

# Attentional capture by a perceptually salient non-target facilitates target processing through inhibition and rapid rejection

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Perceptually salient distractors typically interfere with target processing in visual search situations. Here we demonstrate that a perceptually salient distractor that captures attention can nevertheless facilitate task performance if the observer knows that it cannot be the target. Eye-position data indicate that facilitation is achieved by two strategies: *inhibition* when the first saccade was directed to the target, and *rapid rejection* when the first saccade was captured by the salient distractor. Both mechanisms relied on the distractor being perceptually salient and not just perceptually different. The results demonstrate how bottom-up attentional capture can play a critical role in constraining top-down attentional selection at multiple stages of processing throughout a single trial.

Keywords: attentional capture, salience, attentional selection, inhibition, rapid rejection, oculomotor capture, saccades

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## Introduction

To behave effectively in natural environments, it is necessary to selectively attend to task-relevant sensory information despite the fact that it almost always co-occurs with enormous amounts of irrelevant information. This tension between attending to either task-relevant or salient-but-irrelevant information has led to the frequent characterization of top-down and bottom-up attentional processes as being in competition (e.g., Bundesen, 1990; Buschman & Miller, 2007; Corbetta, Patel et al., 2008; Duncan & Humphreys, 1989; Gottlieb, 2007; Grent-'t-Jong & Woldorff, 2007; Mort, Perry et al., 2003; Muller & Rabbitt, 1989; Posner, Cohen et al., 1982; Treisman & Gelade, 1980; Wolfe, Cave et al., 1989).

The idea that top-down and bottom-up processes compete for attentional selection has led in part to a debate over the degree to which top-down selection can modulate bottom-up attentional capture by non-target stimuli. Some have argued that bottom-up selection depends on current top-down goals (e.g., Bacon & Egeth, 1994; Folk & Remington, 1998; Muller, Geyer et al., 2009; Proulx & Egeth, 2006a, 2006b; Proulx & Serences, 2006; Treisman & Gelade, 1980; Wolfe et al., 1989). These studies demonstrate that the likelihood of bottom-up attentional capture depends on the similarity of the non-target to the current target or task definitions (e.g., Bacon & Egeth, 1994; Folk, Remington et al., 1992; Hickey, McDonald

et al., 2006; Lavie & De Fockert, 2005; Leblanc, Prime et al., 2008; Serences & Yantis, 2007; Treue & Martinez Trujillo, 1999; Yantis & Egeth, 1999). Others have argued for greater independence between bottom-up selection and top-down goals and have shown that it is difficult (if not impossible) to completely suppress bottom-up attentional capture by stimuli with high default perceptual salience (e.g., Bruce & Tsotsos, 2009; Irwin, Colcombe et al., 2000; Muller & Rabbitt, 1989; Posner, Snyder et al., 1980; Theeuwes, 1995; Theeuwes, De Vries et al., 2003; Watson & Humphreys, 1997; Yantis & Hillstrom, 1994; Yantis & Johnson, 1990). Salient non-targets that produce attentional capture in these studies generally interfere with task processing.

While these previous studies have focused mainly on whether or not top-down processes can modulate bottom-up selection, the current study examines top-down attentional strategies for selection that occur in partnership with bottom-up attentional capture. The results demonstrate the interactive nature between top-down and bottom-up attentional processes and the degree to which the two can flexibly modulate each other. We use saccadic eye movements as a proxy for attentional selection and find evidence for the dynamic deployment of top-down strategies in response to attentional capture by a salient, but known, non-target on a trial-by-trial basis.

Voluntary saccades are thought to be preceded by shifts of covert attention (although saccades do not necessarily follow shifts of covert attention) and there is mounting

