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# Oculomotor Inhibition of Salient Distractors: Voluntary Inhibition Cannot Override Selection History

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## Abstract

Several studies have demonstrated that salient distractors can be proactively inhibited to prevent attentional capture. Traditional theories frame attentional guidance effects such as this in terms of explicit goals. However, several researchers have recently argued that that unconscious factors— such as the features of attended and ignored items on previous trials (called *selection history*)— play a stronger role in guiding attention and can overpower explicit goals. The current study assessed whether voluntary inhibition can overpower selection history. We directly compared both forms of top-down control by measuring the control of eye movements, which offer an unambiguous measure of which location has won the competition for attention. We repeatedly found that selection history overpowered any effects of voluntary goals, such that observers were unable to avoid fixating a salient distractor of a known color if the target had been presented in that color on the previous trial. Moreover, a salient distractor of a particular color captured gaze even when the observer had voluntarily chosen this color to be the distractor color just moments before. Taken together, these experiments suggest that the ability to inhibit a salient color singleton is primarily a result of recent experience and not a result of explicit goals.

## Keywords

attentional capture; inhibition; selection history; priming; eye movements

A key question in research on visual attention is whether physically salient items can involuntarily capture visual attention. That is, can salient objects—such as a neon construction cone or a bright red stop sign—attract visual attention even when we are busy looking for something else? Although this question is seemingly straightforward, empirical research on the topic has led to conflicting results.

Traditionally, there have been two predominant classes of models of attentional capture. *Bottom-up models* propose that physically salient items automatically attract visual attention

regardless of the observer's goals (Theeuwes, 1992; Yantis & Jonides, 1984). According to these models, certain types of stimuli, such as a uniquely colored item (called a *color singleton)* amongst homogenously colored items, have an automatic power to capture our attention, even when we are busy searching for some other object. On the other hand, *top-down models* of attentional capture propose that only items matching the observer's current attentional template will capture attention (Folk, Remington, & Johnston, 1992; Lien, Ruthruff, & Johnston, 2010). Thus, according to top-down models, the visual system can tune itself to selectively search items that match the feature values of the search target, effectively excluding irrelevant salient items from visual search.

Bottom-up and top-down models of attentional capture make directly opposing predictions, and both have been supported by a large number of studies. As a potential resolution to this apparent discrepancy, we have proposed that salient items have an intrinsic ability to attract attention but that the visual system can inhibit these items. This inhibition can be weaker or stronger depending on the task and the observer's state, such that salient items may automatically capture attention on some trials and in some tasks. There is now considerable evidence that salient items can be inhibited in order to prevent attentional capture (Gaspar & McDonald, 2014; Gaspelin, Leonard, & Luck, 2015, 2017; Gaspelin & Luck, 2018c, 2018b, 2018a; Sawaki & Luck, 2010). Previously, we assumed that this inhibition is a direct result of an intentional, explicit goal (Gaspelin & Luck, 2018c). However, there is now growing evidence that attentional control may often be the result of implicit learning (sometimes called *selection history)* rather than explicit goals (Awh, Belopolsky, & Theeuwes, 2012; Chun & Jiang, 1998; Maljkovic & Nakayama, 1994; Theeuwes, 2018a; Wang & Theeuwes, 2018). The current study was therefore designed to investigate whether inhibition of salient items is primarily the result of an explicit goal to ignore a salient feature or whether recent experience plays a fundamental role.

## Inhibition Models of Attentional Capture

According to the *signal suppression hypothesis*, physically salient items can be avoided by means of a proactive inhibitory process that prevents attentional capture (Gaspelin & Luck, 2018c). Importantly, the effectiveness of this inhibitory process can wax and wane as a function of task demands and stimulus parameters. This will lead to capture under certain experimental conditions but no capture under other experimental conditions. Consistent with this hybrid model, there is now converging evidence that salient items can be proactively suppressed, coming from studies of psychophysics (Gaspelin et al., 2015; Vatterott & Vecera, 2012), eye movements (Gaspelin et al., 2017; Gaspelin & Luck, 2018a), event-related potentials (Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018b; Sawaki & Luck, 2010) and single-unit recordings in monkeys (Cosman, Lowe, Woodman, & Schall, 2018).

One key piece of evidence for the signal suppression hypothesis comes from studies of overt eye movements. In one such study, Gaspelin et al. (2017) adapted the well-known *additional singleton* paradigm for eye tracking (Theeuwes, 1992; Theeuwes, Kramer, Hahn, & Irwin, 1998). Participants searched displays of shapes for a target shape (e.g., a diamond) and made a speeded manual response regarding the orientation of a small line inside the target. On half

of trials, one distractor item was a uniquely colored compared to the other search items (e.g., a lone red distractor amongst several green shapes). Although the singleton distractor was physically salient, gaze was much less likely to be directed to the singleton distractor than other search items (an *oculomotor suppression effect)*. This occurred even when eye movements were initiated relatively quickly and was taken as evidence that salient items can be proactively suppressed to prevent attentional capture.

The signal suppression hypothesis is a *proactive* model of inhibition - the salient item is suppressed before visual attention is shifted. However, there have also been some notable studies suggesting that suppression may only be possible <u>after</u> the first shift of attention. For example, Beck and colleagues (2018) had participants search displays of Landolt Cs for a target with an upright or downright gap and make a speeded button-press to report the location of that gap (top or bottom). On each trial, before the search array appeared, a central cue denoted either the color of the upcoming target or the color of upcoming distractor items. Interestingly, when the upcoming distractor color was cued, the first eye movement was biased <u>toward</u> items with the to-be-ignored color. Subsequent eye movements were then biased <u>away</u> from the to-be-ignored color. This was taken as evidence in support of *mandatory reactive inhibition models*: attention first shifts to the to-be-ignored color and then it is suppressed. There are many variants of mandatory reactive inhibition models, including rapid disengagement models (Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000) and search-and-destroy models (Moher & Egeth, 2012).

In summary, many researchers agree that salient items can be inhibited during visual search. But the nature of this inhibition is unclear. Some studies suggest that salient items can be suppressed <u>before</u> an initial shift of visual attention, whereas others suggest that they can only be suppressed <u>after</u> an initial shift of visual attention. This inconsistency between studies needs to be resolved to develop a coherent model of attentional capture.

## Selection History as a Potential Resolution

A hint at a potential resolution between these seemingly conflicting findings comes from discussions about the influence of recent experience on visual search. Since the 1980s, most models of visual search have assumed that visual attention is guided by *explicit goals* (Egeth, Virzi, & Garbart, 1984; Folk et al., 1992; Wolfe, 1994). For example, if you are looking for a friend who typically wears a red sweater, you might selectively search red items when trying to find that friend at a coffee shop. However, there is now considerable evidence that attention is also guided—in a largely automatic and unconscious manner—by *selection history*. For example, participants are typically faster at detecting a popout target during visual search if its color matches the color of the previous target (Maljkovic & Nakayama, 1994). Similarly, participants are faster at searching displays that they have previously searched, even when they have difficulty explicitly identifying whether they have seen the display before (called *contextual cueing*; Chun & Jiang, 1998, 1999). There are dozens of additional demonstrations that recent experience and situational context play a key role in the guidance of attention, seemingly without awareness or explicit intentions (Anderson, Laurent, & Yantis, 2011; Cosman & Vecera, 2013, 2014; Geng & Behrmann, 2002; Olivers & Humphreys, 2003; Torralba, Oliva, Castelhano, & Henderson, 2006).

Some researchers have made the provocative claim that selection history dominates explicit goals in visual search (Theeuwes, 2018b), especially in tasks that involve avoiding salient distractors (Awh et al., 2012). According to these accounts, many previous studies may have underestimated the contribution of selection history on attentional guidance by maintaining a constant target definition for long blocks of trials or even an entire experiment. For example, imagine that a participant is instructed to search for a green X target for a block of 100 trials. This instruction will produce an explicit goal of finding green Xs, but the experience of finding the green X on the first few trials of the experiment may also produce an automatic attentional bias toward green Xs on subsequent trials (see Carlisle, Arita, Pardo, & Woodman, 2011).

Selection history may play a key role in resolving the apparent inconsistency between proactive and reactive inhibition models. Specifically, the ability to proactively inhibit salient items may be a result of recent experience, not an explicit goal. When participants are given an instruction or cue that creates the explicit, voluntary goal of proactively ignoring salient items, this may (ironically) serve to attract attention to the tobe-ignored item. After attention is captured by this distractor, the voluntary goal then leads to reactive inhibition of this item and a shift of attention to a relevant item. After multiple trials of this reactive inhibition, however, implicit learning may build up, leading to proactive suppression of the salient items.

