Figure 2A). There were no significant differences in manual error rates for high-salience singletons (1.8%) and low-salience singletons (2.1%), $t(23) = .81$, $p = .43$, $d_z = .17$. Altogether, these results suggest the high-salience targets were much easier to find than the low-salience targets.

Saccadic Latency

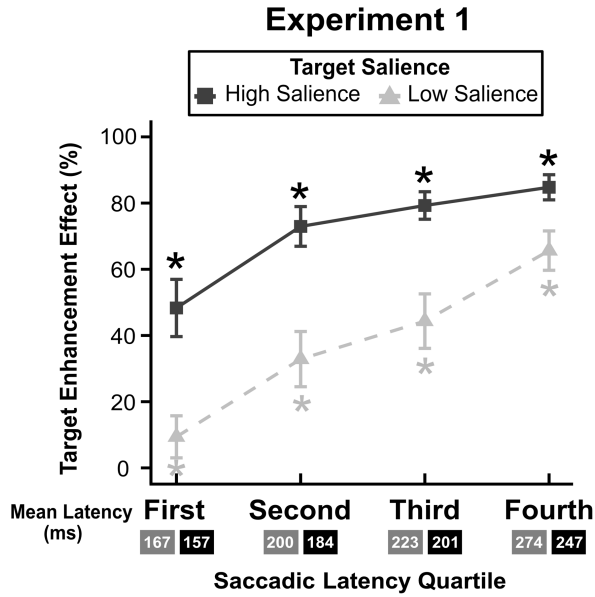
Saccadic latencies were faster for trials with high-salience targets (196 ms) than low-salience targets (215 ms), $t(23) = 10.62$, $p < .001$, $d_z = 2.17$. This is consistent with the notion that high-salience targets were easier to find than low-salience targets, resulting in faster initial shifts of gaze.

First Saccade Destination

We next assessed the destination of the first saccades to determine if the singleton target was more easily found when it was highly salient. We first calculated the percentage of first saccades to each search item: the singleton target and nonsingleton distractors (i.e., the nontarget items in the display). The percentage of saccades to the nonsingleton distractors has been divided by five to provide a per-item estimate of the probability of being fixated. The percentage of saccades to each item was calculated separately for low- and high-salience conditions. As shown in Figure 2B, first saccades were more likely to be directed to the singleton target than to the average nonsingleton

distractor in both low- and high-salience conditions. Importantly, this target enhancement effect was larger for high-salience targets than for low-salience targets. This pattern of results suggests that the high-salience targets were easier to find than the low-salience targets.

We computed *target enhancement effects* as a difference score between the percentage of first saccades to the singleton target minus the average nonsingleton distractor (Figure 2C). This difference score indicates how strongly first saccades were directed to the target, with a higher value meaning stronger guidance toward the target over the nonsingleton distractors. Target enhancement effects were computed separately for high- and low-salience targets. One-sample t tests were used to evaluate the significance of each target enhancement effect. Target enhancement effects were significant for both high-salience targets (72.2%), $t(23) = 31.46$, $p < .001$, $d_z = 6.72$ and low-salience targets (40.2%), $t(23) = 13.88$, $p < .001$, $d_z = 3.75$. Crucially, the target enhancement effects were significantly larger for high-salience targets than low-salience targets, $t(23) = 17.41$, $p < .001$, $d_z = 3.55$. These results provide evidence that the salience manipulation was successful: Making the target highly salient nearly doubled the strength of guidance toward the target stimulus.

Figure 3*Target Enhancement Effects by Saccade Quartile for Experiment 1*

Target enhancement effects as a function saccadic latency quartile for low- and high-salience targets in experiment 1. The mean saccadic latency for each quartile (low-salience/high-salience) is provided below the x-axis labels. Error bars represent within-subject 95% confidence intervals. * $p < .001$.