evidence that the two processes rely on similar mechanisms (e.g., Bisley & Goldberg, 2003; Corbetta, Akbudak et al., 1998; Deubel, 2008; Deubel & Schneider, 1996; Eimer, Van Velzen et al., 2006; Moore & Armstrong, 2003; Peterson, Kramer et al., 2004; Sato, Watanabe et al., 2003; Van Ettinger-Veenstra, Huijbers et al., 2009; Walker, Techawachirakul et al., 2009). Similarly, stimuli that capture covert attention automatically also produce oculomotor capture, a phenomena where saccadic eye movements are automatically directed toward salient objects (e.g., Godijn & Theeuwes, 2002; Hunt, Olk et al., 2004; Hunt, von Muhlenen et al., 2007; Irwin et al., 2000; Mulckhuyse, van Zoest et al., 2008; Theeuwes, Kramer et al., 1999). Patterns of saccadic eye movements therefore reflect shifts of covert attention and can be used as an indicator of attentional selection. As compared to studies of covert attention where only one measurement of RT or accuracy is acquired at the end of each trial, saccade data in a free viewing paradigm provides higher resolution measurements of behavior throughout a single trial. Such data were instrumental in our task for dissociating mechanisms of top-down selection that produce similar performance in final RT and accuracy.

Our primary findings (Experiment 2) demonstrate that top-down knowledge can modulate processing of a perceptually salient distractor in two ways: the first mechanism inhibits saccades to the salient distractor throughout the trial and the second rapidly rejects the salient distractor when it captures attention. Both mechanisms result in better performance compared to trials where the distractor is non-salient. To our knowledge, this is the first study in which facilitation in performance due to a perceptually salient distractor could be attributed to two different mechanisms based on trial-by-trial variability in the initial outcome of attentional competition. This finding suggests that prior knowledge and attentional selection interact at multiple time points throughout processing and that the strategic use of top-down knowledge can vary dynamically on a trial-by-trial basis.

## Experiment 1

Experiment 1 was conducted to first establish the efficacy of our manipulation of perceptual salience to capture

attention. Targets and distractors were equally likely to be perceptually salient and there was therefore no prior bias to select either the salient or non-salient object on each trial. The salient stimulus was expected to capture attention and the first saccade, irrespective of whether it was the target or distractor.

## Methods

Thirteen healthy young volunteers participated for class credit (12 females, ages 19–28 years, 11 right-handed). All gave written informed consent in accord with the local ethics clearance as approved by NIH. All had normal or corrected-to-normal vision. As with all reported experiments, handedness was determined by a shortened version of the Edinburgh handedness inventory (Oldfield, 1971). Data from two participants were excluded due to poor signal to noise in the eye-position data.

Each trial began with a fixation diamond on for a random interval varying between 1500 and 2000 ms to reduce anticipatory saccades. The blank interval was followed by the appearance of the visual search display for 600 ms. We chose a limited display duration in order to pressure subjects to employ a maximally efficient strategy. Stimuli were composed of “t”-like stimuli (see below; Figure 1). The stimuli were either low contrast (Michelson Contrast Ratio = 0.51; foreground luminance = 5.4 cd/m<sup>2</sup>, background luminance = 16.8 cd/m<sup>2</sup>) or high contrast (Michelson Contrast Ratio = 0.96; foreground luminance = 0.54 cd/m<sup>2</sup>, background luminance = 30.5 cd/m<sup>2</sup>). We chose to manipulate salience along contrast since high contrast stimuli are easily perceived, difficult to ignore behaviorally, and also elicit earlier and larger neuronal responses than lower contrast stimuli (e.g., Lee, Williford et al., 2007; Ling & Carrasco, 2006; Mansfield, 1973; Proulx & Egeth, 2006a, 2006b; Tartaglione, Goff et al., 1975; Theeuwes, 1995; Williford & Maunsell, 2006). We therefore refer to the high contrast stimulus as being “salient” and the low contrast stimulus as “non-salient”. The background was gray (9.8 cd/m<sup>2</sup>). The target was located randomly in the left or right lower visual field (6.3° of horizontal and vertical visual angle from fixation) and subtended approximately 0.9° of visual angle at fixation. Distractors were 90° rotations of target stimuli.

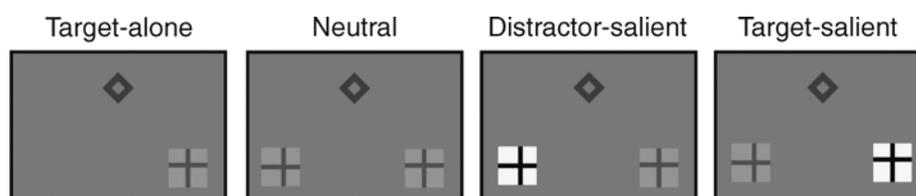


Figure 1. Example of the four conditions with an upright “t” target in the right visual field. Note that for illustrative purposes items are not drawn to scale.