Consistent with this hypothesis, many studies supporting proactive inhibition hold the colors of search items constant for the entire experiment, which allows priming to build throughout the experimental session (Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018b). Many studies demonstrating reactive inhibition, however, randomly vary the to-be-ignored feature across trials and use a cue to denote the upcoming color of the to-be-ignored item (Beck, Luck, & Hollingworth, 2018; Moher & Egeth, 2012). The cue ensures that participants can establish a clear explicit goal for the to-be-ignored feature, but the random assignment of display colors weakens priming by recent experience. If inhibition was the result of selection history, then it would be relatively weak under these circumstances.

In summary, there are several studies indicating that implicit learning processes play a crucial role in visual search. However, the role that selection history plays in the inhibition of salient-but-irrelevant items is currently unclear (but see Becker, 2010; Cunningham & Egeth, 2016; Feldmann-Wüstefeld & Schubö, 2016; Gaspelin & Luck, 2018a; Graves & Egeth, 2016; Vatterott & Vecera, 2012). Importantly, selection history could offer a simple resolution between the seemingly discrepant findings between studies showing that salient items can be proactively inhibited or studies showing that attention must first be shifted to the to-be-ignored items before inhibition.

## The Current Study

The purpose of the current experiments is to assess whether selection history can overpower voluntary inhibition of salient items. All experiments used an additional singleton paradigm (Theeuwes, 1992) that was adapted for measuring eye movements (see Figure 1; Gaspelin et

al., 2017). Participants searched for a target of a specific shape (e.g., diamond) and reported the orientation of a small line inside the target. Each display contained a salient distractor item that participants attempted to ignore. The destination of the first saccade on a given trial was used as a direct means of quantifying the probability that attention was attracted to the singleton distractor. If the singleton captures attention, then initial saccades should be <u>more</u> likely to be directed to the singleton distractor than toward the average nonsingleton distractor (an *oculomotor capture effect)*. If the singleton is suppressed, then initial saccades should be <u>less</u> likely to be directed to the singleton distractor than toward the average nonsingleton distractor (an *oculomotor suppression effect)*.

Our previous research has shown that, when the color of the target and singleton are fixed for the entire experiment, color singletons are suppressed. Experiments 1 and 2 replicate this *fixed-colors condition*, and contrast it with a new *alternating colors condition*, where the color of the target and singleton swap on each trial, to test whether voluntary inhibition can overpower selection history. Experiment 3 uses a similar technique, but the color is swapped every five trials - which allows feature-based priming to accumulate over several trials. Experiment 4 takes a different approach and attempts to evaluate whether voluntary inhibition of salient items is possible, even in the absence of priming via selection history.

## Experiment 1

Experiment 1 tested the relative impact of selection history and voluntary inhibition on the ability to ignore salient distractors. This experiment used an *alternating-colors condition*, in which the color of the singleton and the color of the target swapped on every trial (see Figure 1b; Maljkovic & Nakayama, 1994). This manipulation puts selection history and voluntary inhibition in direct competition. On the one hand, the singleton distractor on the current trial is always the same as the target color on the previous trial, and priming from the previous trial should encourage attentional capture by the singleton distractor. On the other hand, the singleton's color is completely predictable on every trial, giving voluntary inhibition an opportunity to suppress the singleton.

If voluntary inhibition can overpower selection history, knowledge of the upcoming singleton color on a given trial would allow the observer to ignore it (i.e., the singleton is entirely predictable). This would result in a large oculomotor suppression effect, whereby the singleton should be less likely to be overtly fixated than baseline levels. Alternatively, if selection history overpowers voluntary inhibition, however, then visual attention should be primed by the previous target color and attention should be guided toward the salient item (because it has the same color as the previous target). Performance in this new alternating colors condition was compared with a *fixed-colors condition*, where both priming and voluntary inhibition should guide visual attention away from the salient item (Gaspelin et al., 2017).

### Method

**Participants.—**An a priori sample size of 32 participants for each condition (fixed-colors and alternating-colors) was chosen on the basis of similar eye-tracking experiments (Gaspelin et al., 2017). This yielded 64 participants total. Given the effect sizes observed in

our previous experiments on oculomotor capture and oculomotor suppression, this gave us >.999 power to detect capture and suppression effects within each group. The magnitude of the between-groups difference between the fixed- and alternating-colors was unknown, however, and we chose a relatively large sample size to err on the side of higher rather than lower power.

The participants were students at Binghamton University, State University of New York, who participated to receive course credit. Of the final sample, 37 were female and 27 were male. The mean age was 19.4 years. All participants had normal color vision as assessed by an Ishihara color vision test and had normal or corrected-to-normal visual acuity.

**Apparatus.—**Stimuli were presented using PsychToolbox (Brainard, 1997) for Matlab on an HP 24uh LCD monitor with a black background, placed at a viewing distance of 100 cm. A photosensor was used to measure the timing delay of the video system (15 ms), and this delay was subtracted from all latency values reported in this paper. An SR Research Eyelink 1000 desk-mounted system recorded eye position monocularly from the right eye at 500 Hz.

**Stimuli & Procedure.—**The stimuli and procedure were similar to those in our previous oculomotor capture studies (Gaspelin et al., 2017; Gaspelin & Luck, 2018a) and are illustrated in Figure 1. Each search display contained 6 items distributed at equal distances around a notional circle with a radius of 4.5°. The shapes were diamonds (0.8° by 0.8°), circles (0.9° diameter), triangles (0.9° in height and base), and hexagons (0.9° by 0.9°). The shapes were drawn in pink (17.5 cd/m², $x = .317$, $y = .146$), green (17.5 cd/m², $x = .289$, $y = .628$), orange (17.5 cd/m², $x = .537$, $y = .409$), and blue (17.5 cd/m², $x = .204$, $y = .258$). Each shape contained a black line that subtended $0.3° \times 0.05°$ and was tilted 45° to the left or right. Before the search array, we presented a fixation point, which was a gray circle (17.5 cd/m², 0.5° in diameter) with a black crosshair inside (0.5° in height and width, 0.6° thick) at the center of the display.

At the beginning of the experiment, participants were randomly assigned to one of two conditions (Figure 1b). In the *fixed-colors condition*, the search target was defined as a specific shape (diamond or circle) of a specific color (green, pink, orange, or blue). This color and shape remained constant for the entire experimental session for each participant. The nonsingleton distractors were always the same color as the target. To ensure that the singleton distractors "popped out" from the nonsingleton items, the nonsingleton color in a given display was paired with a singleton color that was far away in hue within our color space (i.e., orange with blue and pink with green). In the *alternating-colors condition*, the singleton color and target color alternated reliably from trial to trial, but the target shape remained constant. At the beginning of each session, the participant was assigned to a color pair (e.g., pink-green) and a target shape (e.g., diamond). Participants were explicitly told that the target and singleton color would swap each trial and were encouraged to track the upcoming target color. For example, if the singleton was pink and the target was green on one trial, the participant would know with 100% certainty that the singleton would be green and the target would be pink on the next trial (and vice versa). Thus, the target and singleton colors were equally predictable in the fixed-colors and alternating-colors conditions. One

might be concerned that the predictability in the alternating-colors condition was too subtle to control attention; this possibility is ruled out in Experiment 2.

A color singleton was present on every trial. Its location was random except that the target was never the singleton. The target location was also chosen at random. All distractor shapes were chosen at random with the constraint that each display contained at least one triangle, one hexagon, and one diamond or circle (depending on the chosen target shape - e.g., if the target was a diamond, this final distractor shape was a circle).

The colors of the target and singleton were equally predictable in the fixed- and alternating-colors conditions. Thus, in the absence of automatic priming from the previous trial, participants should have been equally able to direct attention toward the target item and away from the singleton item. If, however, participants cannot overcome priming, then they will tend to fixate the singleton color more in the alternating-colors condition (in which the singleton color on the current trial was always the target color on the previous trial) than in the fixed-colors condition (in which the singleton color on the current trial was always a nontarget color on the previous trial). Moreover, the probability of fixating the singleton versus fixating an average nonsingleton distractor in the alternating-colors condition can be used as a metric of the relative strengths of the explicit goal and the color priming. That is, when the goal of finding a target of a particular color is stronger than the priming of the target color from the previous trial, participants should be more likely to fixate objects of the target color than to fixate an object of the known nontarget color. Because the nonsingleton distractors and the singleton distractor both differed from the target shape, but the nonsingleton distractors shared the target color, any differences in fixation rates between them reflects the extent to which attention was biased on the basis of color (whereas fixation of the actual target reflects the combined effects of color-based and shape-based attentional control). Therefore, the relative rates of fixation of singleton and nonsingleton distractors provides a metric of the competition between the goal of attending to the color of the current target and the priming of the colors from the previous trial.