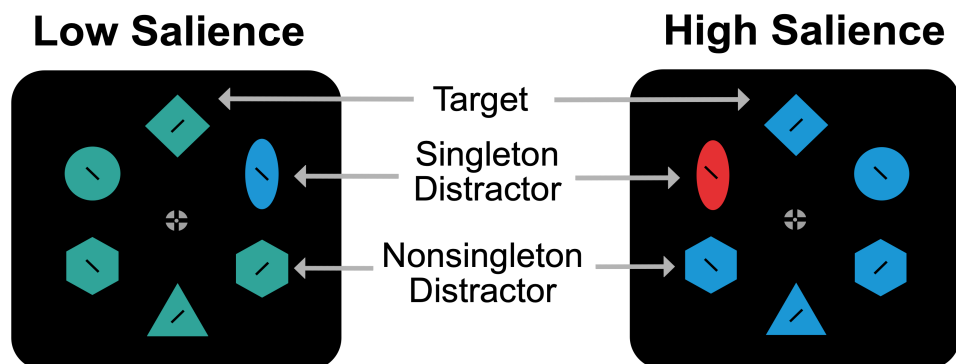
Target Enhancement Effects by Saccadic Latency Quartile

We also conducted an analysis to explore the time course of the target enhancement effects on saccade destination. The first-saccade destination data was divided into four quartiles of saccadic latency for each subject and target-salience condition. We then computed target enhancement effects using the percentage of first eye movements to each item type (as in the previous section). As shown in Figure 3, target enhancement effects generally increased with saccadic latency and were generally larger for high-salience targets than low-salience targets.

A two-way ANOVA was conducted on target enhancement effects with factors of target salience (low-salience, high-salience) and saccadic-latency quartile (first, second, third, fourth). There was a significant main effect of target salience, indicating that target enhancement effects were generally larger for high-salience targets than low-salience targets, $F(1, 23) = 296.07$, $p < .001$, $\eta_p^2 = .93$. There was also a

significant main effect of saccadic-latency quartile, indicating that target enhancement effects gradually strengthened over time (i.e., at later quartiles), $F(3, 69) = 172.36$, $p < .001$, $\eta_p^2 = .88$. Moreover, there was a significant interaction effect of target salience and saccadic-latency quartile indicating that the difference in target enhancement effects between low- and high-salience targets was larger at the fastest quartile than the slowest quartile, $F(3, 69) = 12.49$, $p < .001$, $\eta_p^2 = .35$. One-sample t -tests were conducted to assess whether each target enhancement effect was significantly greater than zero. High-salience targets led to a significant target enhancement effect in all saccadic latencies (p 's $< .001$), including the fastest quartile ($M = 157$ ms). Low-salience targets also led to a significant target enhancement effect in all saccadic latencies (p 's $< .001$), including the fastest quartile ($M = 167$ ms). Altogether, this analysis further suggests that high-salience targets were easier to find based upon their popout than low-salience targets, especially at faster saccadic latencies.

Figure 4
Stimuli and Task from Experiment 2



Search stimuli were identical to Experiment 1, except that the color singleton was now a task-irrelevant distractor. This allowed us to assess whether high- and low-salience singletons would automatically capture attention.

Discussion

Experiment 1 verified the salience manipulation in a control task where the color singletons were task relevant. Participants performed a search task where they looked for a salient color singleton. Importantly, the color of the singleton was unpredictable, meaning the singleton could not be found using top-down guidance for a specific color. Instead, the target had to be found solely based upon its bottom-up salience. If the salience manipulation was successful, high-salience singletons should be easier to find than low-salience singletons. The results were clearly consistent with this prediction. Manual RTs and saccadic latencies were shorter for high-salience targets than low-salience targets, suggesting they were easier to find. Additionally, shifts of gaze were more likely to be directed to high-salience targets than low-salience targets, even at the fastest quartile of eye movements. These results confirm that salience can strongly affect attentional guidance when salience is made task relevant.

distractor, not the target (similar to Gaspelin et al., 2017; Stilwell et al., 2023). Participants searched for a target object that was a specific color and shape (e.g., a blue diamond). On some trials, a color singleton appeared as a distractor and could never be the target. The key question was whether the singleton distractor would involuntarily capture attention due to its salience.

According to the *low-salience account*, which is a subvariant of a stimulus-driven account, salient stimuli automatically capture attention even when they are task irrelevant (Theeuwes, 2010, 2018, 2023). This account, therefore, predicts that saccades should be involuntarily directed toward the salient distractor, and this capture should increase when the singleton distractor is more salient. Simply put, high-salience distractors should capture attention more strongly than low-salience distractors. According to the signal suppression hypothesis, however, salient distractors can be suppressed to prevent capture (Gaspelin et al., 2017; Gaspelin & Luck, 2018a, 2019, 2021). This means that shifts of gaze should be preferentially directed away from the salient distractor, even when it is highly salient (a distractor suppression effect).