A target was present on every trial. Distractors, when present, always appeared simultaneously with the target. There were four conditions: target-alone, neutral, distractor-salient, and target-salient (see Figure 1). The neutral condition consisted of a non-salient target and a distractor and served as a baseline control condition from which we could measure facilitation and interference effects as a function of target or distractor salience. The fixation diamond remained visible after the stimuli offset; the next trial began after the participant responded. Although the response was unsped, the display was only visible for 600 ms (see above). There were a total of 352 trials preceded by 20 practice trials.

Subjects were instructed to determine whether an upright or inverted “t” stimulus was present and to press the “j” key with their right middle finger if the “t” was upright and the “n” key with their index finger if it was inverted. Reaction times and accuracy data were collected for each trial. Subjects were told to be as accurate as possible. They were additionally instructed to fixate the diamond when no stimuli were visible but to move their eyes freely once the visual search display appeared. Eye-position data were recorded from the onset of the stimuli until a manual response was made. Fixation durations and saccade directions were analyzed.

Compliance with instructions to fixate the fixation diamond prior to each trial was monitored by experimenter observation and an automatic prestimulus fixation checker. Eye position was collected using an EyeLink 2K desk-mounted system (SR Research, ON) sampling at 250 Hz. Data from a trial were included only if the signal was adequate to determine that the first saccade was initiated from the fixation diamond within 500 ms and each fixation was within 1.25° from a stimulus edge (i.e., a 3.4° window).

## Results and discussion

Overall accuracy was high: 7% of the data were excluded based on behavioral errors and an average of 15% of trials was excluded based on eye-position criteria (see Methods section). Analyses of reaction time (RT) data were only conducted with trials for which correct behavior and eye data were obtained. We first conducted a repeated measures ANOVA with factors target location (left, right) and salience (target-alone, neutral, distractor-salient, target-salient) on RT data to test for any effect of target location on performance. The effect of target location on RT was not significant ( $F(1,10) = 0.0006$ ) nor was the interaction between target location and salience ( $F(3,30) = 0.2$ ). Based on this null result, we collapsed across target location in all subsequent analyses.

To test for more specific effects of perceptual salience on visual search performance, trials in each condition were classified based on whether the first saccade went to the target (*target-first* trials) or to the distractor (*distractor-first* trials). We first analyzed the proportion of *target-first*

trials in each condition to determine the likelihood of the first saccade being directed to the target or the distractor based on stimulus salience. We then describe the results for *target-first* and *distractor-first* trials separately in more detail.

The proportion of *target-first* trials in each condition were entered into a one-way repeated measures ANOVA. Only the three conditions where a distractor was present were included in this analysis since target-alone trials always resulted in first saccades to the target. The effect of salience on the proportion of *target-first* trials between conditions was significant ( $F(2,20) = 57.5$ ,  $p < 0.0005$ ), and all pairwise comparisons were also significant (all  $t(10) > 6$ ,  $p < 0.0005$ ; see Figure 2A).

As expected, the first saccade was more likely directed to the salient object, irrespective of whether it was the target or distractor (target-salient: 68% *target-first* trials; distractor-salient: 34.3% *target-first* trials). When neither object was salient, there were an equal number of first saccades to the target as to the distractor (neutral: 48.4% *target-first* trials). These data demonstrate that our manipulation of salience produced strong bottom-up capture that won the competition for selection and captured attention and the first oculomotor response. We next analyzed *target-first* and *distractor-first* trials independently to test for specific differences in performance between salience conditions, given the destination of the first saccade (Figure 2B).

### Target-first trials

Among *target-first* trials, a repeated measures ANOVA revealed a significant effect of salience on manual RT ( $F(3,30) = 28.6$ ,  $p < 0.0005$ ). Distractor-salient trials were significantly slower than target-salient trials ( $t(10) = 2.3$ ,  $p < 0.05$ ; Figure 2) but neither differed from neutral trials ( $t(10) < 1.5$ ). There was no significant difference in accuracy between conditions ( $F(2,20) = 1.4$ ). All distractor conditions were slower and less accurate than the target-alone condition ( $p < 0.05$ ; all post-hoc pairwise comparisons significant with Bonferroni correction unless otherwise stated).