Each trial began with the presentation of a blank screen for 500 ms. This was followed by a fixation screen containing only the fixation point; this screen remained visible until the participant maintained fixation within a 1.5° radius of the center of the display for 500 ms. The fixation point then disappeared and the search array appeared, remaining visible until the response. If participants took more than 3000 ms to respond, a timeout display appeared with the text "Too Slow" for 500 ms. If the response was incorrect, a 200 Hz tone sounded for 500 ms. The blank screen for the next trial then appeared immediately.

Participants practiced the search task for two blocks of 60 trials. The main experiment consisted of ten blocks of 60 trials, yielding 600 trials. At the beginning of each block, the eyetracker was calibrated using a nine-point calibration protocol. During the main task, the eyetracker was recalibrated if a participant failed to fixate the central cross for more than 8 seconds at the beginning of a trial. At the end of each block, participants received feedback on mean response time (RT) and accuracy.

**Analysis.—**The onset of a saccade was defined using a minimum eye velocity threshold of 30°/s and a minimum acceleration threshold of 9500°/s$^2$. To classify the landing position of the first saccade on each trial, an annulus was defined that was centered on the fixation cross, with an inner radius of 1.5° and an outer radius of 7.5°. As in our previous studies (Gaspelin et al., 2017; Gaspelin & Luck, 2018a), our analyses focused on the first saccade that was made on each trial: Once the first saccade has been made, the visual input varies according to the new point of gaze, making it difficult to conduct well-controlled analyses of subsequent saccades. First saccades were defined as the first eye movement landing inside the annulus. The landing position was then classified by selecting the nearest search item. This technique effectively created wedge-shaped interest areas around each search item (for studies using a similar technique, (Gaspelin et al., 2017; Gaspelin & Luck, 2018a; Leonard & Luck, 2011). Saccade latency was measured as the start time of the first saccade that landed in the annulus.

In our statistical analyses of the saccade destinations, we avoided using ANOVAs because of issues of nonindependence (i.e., an increase in the percentage of first saccades to one search item necessarily means a decrease in the percentage of saccades to other items). Instead we used a series of planned *t* tests to compare probabilities of fixation against chance probability, which effectively avoids issues of nonindependence. The details of these *t* tests are described in the Results section.

Practice blocks were excluded from all analyses. Additionally, the first trial of each block was excluded from analysis because the singleton color could not be predicted on these trials in the alternating-colors condition and because any priming on this trial likely differs from the priming on the subsequent trials (e.g., because of the eyetracker calibration and a change in experimental conditions between blocks).

We implemented a set of a priori criteria for excluding aberrant trials, matching the methods of our prior oculomotor suppression experiments (Gaspelin et al., 2017; Gaspelin & Luck, 2018a). First, trials were excluded if participants made no eye movements (6.7% of trials). Trials with an abnormal manual RT (less than 200 ms or greater than 2000 ms, accounting for 0.3% of trials) or an abnormal saccade latency (less than 50 ms or greater than 1000 ms, accounting for 2.3% of remaining trials) were also excluded from analysis. Additionally, trials with manual response errors (2.8%) were excluded from all analyses except manual response error analyses. Altogether, 11.1% of trials were removed.

## Results

**Manual Responses and Saccade Latency—**Manual RT was slightly but nonsignificantly faster in the alternating-colors condition (737 ms) than in the fixed-colors conditions (786 ms), $t(62) = 1.611$, $p = .112$, $d = .403$. Note that the absence of a significant effect of this between-group comparison likely reflects the considerable variance between individuals in manual RT (SD = 123 ms), and this effect went in the opposite direction in Experiment 2. There were extremely few manual response errors in either the fixed-colors condition (3.0%) or alternating-colors condition (2.5%), $t(62) = 1.068$, $p = .290$, $d = .267$. The latency of the first saccade was nearly identical in the fixed-(200 ms) and alternating-colors (197 ms) conditions, $t(62) = .312$, $p = .756$, $d = .078$.

The singleton was present on every trial in this experiment, so we were unable to assess traditional RT-based capture effects. Instead, the first eye movement on each trial was used to assess overt attention capture.

### First Saccade Destination

**<u>Oculomotor Capture/Suppression Effects.</u>:** The heat maps in Figure 2a show the landing point of the first saccade, aggregated across all trials and all participants. The plots show every possible location of the singleton relative to the target, but the data were rotated so that the target appears at the top position in each heat map. The white arrow points to the singleton location. The difference between the fixed- and alternating-colors condition is clear. In the fixed-colors condition, gaze was <u>less</u> likely to move to the singleton distractor than to the average of the nonsingleton distractors (an *oculomotor suppression effect)*, replicating previous research (Gaspelin et al., 2017). In the alternating-colors condition, however, the first saccade was <u>more</u> likely to be directed to the singleton distractor than to the average of the nonsingleton distractors (an *oculomotor capture effect*). In other words, when the singleton color was the same as the target color from the previous trial, the singleton captured the eyes even though the target and singleton colors were just as predictable in this condition as in the fixed-colors condition.

For the sake of simplicity, we analyzed the data shown in the heat maps by quantifying the percentage of first saccades directed to each search item, pooled across target-singleton distances (Figure 2b). We divided the number of saccades directed to all of the nonsingleton distractors by the number of nonsingleton locations, providing a "per location" measure (to allow for a fair comparison of singletons and nonsingleton distractors). To statistically compare the oculomotor capture/suppression effects in the fixed- and alternating-colors conditions, we computed the difference between the percentage of first saccades to the singleton distractor and the percentage of first saccades to the average nonsingleton distractor in each participant.

These difference scores are shown in Figure 2c. Separate one-sample $t$ tests in each condition assessed whether the difference scores were significantly different from zero (where zero means that there was no net effect of color on saccade destination). In the fixed-colors condition, there was a statistically significant 8% oculomotor <u>suppression</u> effect, $t(31) = 13.59, p < .001, d = 2.403$. In the alternating-colors condition, there was a statistically significant 7% oculomotor <u>capture</u> effect, $t(31) = 5.482, p < .001, d = .969$.

We then compared the difference scores from the fixed- and alternating-colors conditions with an independent-samples $t$ test. The oculomotor capture effect was larger in the alternating-colors condition (7%) than in the fixed-colors condition (−8%), $t(62) = 10.64, p < .001, d = 2.660$. Thus, participants were able to suppress the singleton distractor when it was both primed by the previous trials and consistent with the explicit goal of finding the target (i.e., in the fixed-colors condition), but this suppression was overpowered by priming when the target color on one trial became the singleton color on the next trial and vice versa (i.e., in the alternating-colors condition). Note that this design does not make it possible to determine whether the capture and suppression effects reflect orienting attention toward one color or away from the other color, but this is not relevant for the question of whether the

orienting is controlled by priming or by explicit goals. Note also that the physical stimuli on a given trial were identical in these two conditions, so this difference cannot be explained by differences between conditions in bottom-up salience.

**Search Item Analysis.:** We also compared the percentage of first saccades to each search item (target, nonsingleton, and singleton) as a function of color condition (Figure 2b). Planned *t* tests compared the percentage of first saccades between the fixed-colors condition and alternating-colors condition for each item type (target, singleton distractor, and non-singleton distractor). First saccades were approximately equally likely to land on the target in the fixed-(41%) and alternating-colors (42%) conditions, $t(62) = .039$, $p = .969$, $d = .010$. First saccades were more likely to land on a nonsingleton distractor in the fixed-colors condition (13%) than in the alternating-colors condition (10%), $t(62) = 4.166$, $p < .001$, $d = 1.042$. First saccades were less likely to land on the singleton distractor in the fixed-colors condition (5%) than in the alternating-colors condition (17%), $t(62) = 8.883$, $p < .001$, $d = 2.221$. These analyses converge with the difference-score analyses provided in the previous paragraph.

### Discussion

This experiment tested whether voluntary inhibition could overpower priming of a salient item via selection history. When the target and singleton color were fixed, participants had no difficulty averting gaze from the salient item. However, when the target color and singleton color alternated from trial to trial, participants could not help but direct gaze to the salient singleton - which was primed by the previous target color. This pattern of results indicates that voluntary inhibition cannot overpower priming, at least under this set of conditions.

## Experiment 2

One possible explanation for the lack of singleton suppression in the alternating-colors condition of Experiment 1 is that participants did not bother keeping track of the colors from the previous trial to predict the singleton color on the current trial. Experiment 2 was designed to address this possibility by adding an explicit cue at the beginning of each trial that indicated the to-be-attended target color. Previous studies have demonstrated that people can easily use color precues in visual search tasks to create explicit goals that guide attention toward specific features (Beck et al., 2018; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). If these goals are strong enough to overcome priming from the previous trials, then participants should suppress the singleton (as in the fixed-colors condition of Experiment 1). However, if explicit goals cannot overpower selection history, then gaze should be captured by the singleton because its color is primed by the target color on the preceding trial.

### Methods

All methods were identical to the alternating-colors condition of Experiment 1 except for the following changes (see Figure 3). We ran a new sample of 32 participants (23 female and 9 male; mean age = 19.3 years).