EXPERIMENT 2

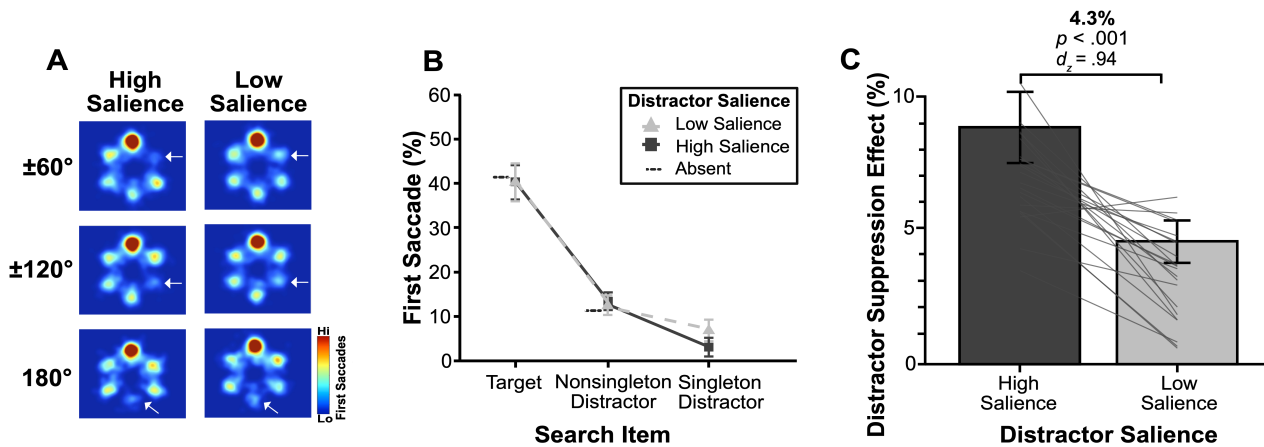
Experiment 2 tested how salience influences the ability to ignore task-irrelevant distractors. The search displays and salience manipulation were identical to Experiment 1 (see Figure 4). The only difference is that the task was modified so that the color singleton was a

Method

The methods were identical to Experiment 1 except as follows.

A new set of 24 students from the University of Missouri participated (8 men and 16 women, $M_{\text{age}} = 18.9$ years). The sample size was determined based on

Figure 5
Results from Experiment 2



(A) Heat maps of first saccades as a function of distractor salience and angular distance between the target and singleton distractor. The heat maps were generated so that the target was always at the top position and the white arrow pointed to the singleton position. (B) The percentage of first saccades to each search item as a function of distractor salience. (C) Distractor suppression effects as a function of distractor salience. Error bars represent within-subject 95% confidence intervals. * $p < .001$. The gray lines depict individual participants in panel C.

the effect size ($d_z = 1.05$) of oculomotor suppression in Stilwell et al. (2023). Fourteen participants would be needed to obtain 95% power to detect the distractor suppression effect. No participants were removed as outliers.

The search displays were identical to Experiment 1, but the task was adapted so that the color singleton was a distractor as in prior studies of signal suppression (e.g., Adams et al., 2023; Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018b; Stilwell et al., 2023). A target shape and target color were assigned at the beginning of the experiment (e.g., blue diamond). This target shape appeared amongst heterogeneous distractors, which was meant to encourage feature-search mode (Bacon & Egeth, 1994; Leber & Egeth, 2006). The target shape was counterbalanced across participants, a diamond for half of the participants and a circle for the other half. Additionally, the specific target color was counterbalanced across participants as blue, teal, pink, or red. The singleton color was determined as the high-salience or low-salience color for the respective target color. For example, for a blue-target experiment, the high-salience singleton would be red, and the low-salience singleton would be teal. On each trial, the location of the target and singleton

distractor were selected at random, with the constraint that the target could never be a singleton. In addition, the singleton distractor was randomly selected as either high-salience, low-salience, or absent with an equal probability. The experiment consisted of 60 practice trials and 480 formal trials, organized into 9 blocks.

As in Experiment 1, the first block was excluded from analysis as practice. Trials with RTs less than 200 ms or greater than 2000 ms were removed from analysis (0.9% of trials). Trials in which participants did not move their eyes from central fixation (0.3%) and trials with abnormal saccade latencies (less than 50 ms or greater than 1,000 ms, comprising 3.0% of trials) were also removed. Trials with incorrect responses (2.0%) were omitted from analyses. In total, 6.0% of trials were excluded.