Saccade latency did not differ significantly between conditions ( $F(3,30) = 1.7$ ), but distractor salience determined the likelihood of an additional second saccade being directed to the distractor after the target had already been fixated. Target-salient trials resulted in significantly fewer additional saccades to the distractor than distractor-salient trials ( $t(10) = 2.7$ ,  $p < 0.05$ ), but neither were significantly different from neutral trials ( $t(10) < 1.7$ ,  $p > 0.1$ ; % trials with additional saccades to the distractor: neutral = 72.3%, target-salient = 66.5%, distractor-salient = 79.7%).

A large proportion of trials in all conditions included second saccades to the distractor; this may have been due to a default strategy of planning saccades to both locations in order to maximize the chance of fixating the target within

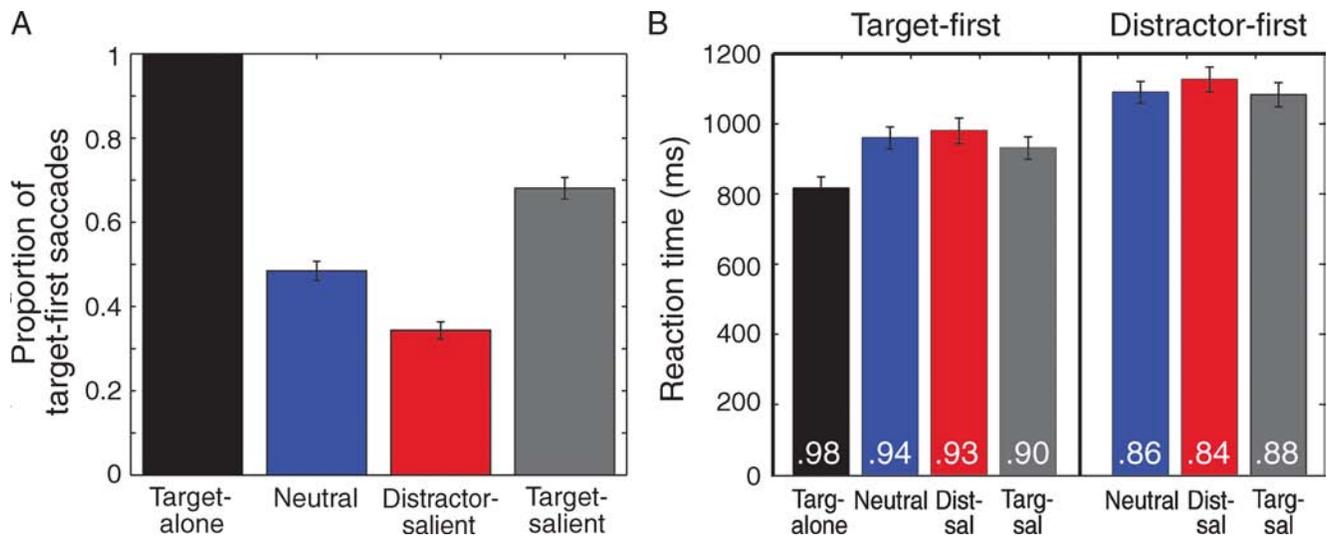


Figure 2. **Experiment 1.** (A) Proportion of *target-first* trials for each condition. First saccades were biased toward the salient item, irrespective of whether it was the target or distractor. (B) RT in each condition was divided into *target-first* trials where the first saccade was to the target (left panel) and *distractor-first* trials where the first saccade was to the distractor (right panel). Accuracy data for each condition are listed within the corresponding bar. When a distractor was present, RTs were longest when the distractor was salient and shortest when the target was salient. Error bars are standard error of the mean.

the short visual search exposure duration. However, the differences between conditions suggest that salience modulated the likelihood of a second saccade being executed. Salient targets were more likely to “hold” fixation on the target and salient distractors were more likely to capture a second saccade. This suggests that the sensory strength of the distractor continued to influence attentional and oculomotor selection throughout processing until a final decision was made (as indicated by a manual button press).