There was no fixed-colors condition. Instead, the singleton color and target color predictably alternated each trial (just as in Experiment 1). However, before the fixation display, a letter appeared at the center of the screen denoting the upcoming target color ("P" for pink, "G" for green, "O" for orange, and "B" for blue. This white letter was drawn in Arial typeface, subtended 0.9° vertically, and appeared for 1000 ms. Participants were instructed that this letter indicated (with 100% probability) the color of the target on each trial. Because only two colors were possible for a given participant, this cue also made the color of the singleton easily predictable.

For many of the analyses below, we compared the alternating-colors condition from Experiment 2 with the fixed-colors condition from Experiment 1.

## Results

**Manual Responses and Saccade Latency**—Manual RT was numerically slower in Experiment 2 (807 ms) than in the fixed-colors condition of Experiment 1 (786 ms), but this was not statistically significant, $t(62) = .613$, $p = .542$, $d = .153$. Error rates were virtually identical in the current experiment (2.9%) and the fixed-colors condition of Experiment 1 (3.0%), $t(62) = .228$, $p = .820$, $d = 057$. Saccade latency was also similar in the current experiment (191 ms) and the fixed-colors condition of Experiment 1 (200 ms), $t(62) = .831$, $p = .409$, $d = .208$.

### First Saccade Destination

**Oculomotor Capture/Suppression Effects.:** As can be seen in the heat maps Figure 4a, first eye movements in Experiment 2 were <u>more</u> likely to be directed to the singleton distractor than to the average nonsingleton distractor. Thus, these results nicely replicate the singleton capture effect observed in the alternating-colors condition from Experiment 1. In other words, even with a cue that explicitly indicated the upcoming target color, overt attention was still biased toward the color singleton.

A one-sample $t$ test confirmed that the 5% oculomotor capture effect in Experiment 2 (Figure 4c) was significantly greater than zero, $t(31) = 3.386$, $p = .002$, $d = .599$. In addition, the oculomotor capture effect was greater in Experiment 2 (5%) than in the fixed-colors condition of Experiment 1 (−8%), $t(62) = 8.055$, $p < .001$, $d = 2.014$. Thus, when the target and singleton colors alternated, the singleton captured attention even when the target color was explicitly cued on every trial.

It is worth mentioning that the 5% oculomotor capture effect in the current experiment was numerically smaller than the 7% oculomotor capture effect from the alternating-colors condition of Experiment 1. However, these two effects were not significantly different, $t(62) = .946$, $p = .348$, $d = .237$.

**Search Item Analysis.:** Planned $t$ tests compared each item type in the present experiment with the fixed-colors condition of Experiment 1 (see Figure 4b). There were no differences in first saccades to the target, $t(62) = .354$, $p = .725$, $d = .088$. First saccades were more likely to land on the nonsingleton distractor in the fixed-colors condition of Experiment 1 (13%) than in Experiment 2 (11%), $t(62) = 2.774$, $p = .007$, $d = .694$. First saccades were

less likely to land on the singleton distractor in the fixed-colors condition of Experiment 1 (5%) than in Experiment 2 (16%), $t(62) = 7.139$, $p < .001$, $d = 1.785$. This is the same pattern of differences observed when the fixed- and alternating-colors conditions of Experiment 1 were compared.

### Discussion

Experiment 2 again tested whether participants could use explicit goals to overpower priming and thereby avoid a salient distractor. The color of the upcoming search array was completely predictable and explicitly cued at the beginning of each trial. Nonetheless, we found that overt eye movements were biased toward the salient item (which was always primed by the previous target color). This suggests that an explicit goal to inhibit a salient item cannot overcome feature priming of a salient item.

## Experiment 3

Experiments 1 and 2 showed that participants could not suppress a singleton when the target and singleton colors swapped every trial, whereas the fixed-colors condition of Experiment 1 and previous experiments reported by Gaspelin et al. (2017) have shown that the singleton can be suppressed when the target and singleton colors remain constant for an entire trial block (see also Vatterott & Vecera, 2012). This suggests that there must be some transition point at which capture changes into suppression. Experiment 3 therefore asked how many trials of a repeated color assignment are needed to observe suppression of the singleton. One possibility is that the effect of selection history are relatively short-lived, with the current trial only influencing inhibition on the subsequent trial. Another possibility, however, is that the effect of selection history is relatively gradual, affecting inhibition of salient distractors for several trials. Indeed, past studies of priming of popout give good reason to expect the latter (e.g., see Maljkovic & Nakayama, 1994, Experiment 5).

Experiment 3 used the same displays as the alternating-colors condition of Experiment 2, where the target color and singleton color swapped. But instead of swapping each trial, the color configuration was held constant for five trials before swapping (for a similar manipulation, see Maljkovic & Nakayama, 1994). This allows priming of the to-be-attended color to accumulate over several trials. If the effects of priming on inhibition are short-lived, then inhibition should return quickly after the initial switch trial. If the effects of priming on inhibition are more long-term, however, then inhibition should take several trials to reach full strength.

### Methods

All methods and stimuli were identical to the alternating-colors condition of Experiment 2 except for the following changes. We ran a new sample of 32 participants (15 female and 17 male; mean age = 24.5 years). One subject was replaced for making eye movements on only 56% of trials, which was more than 4 standard deviations from the group mean of 95%.

The color of the target and the singleton were held constant for five trials before alternating. Just as in Experiment 2, on each trial, a letter appeared at the center of the screen denoting the upcoming target color ("P" for pink, "G" for green, "O" for orange, and "B" for blue).

Because only two colors were possible for a given participant, this cue also made the color of the singleton easily predictable. Participants were instructed that display colors would swap every 5 trials and were strongly encouraged to use the letter cues to help them avoid the salient item.

The first five trials of each block (60 trials each) were excluded from analysis because the singleton color could not be predicted on these trials in the alternating-colors condition and because any priming on this trial likely differs from the priming on the subsequent trials (e.g., because of the eyetracker calibration and a change in experimental conditions between blocks).

## Results

**Manual Responses and Saccadic Latencies**—Just as in Experiments 1 and 2, the singleton was present on every trial, making it impossible to assess traditional measures of attentional capture such as singleton-presence costs. However, with this new methodology, we could now assess overall RT as a function of the number of consecutive trials with the same target/singleton color assignment. If the singleton captures attention on the swap trial, this should delay detection of the target and decrease overall response time.

As can be seen in Figure 5a, manual response times generally decreased as participants gained experience with a specific target/singleton color pair. In other words, the manual response time was slowest on the swap trial (880 ms) and became substantially faster on the subsequent trials (842 ms, 838 ms, 839 ms, and 841 ms). This is consistent with the possibility that the singleton captured attention on the initial color swap trial, slowing the overall time it took to detect the target. We formally analyzed this with a one-way ANOVA comparing manual RT with the factor of the number of same-color trials (i.e., the number of trials since the swap). This revealed a main effect of number of trials with the same color pair, $F(4, 124) = 16.91$, $p < .001$, $\eta^2 = .353$.

We also performed the same analysis on mean saccade latency. Saccade latencies also became faster as the number of trials with the same display colors increased, $F(4, 124) = 6.981$, $p < .001$, $\eta^2 = .184$. On the first trial with new display colors, mean saccade latency was 211 ms, and this gradually decreased over the next four trials with the same display colors (207 ms, 206 ms, 205 ms, 205 ms). However, this was much smaller than the effect on manual RT, presumably because manual RT was impacted by the destination as well as the time of the first saccade.

We also performed the same analysis on mean error rates. Mean error rates did not significantly differ as a function of the number of trials with the same color assignment, $F(4, 124) = 0.040$, $p = .994$, $\eta^2 = .001$.

### First Saccade Destination

<u>**Oculomotor Suppression/Capture Effects.:**</u> Table 1 shows the percentage of first saccades to be directed to each item as a function of the number of trials with the same color. Figure 5b shows oculomotor capture effects as a function of the number of trials with the same color assignment. Oculomotor capture effects were calculated exactly as they were in the

previous experiments – by subtracting the percentage of fixations to the average nonsingleton distractor from the percentage of fixations to the singleton distractor. A positive value indicates capture (the singleton distractor is *more* likely to be fixated than the average nonsingleton distractor), whereas a negative value indicates suppression (the singleton distractor is *less* likely to be fixated than the average nonsingleton distractor). On "swap" trials, where the color of the singleton distractor was the same as the color of the target on the immediately preceding trial, a large oculomotor capture effect was observed. In other words, when the singleton color was primed by the preceding 5 trials, there was an extremely large oculomotor capture effect. However, as participants gained experience with the current singleton color, an oculomotor suppression effect gradually emerged (see also Gaspelin & Luck, 2018a).