Results

Manual Responses

If the singleton captures attention, manual RTs should be slower on singleton-present trials than singleton-absent trials (Theeuwes, 1992). If anything, the pattern of results was in the wrong direction as these predicted

results (see also Chang & Egeth, 2019; Gaspelin et al., 2017). Manual RTs were not significantly different for singleton-absent trials (926 ms) for both high-salience singleton (919 ms), $t(23) = 1.22$, $p = .23$, $d_z = .25$, or low-salience singleton (918 ms), $t(23) = 1.73$, $p = .097$, $d_z = .35$. Manual error rates were generally quite low and were not significantly different for singleton-absent trials (2.0%) for both high-salience singleton (2.2%), $t(23) = .61$, $p = .55$, $d_z = .12$ or low-salience singleton (2.2%), $t(23) = .52$, $p = .61$, $d_z = .11$.

Saccadic Latency

Saccadic latencies were not significantly different for singleton-absent trials (213 ms) for both high-salience singleton (213 ms), $t(23) = .05$, $p = .96$, $d_z = .01$, or low-salience singleton (214 ms), $t(23) = .63$, $p = .54$, $d_z = .13$. This suggests that the presence of the singleton did not slow eye movements.

First Saccade Destination

The primary question was how salience would influence the ability to ignore a singleton that was task irrelevant. Figure 5A depicts heat maps of first saccades for each potential target-singleton angular distance. Heat maps were plotted so that the target always appeared at the top position and the singleton location is indicated by a white arrow. For -60° and -120° , the heat maps were adjusted (by inverting the x-axis) so that they could be pooled with the positive angular distances. As can be seen, first saccades were preferentially directed away from the singletons consistent with prior studies of signal suppression (Gaspelin et al., 2017). If anything, high-salience distractors were suppressed more strongly than low-salience singletons (Stilwell et al., 2023).

To formally analyze this, first saccades were pooled across all angular distances. The percentage of first saccades to each search item (target, nonsingleton distractors, singleton distractors) was computed for both salience conditions. The nonsingleton distractor was divided by the number of nonsingleton distractors to provide a per-item estimate of the probability of being fixated (i.e., divided by 4 when the singleton distractor was present and divided by 5 when the singleton was absent). As shown in Figure 5B, first saccades were less likely to be directed to the singleton distractor than to the average nonsingleton distractor in both low- and high-salience distractor conditions (for similar results, see Gaspelin et al., 2017; Stilwell et al., 2023).

Distractor suppression effects were computed as

a difference score of the percentage of first saccades to the average nonsingleton distractor minus the percentage of first saccades to the singleton distractor (Figure 5C; as in Gaspelin et al., 2017; Gaspelin & Luck, 2018b). One-sample t tests were used to evaluate the significance of each distractor suppression effect. Distractor suppression effects were significant for both low-salience distractors (4.6%), $t(23) = 9.59$, $p < .001$, $d_z = .41$, and high-salience distractors (8.9%), $t(23) = 11.03$, $p < .001$, $d_z = .79$. Crucially, the suppression effect was significantly larger for high-salience distractors than low-salience distractors, $t(23) = 4.60$, $p < .001$, $d_z = .94$. This result is in the wrong direction as that predicted by the low-salience accounts, which would seem to predict weaker suppression of the high-salience distractor. The results are instead consistent with an account whereby high-salience distractors are easier to quickly detect and ignore (see also Stilwell et al., 2023).

Distractor Suppression Effects by Saccadic Latency Quartile

To assess the time course of suppression, first-saccade destination data was divided into four quartiles of saccadic latency for each subject and distractor-salience condition. We then computed distractor suppression effects for each quartile and salience condition. As shown in Figure 6, distractor suppression effects increased with saccadic latency and were larger for high-salience distractors than low-salience distractors.