### Distractor-first trials

The additional time involved in making a saccade to the distractor before the target was fixated resulted in longer RTs overall on *distractor-first* trials compared to *target-first* trials ( $F(1,10) = 58.6, p < 0.005$ ). Additionally, because the search display was only visible for 600 ms, *distractor-first* trials were also more likely to result in a failure to fully process the target and lower accuracy ( $F(1,10) = 5.8, p < 0.05$ ).

Despite the overall cost in performance on *distractor-first* trials, salience had a significant effect on manual RTs ( $F(2,20) = 5.1, p < 0.05$ ); similar to *target-first* trials, RTs were longer for distractor-salient trials compared to target-salient trials ( $t(10) = 3.0, p < 0.05$ ) and neutral trials ( $t(10) = 2.9, p < 0.05$ ). Target-salient and neutral trials did not differ from each other ( $t(10) = 0.4$ ; **Figure 2B**). None of the conditions differed in accuracy (all  $t(10) < 1.3$ ). Even among *distractor-first* trials, salient distractors interfered

with target processing more than non-salient distractors demonstrating the efficacy of the salient object to capture attention (**Figure 2B**). There were no reliable differences in measurements of the saccade data.

## Experiment 2

The previous experiment established that the salient object tended to capture attention and the first saccade. The behavioral consequence of this capture was facilitation when the salient object was the target and interference when it was the distractor. We next asked whether knowledge that the salient item could never be the target would allow strategic mechanisms to use bottom-up salience to enhance, instead of interfere with, performance.

### Methods

Eleven healthy young volunteers participated for class credit (11 females, ages 19–24 years, 10 right-handed). These subjects did not participate in the previous experiment. Data from one participant were excluded due to poor quality eye-position data. The experimental design and analysis procedures were identical to **Experiment 1**, but now included only the target-alone, neutral, and distractor-salient

conditions. There were a total of 360 randomly interleaved trials preceded by 20 practice trials. Participants were explicitly told that the target would never be salient (i.e., high contrast) and to be as accurate as possible.

## Results and discussion

Overall accuracy was high: 10% of the data were excluded based on behavioral errors and an average of 11% of trials was excluded based on eye-position data. All subsequent analyses included data only from trials with correct manual responses and clean eye data. The analysis procedures were identical to [Experiment 1](#). As before, we first tested for the effect of target location on manual RT using a repeated measures ANOVA. There was no overall effect of target location on RT ( $F(1,9) = 0.44, p > 0.5$ ), nor an interaction between target location and distractor salience ( $F(2,18) = 2.6, p > 0.1$ ); target location was therefore collapsed in all subsequent analyses.

The data were next divided into *target-first* and *distractor-first* trials based on the destination of the first saccade. Although participants knew that saliency was never a feature of the target, this prior knowledge was insufficient to entirely override oculomotor capture by the salient distractor; there were significantly more *target-first* saccades on neutral (55%) compared to distractor-salient (43%) trials ( $t(9) = 3.8, p < 0.005$ ; [Figure 3A](#)). This suggests that the salient stimulus won the competition for attention and the first saccade, despite top-down knowledge that it could not be the target. Next, we examined the consequence of this tendency for the salient distractor to still capture attention on saccade performance and manual responses.

### Target-first trials

RT and accuracy data from all *target-first* trials ([Figure 3B](#)) were analyzed using repeated measures ANOVA. Manual RTs were distributed as a function of distractor competition ( $F(2,18) = 41.8, p < 0.0005$ ): RTs were shortest on target-alone trials and longest on neutral trials and both were significantly different from distractor-salient trials, which were intermediate (all  $t(9) > 4.9, p < 0.005$ ). Accuracy data produced a similar pattern of effects ( $F(2,18) = 4.3, p < 0.05$ ), but now only the comparison between target-alone and neutral trials was significant ( $t(9) = 2.3, p < 0.05$ , uncorrected).