We formally analyzed this pattern with a one-way ANOVA comparing oculomotor capture effects as a function of the number of trials with the same color assignment. There was a main effect of the number of trials, $F(4, 124) = 40.95$, $p < .001$, $\eta^2 = .569$. We also tested each oculomotor capture effect against zero with a one-sample $t$ test. There was a 11% oculomotor capture effect on the first trial with a new color singleton, $t(31) = 5.561$, $p < .001$, $d = .983$. There were no significant oculomotor capture effects on the second trial $(-2\%)$, $t(31) = 1.268$, $p = .214$, $d = .224$. Significant oculomotor suppression was observed on the third trial $(-3\%)$, $t(31) = 3.60$, $p = .001$, $d = .636$, the fourth trial $(-3\%)$, $t(31) = 2.752$, $p = .01$, $d = .486$, and the fifth trial $(-4\%)$, $t(31) = 3.707$, $p < .001$, $d = .655$.

It is worth noting that the 4% oculomotor suppression effect on the final "repeat" trial (trial 5) was not as large as in the fixed-color condition of Experiment 1 (7%), in which the singleton color was held constant for the entire experiment. We compared these oculomotor suppression effects with a $t$ test and this revealed that oculomotor suppression effect was significantly smaller on trial 5 of Experiment 3 than in Experiment 1, $t(62) = 2.511$, $p = .015$, $d = .628$. This suggests that it takes more than five trials to reach maximal suppression. Previous research in our lab suggested that it can take as much 20–40 trials for oculomotor suppression to reach its peak (see Gaspelin & Luck, Experiment 4, 2018).

## Discussion

In this experiment, we swapped the target and singleton colors after every 5 trials. On the swap trials (i.e., when the singleton distractor color on the current trial was the same as the target color on the immediately preceding trial), there was a large oculomotor capture effect. However, after a few repetitions of the same singleton color, first eye movements gradually became biased away from the singleton distractor (i.e., an oculomotor suppression effect). This suggests that the influence of selection history on the inhibition of salient items can be relatively gradual and may take several trials to fully recover. This finding is consistent with previous studies showing that inhibition develops gradually as participants gain experience with a given singleton color (Gaspelin & Luck, 2018a; Stilwell & Vecera, 2018; Vatterott & Vecera, 2012).

## Experiment 4

In Experiments 1–3, participants were captured by a salient distractor that was primed by recent experience even though they were given the opportunity to form an explicit goal of suppressing the salient distractor. It is, therefore, tempting to conclude that salient items cannot be suppressed by an act of will. However, one possibility is that participants can use explicit goals to avoid salient items but that the ability to suppress the salient items was not strong enough to compete with priming from the previous trial. Moreover, we have no independent evidence that participants paid attention to the cues indicating the color of the target or distractor on the upcoming trial; they may have simply ignored these cues. Thus, although our experiments confirm previous results indicating that suppression is possible when the same features repeat from trial to trial (Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018b), and our experiments provide no evidence that participants can use voluntary goals to overcome priming from previous trials, Experiments 1–3 do not unequivocally demonstrate that participants are unable to use voluntary goals to suppress salient singletons. Experiment 4 was designed to test, in the most direct possible manner, whether participants can suppress a salient color singleton solely by an act of will.

To accomplish this, the participants were given the opportunity to choose the to-be-ignored singleton color on each trial. The basic paradigm was identical to that used in Experiments 1–3, except that the participants chose the singleton color for the upcoming search display at the beginning of each trial. The target color was then randomly selected from the remaining three unpicked colors. If salient items can be suppressed via the establishment of an explicit, voluntary goal, then participants should be able to direct gaze away from the singleton color when they voluntarily choose this color on each trial. By contrast, if the ability to ignore salient items results from some implicit history-based mechanism, participants should not be able to ignore the salient item even when they choose the color of this item. In fact, participants may actually be captured by the color that they just selected to ignore. This is sometimes called an *attentional white bear effect* (Beck et al., 2018; Cunningham & Egeth, 2016; Moher & Egeth, 2012; Tsal & Makovski, 2006), refering to the classic idea that it is difficult to follow the instruction "try not to think of a white bear" (Wegner, 1994).

### Methods

The methods were similar to those of the previous experiments except as follows. We tested a new sample of 32 participants. One participant was replaced for having an unusually high error rate (>9% which was more than 2.5 standard deviations from the mean). Five participants were replaced for selecting one of the four potential singleton colors on less than 10% of trials. Such a strategy would result in a relatively low number of switch trials. It also makes it challenging to conduct some of the follow-up analyses in the next section. In the final sample of participants, 15 were female and 17 were male. The mean age was 24.4 years.

Participants performed the same attentional capture task as in the previous experiments. They searched for a target shape, while attempting to ignore a salient singleton. In the current experiment, however, participants *selected* the color of the salient item before the trial began (see Figure 6). At the beginning of each trial, a prompt appeared with "Select a

color to ignore:" in white Arial typeface at the center of the screen. Participants used the left- and right-buttons of the directional pad on a gaming controller to scroll through the potential colors (green, pink, blue, and orange), which were displayed in a font color that matched the color name. To confirm their selection, participants pressed a button on the face of the gamepad. After this, a gray box appeared around the selection screen for 500 ms to provide a visual confirmation to the participant that their response had been registered. Participants were then required to hold gaze on a central fixation cross for 500 ms to initiate the search display (as in Experiments 1 – 3).

In the search array, one distractor item was randomly selected to be the color singleton. This singleton distractor was the color that the participant selected to ignore. The target color was randomly assigned to be one of the three unselected colors. For example, if the singleton color was selected to be blue, the target color could be green, orange, or pink. The target shape was constant for the entire experimental session (e.g., diamond) and participants made a speeded response to classify the tilt of a line inside the target using the shoulder buttons on the gamepad (as in Experiment 1–3).

Participants were explicitly encouraged to avoid selecting the same singleton color from the previous trial and were asked to try to use each color equally as often. At the end of each block, a warning screen appeared if a participant switched the to-be-ignored color on less than 50% of trials.

## Results

**Manual Responses—**Participants switched their choice of the to-be-ignored color on 83% of trials. Participants were approximately equally likely to select each potential color (blue - 29%, green –22%, orange - 22%, pink - 28%). Participants took an average of 1.3 seconds to select the color to ignore. On the search task, mean manual response time was 837 ms and mean saccade latency was 203 ms. Participants made manual response errors on 2.0% of trials.

### First Saccade Destination

<u>**Oculomotor Capture Effect.:**</u> The key question in this experiment was whether participants would be able to avoid attentional capture by a salient singleton that they had just chosen to ignore. Figure 7a shows heat maps of first saccade destinations for each potential target-singleton angular distance. As can be seen, first eye movements were more likely to be directed to the color singleton than to the average nonsingleton distractor. We formally quantified this relationship by calculating the percentage of first saccades to be directed to each search item - collapsing across all potential target-singleton angular distances. Figure 7b shows that first eye movements were much more likely to be directed to the singleton distractor (19%) than to the average of the nonsingleton distractors (11%) - an 8% oculomotor capture effect. We compared these means using a paired-samples $t$ test, which revealed that the difference was significant, $t(32) = 4.994$, $p < .001$, $d = .883$.

<u>**Search Item Analysis.:**</u> We also compared the percentage of saccades to each search item using a repeated measures ANOVA with the factor item type (target, nonsingleton distractor,

singleton distractor). There was a significant main effect of item type, suggesting that certain items were more or less likely to be first fixated than other types of items, $F(2,62) = 48.26$, $p < .001$, $\eta^2 = .609$. We then compared the number of fixations to the target item with the number of fixations to nonsingleton distractors and the singleton item. First eye movements were more likely to be directed to the target (37%) than the average nonsingleton distractor (11%), $t(31) = 8.717$, $p < .001$, $d = 1.541$, or the singleton distractor $t(31) = 5.531$, $p < .001$, $d = .978$. Thus, even when the participant chose which color should be ignored on each trial, the first fixation was more likely to be directed to the item of this color than to the other nontarget items.

**Trials with New Colors.:** To eliminate any effects of repetitions of the target or singleton colors from the preceding trial, we re-analyzed the eye movement data, constraining our analyses to trials on which both the target color and singleton color were different from the previous trial. For example, if the previous trial had a blue singleton and orange target, we excluded the current trial if either the singleton or the target was blue or orange. This gives us a measure of voluntary inhibition that is effectively uncontaminated by feature priming from the previous trial. First eye movements were still more likely to be directed to the singleton item (18%) than the average nonsingleton distractor (11%), a 7% oculomotor capture effect, $t(31) = 3.458$, $p = .002$, $d = .611$. This provides further evidence that salient items cannot be inhibited below baseline levels of processing by an act of will alone.