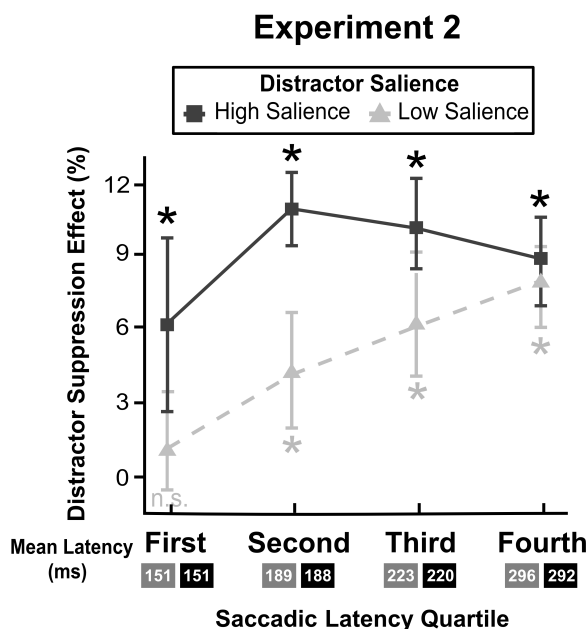
A two-way ANOVA was conducted on distractor suppression effects with factors of distractor salience (low-salience, high-salience), and saccadic-latency quartile (first, second, third, fourth). There was a significant main effect of distractor salience, indicating that distractor suppression effects were larger for high-salience distractors at every quartile, $F(1, 23) = 21.34$, $p < .001$, $\eta_p^2 = .48$. There was a significant main effect of saccadic-latency quartile, indicating that distractor suppression effects gradually strengthen over the time course as the process unfolds, $F(3, 69) = 5.18$, $p = .003$, $\eta_p^2 = .18$. There was a nonsignificant interaction effect of distractor salience and saccadic-latency quartile, $F(3, 69) = 2.19$, $p = .097$, $\eta_p^2 = .09$.

Moreover, preplanned one-sample t tests assessed the significance of the oculomotor suppression effect at each level of salience and saccadic quartile. For high-salience distractors, oculomotor suppression effects were significant at all

quartiles (p 's < .001), including the fastest quartile ($M = 151$ ms). This suggests that the high-salience

Figure 6

Distractor Suppression Effects by Saccade Quartile for Experiment 2



Distractor suppression effects as a function saccadic latency quartile for low- and high-salience distractors in experiment 2. The mean saccadic latency for each quartile (low-salience/high-salience) is provided below the x-axis labels. Error bars represent within-subject 95% confidence intervals. * $p < .001$.

distractor was rapidly detected and ignored. For low-salience distractors, however, oculomotor suppression effects were nonsignificant in the first quartiles ($M = 151$ ms; $t(23) = .70$, $p = .49$, $d_z = .17$), and were significant only in later quartiles (p 's < .001). In short, distractor suppression effects were greater for high-salience distractors than low-salience distractors and were significant even in the fastest quartile of eye movements. This is also consistent with the idea that high-salience distractors were more effectively suppressed than low-salience distractors.

Discussion

Experiment 2 assessed how salience influences the ability of a task-irrelevant distractor to involuntarily capture attention. The displays were identical to Experiment 1, except that the color singleton was made a distractor that participants attempted to ignore. According to the low-salience account, salient stimuli will automatically capture attention, and this capture

should increase as the distractor becomes more salient. The results were inconsistent with this claim. High-salience distractors were more strongly suppressed than low-salience distractors, replicating many previous studies (see also Stilwell et al., 2023; Drisdelle & Eimer, 2023; Moher et al., 2015; Gaspar & McDonald, 2014). Importantly, the lack of capture cannot be attributed to an unsuccessful salience manipulation because Experiment 1 showed the same stimuli produced a robust salience effect when the singletons were task relevant. The results are instead consistent with models that propose top-down control can be used to prevent salient stimuli from capturing attention, such as the signal suppression hypothesis (Gaspelin & Luck, 2018a).

GENERAL DISCUSSION

There has been an ongoing debate about the role of salience in attentional capture. Much recent evidence

has suggested a potential resolution whereby salient distractors can be suppressed to mitigate distraction (Luck et al., 2021; Gaspelin & Luck, 2021). However, it has now been suggested that the distractors used in prior studies of signal suppression may have been lacking in salience. According to this low-salience account, boosting the salience of a distractor will lead it to involuntary capture in line with stimulus-driven accounts (Wang & Theeuwes, 2020). Since this claim, there has been much dispute about the role of salience in the suppression of distracting stimuli (Chang et al., 2021; Chang & Egeth, 2021; Drisdelle & Eimer, 2023; Lien et al., 2022, 2022; Ramgir & Lamy, 2022; Stilwell et al., 2022, 2023; Stilwell & Gaspelin, 2021). Although there has been some evidence against the low-salience account, it has been difficult to test because there are not widely accepted methods to empirically verify a salience manipulation. For this reason, some prior studies have attempted to introduce methods to evaluate salience using computational models (Chang et al., 2021) or psychophysical metrics (Stilwell et al., 2023). Although promising, it remains unclear how these metrics, which are based upon low-level image statistics or perceptual detection thresholds, may be related to attentional allocation, *per se*. The present study builds upon this prior research by using oculomotor behavior during visual search to evaluate whether a manipulation of salience has the potential to influence attentional allocation.²

Search displays were generated with low- and high-salience singletons via manipulation of color contrast (similar to Stilwell et al., 2023). We then compared the effect of salience as a function of task relevance in a search task that measured shifts of gaze. In Experiment 1, the singleton was task relevant in that it was the search target. Importantly, the color of the target varied randomly on each trial, preventing participants from searching for a specific color and forcing them to search for the target via its bottom-up salience. Shifts of gaze were more likely to be directed to the salient target than nonsingleton distractors. Importantly, these target enhancement effects were larger for high-salience targets than low-salience targets. This basic salience effect occurred in all quartiles of eye movements but was especially

pronounced in the fastest quartile. Altogether, these results indicate that the manipulation of salience was successful and greatly improved attentional guidance to a task-relevant object.

Experiment 2 used the same stimuli as Experiment 1, but adapted the task so that the color singleton was task irrelevant. Participants searched for a target defined by shape and attempted to ignore a singleton distractor. This allowed us to investigate how the same manipulation of salience would influence involuntary attentional capture. Both high-salience and low-salience distractors were suppressed. In fact, oculomotor suppression effects were larger for high-salience distractors than low-salience distractors (see also Stilwell et al., 2023). Furthermore, an analysis of suppression effects by saccadic latency showed that suppression for high-salience singletons occurred even in the fastest quartiles (151 ms), whereas suppression of low-salience singletons only occurred in slowest quartiles (189 ms). Altogether, these results indicate that low-salience singletons were not suppressed as effectively as high-salience singletons. In other words, high-salience singletons were easier to ignore.

The results challenge the low-salience account of distractor suppression, which proposes that improving a distractor's salience should make it more difficult to ignore (Wang & Theeuwes, 2020). In Experiment 1, the salience manipulation greatly improved how easily the target could be found; but this same manipulation did not cause the salient object to capture attention in Experiment 2. Instead, the exact opposite occurred: high-salience distractors were easier to ignore than low-salience distractors. The results are instead consistent with models of attention contending that top-down goals can be used to prevent distraction (Bacon & Egeth, 1994; Folk et al., 1992). Specifically, the results demonstrate that salient distractors can be proactively suppressed to prevent them from capturing attention, as predicted by the signal suppression hypothesis (Gaspelin & Luck, 2018c).

The current results complement prior studies that have investigated the role of salience in distractor suppression. Most notably, Stilwell and colleagues (2023) used an oddball detection task which also found evidence that the same manipulation of salience via color contrast led to improved detection of high-

² It is important to highlight that we are not proposing these measures are a direct measure of salience, *per se*. Salience is a psychological phenomenon that occurs as a result of cognitive processes that compare low-level features of neighboring objects in early visual processing (Nothdurft, 1993). Salience is not a physical property of stimuli and therefore cannot be directly measured. For this reason, many previous studies have used attentional impacts and other approaches to indirectly measure salience (e.g., Becker & Ansorge, 2013; Rangelov et al., 2017; Stilwell et al., 2023; Zehetleitner et al., 2013).

salience singletons in an oddball detection task. That is, high-salience singletons were detected more rapidly (ca. 46 ms) than low-salience singletons (ca. 93 ms). The current study expands upon this finding showing that this rapid detection of singletons can then be used to influence attentional guidance. We propose that salient objects can be more rapidly detected at early perceptual stages, and this speeded detection can be used to guide attention toward or away from highly salient objects depending on their task relevance.