**Subsequent Fixations: Initial Capture and Reactive Inhibition**—According to reactive inhibition models, attention is initially guided toward the salient item, followed by the suppression of this item (Beck et al., 2018; Cunningham & Egeth, 2016; Moher & Egeth, 2012). A key prediction of this model is that the first eye movement on a given trial should be biased <u>toward</u> the salient item, but subsequent eye movements should be biased <u>away</u> from the salient item. Testing this claim is challenging because once the first saccade has been made, the number of remaining items has changed, which needs to be considered when quantifying the likelihood that the next saccade is made to an item of a particular type. To overcome this obstacle, we employed an analysis approach developed by Beck et al. (2018).

The eye movements were first separated into *ordinal fixations*, which classifies the order in which different search items were fixated during search. These ordinal fixations treat consecutive fixations of the same object (e.g., fixating one part of an object and then immediately fixating another part of the same object) as a single fixation event. For each ordinal fixation, we classified the probability of fixating that item by chance from among the items that had not yet been fixated. For example, imagine a trial on which the first eye movement is directed to a singleton distractor and the second eye movement is directed to a nonsingleton distractor. The chance probability of the first ordinal fixation to the singleton distractor is 16.7% (1 out of 6) because there is 1 singleton item in the context of 6 items that had not previously been searched. Given that the first saccade went to the singleton, the chance probability that the second ordinal fixation is directed to one of the nonsingleton distractors is 80% (4 out of 5) because there are 4 unsearched nonsingleton distractors and 5 unsearched items. Chance probabilities were calculated for each ordinal fixation on each trial, considering the previous events on that trial and then averaged across trials. We then

compared the observed probability (i.e., the actual proportion of ordinal fixations for each item type) to the chance probability of attending a given item at that ordinal position - called an *odds ratio*. We then log transformed the odd ratio so that the measure is on a linear scale. Before the log transformation, odds ratios of zero were replaced with .083 (1 divided by twice the set size; see Beck et al., 2018). Participants rarely made more than 3 ordinal fixations, so ordinal fixations greater than 3 were excluded from the analysis.

The final log-transformed odds ratios for each ordinal fixation index are provided in Table 2. Positive values indicate that overt eye movements were more likely than chance to be directed to a given item; negative values indicate that the probability was below chance. For each ordinal fixation index, we found that the target was much more likely to be fixated than predicted by chance alone. This is potentially problematic because it will negatively skew the odds ratios for the other search items: the singleton distractors and nonsingleton distractors. Therefore, we subtracted the odds ratio of the nonsingleton distractor from the odds ratio of the singleton distractor to create an *odds ratio capture effect*. This effectively indicates whether the eye movements were more or less biased to be directed to the singleton distractor than the nonsingleton distractors (baseline). Therefore, we subtracted the odds ratio of the nonsingleton distractor from the odds ratio of the singleton distractor to create an *odds ratio capture effect*. This effectively indicates whether the eye movements were more or less biased to be directed to the singleton distractor than the nonsingleton distractors (baseline).

Odds ratio capture effects for each ordinal fixation are depicted in Figure 7c. As can be seen, first eye movements were biased toward the singleton compared to the nonsingleton distractor (*an initial capture effect*). This effectively replicates the effects shown in the above analysis on first eye movements. The key is that the second and third ordinal fixations were biased away from the singleton distractor compared to the nonsingleton distractor (a *reactive inhibition effect*). To formally analyze this pattern, we first ran a one-way repeated measures ANOVA on the odds-ratio capture effects with the factor ordinal index (1, 2, or 3). There was a clear main effect of ordinal fixation index, $F(2,62) = 37.08$, $p < .001$, $\eta^2 = .545$. We then tested the significance of each odds-ratio capture with a one-sample $t$ test. At the first ordinal fixation, there was a significant *capture effect*, $t(31) = 4.781$, $p < .001$, $d = .845$. However, there was a significant *suppression effect* for the second ordinal fixations, $t(31) = 3.427$, $p = .002$, $d = .606$, and for the third ordinal fixations, $t(31) = 4.00$, $p < .001$, $d = .707$.

## Discussion

These results clearly demonstrate that when a participant explicitly chose a color to ignore, first eye movements were more likely to be directed to the to-be-ignored item than predicted by baseline. Second and third eye movements, however, were less likely to be directed to the to-be-ignored item than predicted by baseline. This replicates previous findings of reactive inhibition (Beck et al., 2018; Cunningham & Egeth, 2016; Moher & Egeth, 2012) and provides strong evidence that participants cannot use an explicit goal to suppress a salient item from capturing attention.

It is important to ask whether the capture of attention by the color that the participant had just chosen as the to-be-ignored color was the result of low-level sensory priming. That is,

when the participants chose the to-be-ignored color, this was the last color they saw before the onset of the visual search array. However, previous research has shown that the effects of a color on oculomotor suppression are the same whether the color is cued by a color patch or a color name (see, e.g., Experiment 2 in Beck et al., 2017).

## General Discussion

Previous research has shown that salient distractors can be proactively inhibited to prevent attentional capture. Support for this claim has come from studies of psychophysics (Gaspelin et al., 2015), eye tracking (Gaspelin et al., 2017), event-related potentials (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018b; Sawaki & Luck, 2010), and even single-unit recordings (Cosman et al., 2018). However, it is unclear whether this ability to proactively suppress salient items is the result of a voluntary inhibitory process (i.e., an explicit goal) or an automatic consequence of previous attempts to ignore that feature (i.e., selection history). Problematically, most prior studies demonstrating inhibition of salient items held the colors of the search displays constant for the entire experiment (Cosman et al., 2018; Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018b). This conflates attentional guidance by selection history and attentional guidance by explicit goals. The current study directly tested whether voluntary proactive inhibition of a salient item is possible when that item is strongly primed by the previous target color.

In Experiment 1, we tested whether voluntary inhibition could overcome selection history by introducing a new *alternating colors condition*, in which the color of the singleton and target switched on each trial (see also Maljkovic & Nakayama, 1994). With this manipulation, the singleton on the current trial was primed by the color of the target from the previous trial. However, the singleton's color was also entirely predictable on each trial. If voluntary inhibition can overpower selection history, then participants should have been able to ignore the salient distractor - just as they do when the display colors are fixed for the entire experimental session. But this was clearly not the case - the primed singleton distractor elicited an oculomotor capture effect. This suggests that, even though participants knew the upcoming singleton color, priming of the singleton allowed it to capture attention. Experiment 2 replicated this same experimental design, but attempted to further encourage voluntary inhibition of the salient distractor by using a 100% valid word cue (e.g., "pink") to indicate the upcoming color of the target and singleton. Although previous research has shown that such color cues are very effective when they indicate the to-be-attended color (Beck et al., 2018; Wolfe et al., 2004), we found that they could not be used for suppression: the initial eye movements were biased toward rather than away from the singleton distractor item.

In Experiment 3, the color of the singleton was changed every five trials so that we could observe the transition from capture to suppression (see also Gaspelin & Luck, 2018a; Stilwell & Vecera, 2018; Vatterott, Mozer, & Vecera, 2018; Vatterott & Vecera, 2012). On the first of the five trials with a given singleton color, on which the target color from the previous five trials was now the singleton color, the singleton strongly captured gaze. After the singleton color was repeated for a few trials, however, an oculomotor suppression effect gradually developed. This finding indicates that the effects of selection history on inhibition

of salient items can be relatively long-lived and that it may take several trials for inhibition to build up. Note, however, that the transition from capture to suppression may reflect both a fading of priming from the previous set of five trials and a buildup of inhibition in the current set of five trials. This will be an interesting topic for future studies.

Experiment 4 assessed whether voluntary inhibition of salient distractors is possible even when the to-be-inhibited color was not the target color on the immediately preceding trials. At the beginning of each trial, participants selected the color of the upcoming singleton distractor. According to a straightforward model of volitional inhibition, this should maximize the likelihood that the singleton is suppressed. However, we found that the singleton distractor captured attention even though the participant had chosen it as the to-be-ignored color moments before, similar to previous studies of attentional white bear effects (Cunningham & Egeth, 2016; Moher & Egeth, 2012; Tsal & Makovski, 2006). Thus, Experiment 4 casts doubt on whether it is possible for voluntary control mechanisms to proactively inhibit salient items. However, reactive inhibition appears to be under voluntary control: Although the first eye movement was directed to the distractor, subsequent eye movements were biased away from it (see Beck et al., 2018, for a similar pattern of results).

Together, the results of the current study are clear: proactive inhibition of salient items is certainly possible (e.g., as in the fixed-color condition of Experiment 1 or last color repeat trials of Experiment 3), but it appears to result from multiple trials of experience with the singleton and target colors rather than an act of will. When the goal of suppressing a given color is placed in competition with priming from previous trials, the priming overpowers the goal (Experiments 1–3), and when participants can choose the to-be-ignored color in the absence of priming from the previous trial, they are unable to suppress this color (Experiment 4). These findings are consistent with selection history models of visual attention, which propose that attentional guidance is primarily the result of implicit learning from recent experience. Note that, with sufficient practice, participants may be able to voluntarily guide attention away from salient objects, either by suppressing their first-order features (e.g., Arita, Carlisle, & Woodman, 2012) or by suppressing some generalized salience signal (Sawaki & Luck, 2010; Vatterott, Mozer, & Vecera, 2018). Future research should explore the role of extensive training on the ability to avoid salient features.