The finding that high-salience distractors were easier to ignore than the low-salience distractors in Experiment 2 might seem surprising. But similar results have now been found by many previous studies (e.g., Drisdelle & Eimer, 2023; Gaspar & McDonald, 2014; Moher et al., 2015; Stilwell et al., 2023). For example, Stilwell and colleagues (2023) found nearly identical results to Experiment 2, in which oculomotor suppression effects were stronger for high-salience singletons than low-salience singletons and occurred at early latencies suggesting a more proactive suppression process. Other studies have found similar evidence from event-related potentials. For example, Drisdelle and Eimer (2023) found that the magnitude of the P_0 component, an index of distractor suppression, was greater for high-salience distractors than low-salience distractors, suggesting high-salience distractors were more strongly ignored (see also Gaspar & McDonald, 2014). At first glance, this result might seem counterintuitive: Why would a highly salient object be easier to ignore? As explained above, this might occur because highly salient distractors are easier to detect before the initial shift of attention is generated. This would be broadly consistent with the model proposed by Luck et al. (2021) whereby feature-based gain modulations can influence attentional priority before the first shift of attention. It would also be consistent with recent observations from forced-response methods showing that salient distractors are suppressed very rapidly (ca. 100 ms) without ever attracting covert attention (Zhang et al., 2023, under revision).

Some previous literature has investigated the role of target salience in priming-of-popout (Chen & Cave, 2015; Maljkovic & Nakayama, 1994; Rangelov et al., 2017). In a seminal study, Maljkovic and Nakayama (1994) conducted a series of experiments using a visual search task in which the target had to be found based upon its status as a feature singleton. Their findings revealed that singleton targets were found more quickly when the target feature (e.g., color)

repeated from the previous trial than when it switched. Becker and Ansorge (2013) further explored this effect by manipulating the color contrast between the target and distractors to produce high- and low-salience targets. Their results showed that feature priming can modulate target selection even when the target is highly salient. Increasing the set size did not reduce priming effects by increasing target salience, as expected. These findings suggested that feature priming and target salience are both factors that influence target selection in visual search and may act through different mechanisms (see also Rangelov et al., 2017). Other studies in this domain have shown that cueing the feature dimension of the salient target can improve the detectability of a salient target, further suggesting a role of top-down expectation in the detection of salient targets (Chen & Cave, 2015).

The current study provides a potential method to verify manipulations of salience, in addition to other techniques that measure perceptual thresholds or attempt to compute salience based upon image-based properties (Chang et al., 2021; Stilwell et al., 2023). In theory, the current approach could be applied to any kind of feature singleton (e.g., luminance, line orientation, size, motion). To modulate salience, one could simply modulate the contrast between the feature singleton and other objects. An important design consideration is that the specific feature of the singleton must randomly alternate each trial so that it cannot be found using feature-based attention. In other words, a crucial aspect of the design is that participants must be forced to find the feature singleton based upon its bottom-up contrast with other items, not its simple features.

The low-salience account specifically claims that weak salience occurred in prior studies due to small display sizes (e.g., Gaspelin et al., 2015; Gaspelin & Luck, 2018a). There are reasons to doubt this claim. Several studies have now shown that color singletons can be ignored even at exceptionally high display sizes (e.g., 20–30 items), using probe tasks and event-related potentials (Stilwell & Gaspelin, 2021; Stilwell et al., 2022). Furthermore, it has been questioned the main study supporting this low-salience claim was successful at improving salience compared to the study it was criticizing for low salience. Evidence from the oddball detection task indicated that the color singletons in Wang and Theeuwes (2020) were more difficult to detect the singletons in the original Gaspelin et al. (2015) study, suggesting salience was not actually improved due to several uncontrolled

differences in the stimuli other than display size (Stilwell et al., in press). In any case, a methodological challenge with using display size as a manipulation of salience is that, with measures like eye movements or probe report, increasing the display size will reduce attentional shifts to the average nonsingleton distractor, which will make suppression effects difficult to observe (see Stilwell & Gaspelin, 2021). This floor effect problem will need to be addressed by future studies aiming to alter salience via display size.

In conclusion, the current study shows that salience influences attentional selection differently depending on whether it is relevant to the task. When relevant, we observed large effects of salience on target detection. When irrelevant, we observed that salient objects were clearly ignored. These results challenge recent claims that attentional guidance is entirely stimulus-driven by showing that salience-based attentional guidance is strongly modulated by task relevance. More generally, the current approach could be useful in future studies to verify that manipulation of salience was successful.

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