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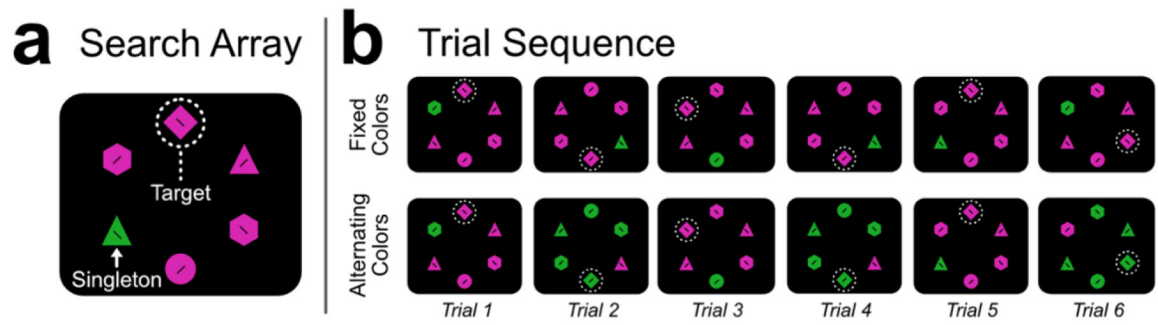
**Figure 1.**

Stimuli from Experiment 1. (A) Each search array contained a target and a singleton distractor. The other items are called nonsingleton distractors. The figure depicts a version of the experiment where the target was the diamond. (B) In the fixed-colors condition, the color of the target remained constant for the entire experimental session. In the alternating-colors condition, the target color and singleton color switched on each trial. In both panels, the target location is circled for illustrative purposes and was not circled in the actual experiment. In grayscale versions of this figure, pink objects are depicted in dark gray and green objects are depicted in white.

## a  Heat Maps of First Eye Movements
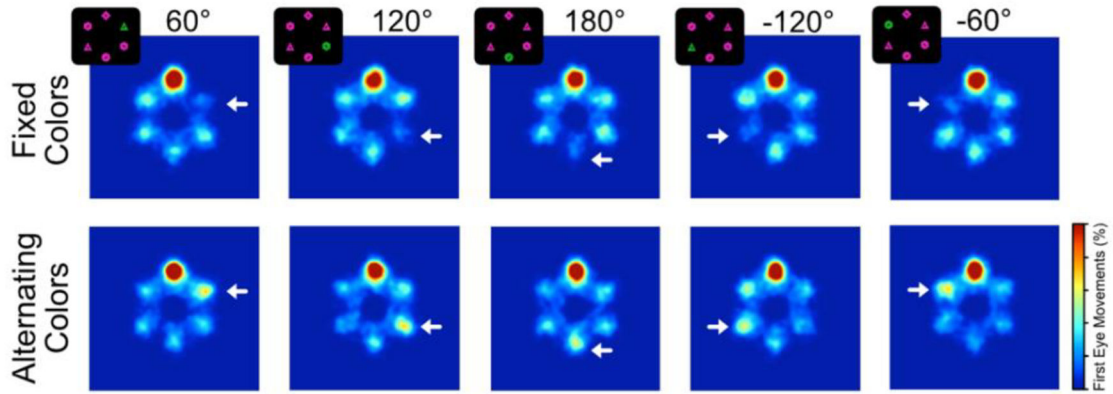


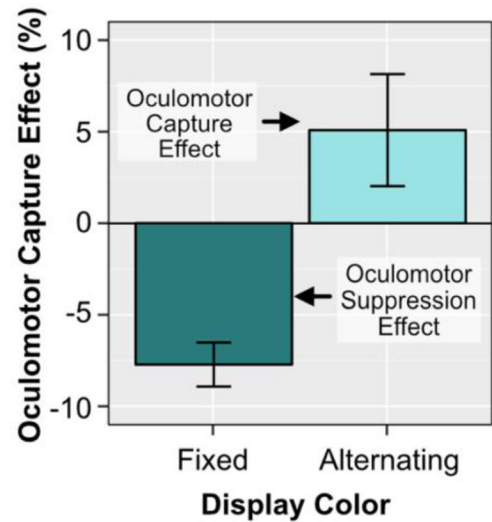## b  First Eye Movements
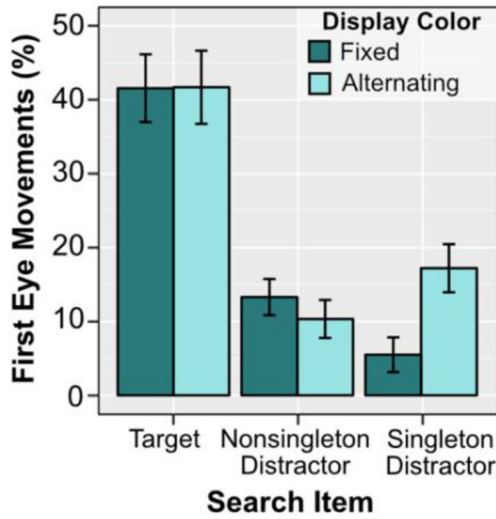
## c  Capture vs. Suppression
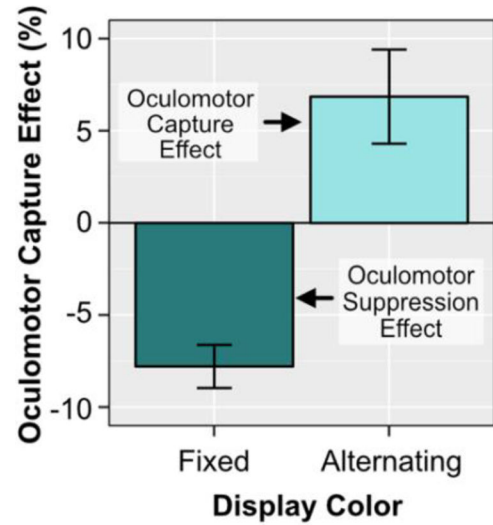


**Figure 2.**

First eye movement results from Experiment 1. (A) Heat maps of first eye movements for each singleton position relative to the target position. The data from each trial have been rotated so that the top location (12 o'clock position) contained the target. All heat maps in this paper were smoothed using a Gaussian kernel of 0.1° in visual angle. (B) Percentage of first eye movements to each search item as a function of display color condition. Error bars indicate the within-subject 95% confidence interval calculated for each group (Morey, 2008). (C) Oculomotor capture effects, which were calculated as the percentage of first eye movements to the nonsingleton distractor minus the percentage of eye movements to the singleton distractor. Error bars indicate the between-subject 95% confidence interval.
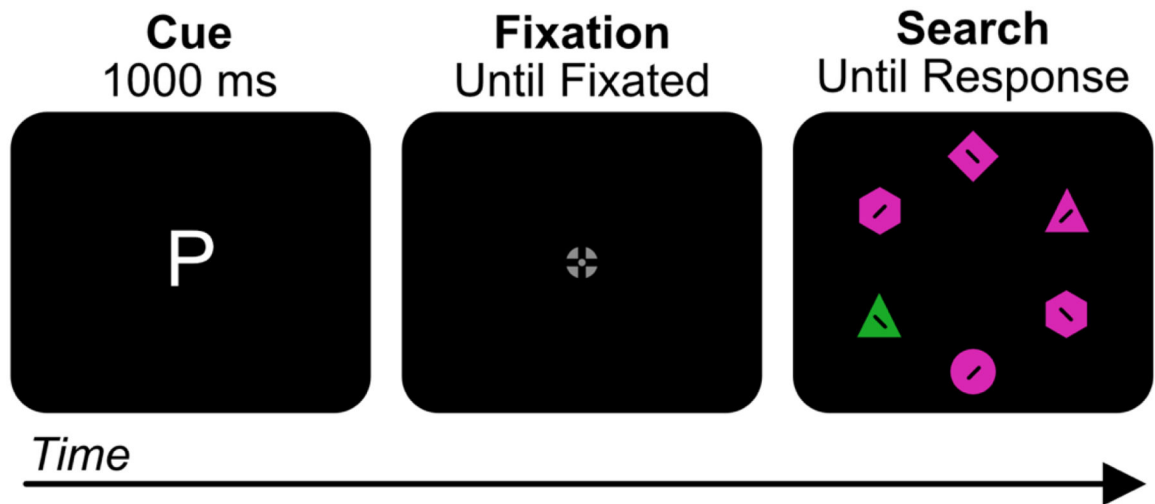
**Figure 3.**
The trial sequence from Experiment 2. This experiment was identical to the alternating-colors condition of Experiment 1, except that a central letter cue denoted the upcoming target color before the search array was presented. In grayscale versions of this figure, pink objects are depicted in dark gray and green objects are depicted in white.

**Figure 4.**
First eye movement results from the alternating-colors condition of Experiment 2 and the fixed-colors condition of Experiment 1. (A) Heat maps of first eye movements for each singleton position relative to the target position. (B) Percentage of first eye movements to each search item as a function of display color condition. (C) Oculomotor capture effects. All plots and error bars were calculated identically to Figure 2.
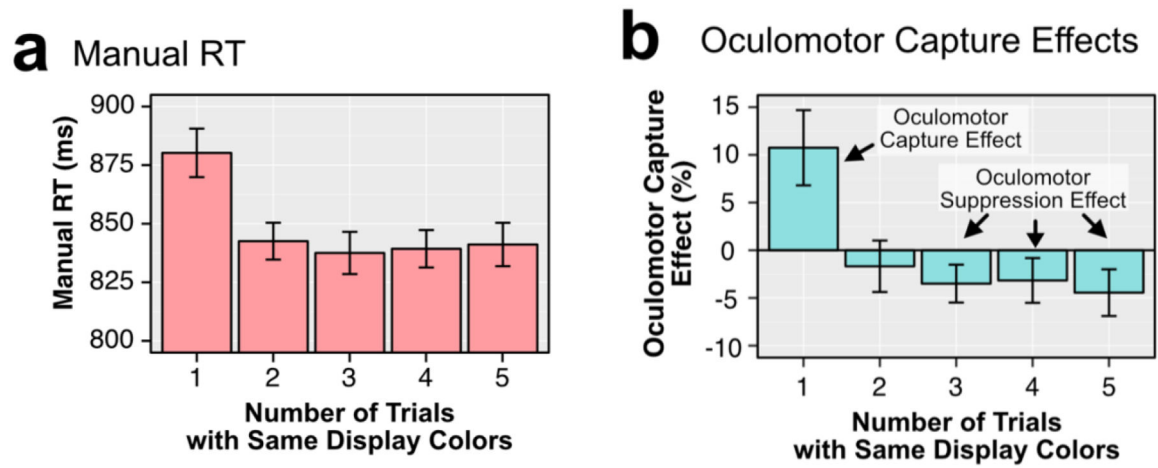
**Figure 5.**
Results from Experiment 3. (A) Manual response time as a function of the number of trials with the same display colors. (B) Oculomotor capture effects as a function of the number of trials with the same display colors. Error bars represent the 95% confidence intervals.
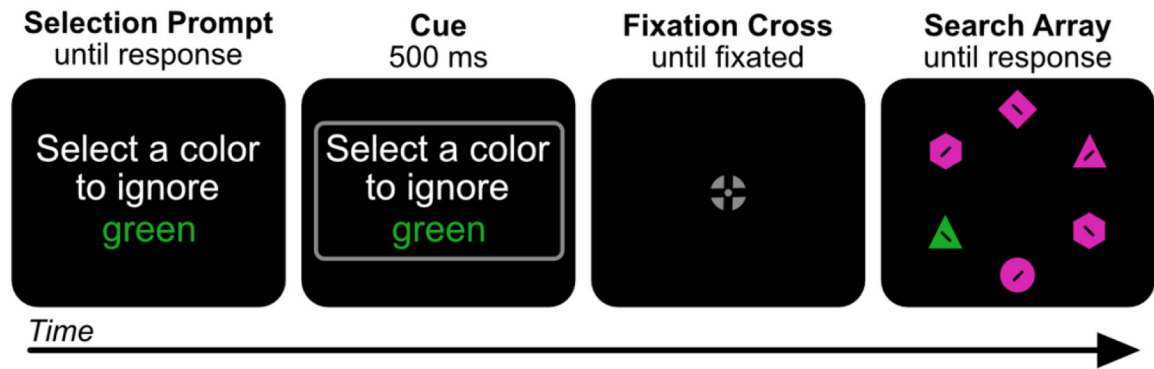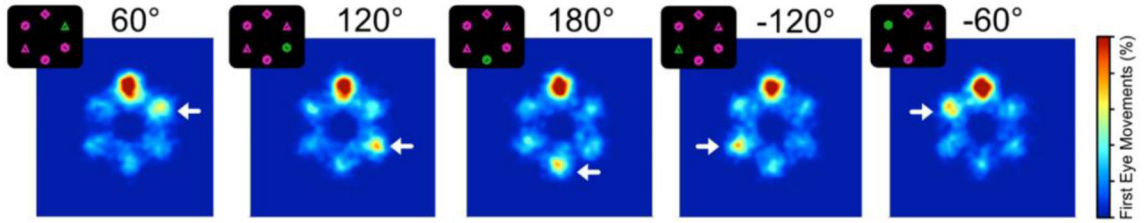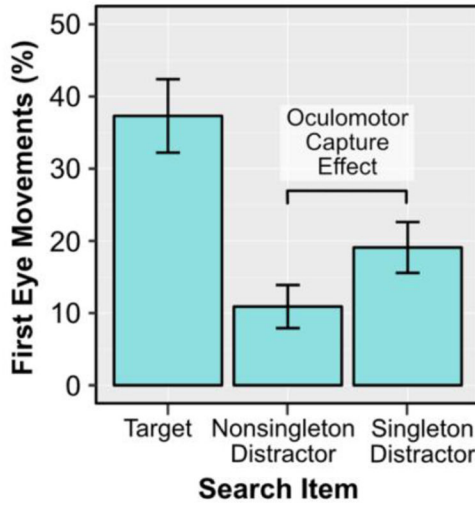
**Figure 6.**
Stimuli from Experiment 4. Participants performed the same attentional capture task from Experiments 1–3, but in this new version, they selected the to-be-ignored color at the beginning of the trial. In grayscale versions of this figure, pink objects are depicted in dark gray and green objects are depicted in white.
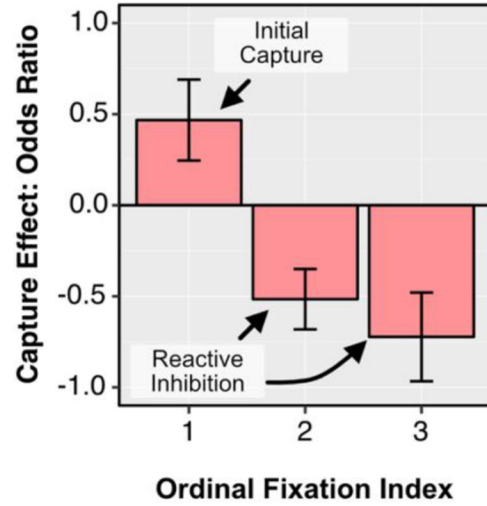
**Figure 7.**
Results from Experiment 4. (A) Heat maps of first eye movements for each singleton position relative to the target position. (B) Percentage of first eye movements to each search item. (C) Capture effects (expressed as a log odds ratio) as a function of ordinal fixation index (see also Beck et al., 2018). First eye movements are clearly biased toward the to-be-ignored item, and subsequent eye movements are biased away from the to-be-ignored item.

**Table 1**

Percentages of First Saccades Directed to Each Search Item as Function of the Number of Trials with the Same Display Color for Experiment 3.

| Number of Trials with Same Display Colors | Target | Nonsingleton Distractor | Singleton Distractor | Oculomotor Capture Effect |
|---|---|---|---|---|
| 1 | 39% | 10% | 21% | 11% |
| 2 | 42% | 12% | 10% | −2% |
| 3 | 43% | 12% | 9% | −3% |
| 4 | 42% | 12% | 9% | −3% |
| 5 | 41% | 13% | 8% | −4% |

Note. Percentages of first saccades to the nonsingleton distractor were corrected for the number of distractors (i.e., the number of all nonsingleton distractor fixations divided by four). Oculomotor capture effects were calculated as percentage of first saccades to the singleton distractor minus the first number of saccades directed to the average nonsingleton distractor. All values have been rounded to zero decimal places.

**Table 2**

Log-transformed odds ratios by search item type and ordinal fixation for Experiment 4.

| Ordinal Fixation | Target | Nonsingleton Distractor | Singleton Distractor | Capture Effect |
|:---:|:---:|:---:|:---:|:---:|
| 1 | 0.78 | −0.35 | 0.12 | 0.47 |
| 2 | 1.24 | −0.89 | −1.41 | −0.52 |
| 3 | 1.06 | −0.99 | −1.71 | −0.72 |

Note. Capture effects were computed as the odds ratio for the singleton distractor minus the odds ratio for the nonsingleton distractor. A positive value denotes capture and negative value denotes suppression.