Importantly, these results are opposite to those from [Experiment 1](#): RTs were now facilitated on distractor-salient trials compared to neutral trials (cf. [Figures 2 and 3](#)). In [Experiment 1](#), saliency was equally likely to be a feature of the target or distractor and under those conditions the salient distractor interfered with discrimination of a less salient target, resulting in longer RTs. In contrast, in [Experiment 2](#), saliency could only be a property of the distractor and now the salient distractor *facilitated* performance such that RTs were shorter when the distractor was salient compared to non-salient.

Eye-position data indicated that the facilitation in manual RT on distractor-salient trials was due to an inhibitory mechanism late in processing that decreased the likelihood of a second saccade to the distractor combined with a second strategy of more rapidly rejecting the distractor when it was fixated. Although it may seem counterintuitive that there should be second saccades to the distractor after the target had already been fixated, recall that the search display was on for a limited duration and subjects may have used a default strategy of planning saccades to both objects in order to maximize target detections. RTs were shorter on

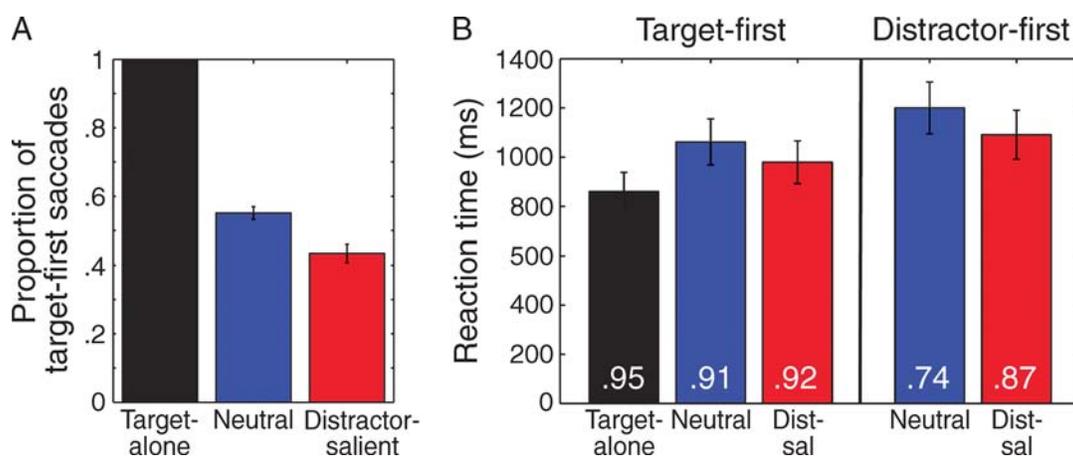


Figure 3. [Experiment 2](#). (A) Proportion of target-first trials for each distractor salience condition. Despite never being the target, salient distractors still captured attention on more than half of trials (i.e., fewer than 50% target-first trials). (B) RT in each salience condition was divided into target-first trials where the first saccade was to the target (left panel) and distractor-first trials where the first saccade was to the distractor (right panel). RTs were significantly faster for distractor-salient compared to neutral trials, both when the first saccade went to the target and when it went to the distractor. Accuracy data for each condition were listed within the corresponding bar. Error bars are standard error of the mean.

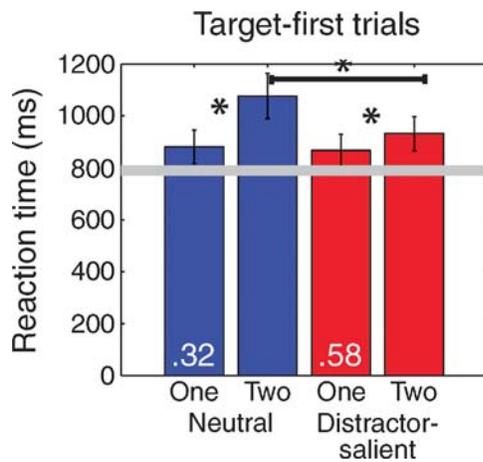


Figure 4. RTs in the neutral and distractor-salient conditions as a function of whether one or two saccades were generated on the trial. Two-saccade trials included a second saccade to the distractor. One-saccade trials were significantly faster than two-saccade trials. The proportion of one-saccade trials in each condition is listed within the corresponding RT bar. There were significantly more one-saccade trials in the distractor-salient condition. Gray line represents RTs on target-alone trials among the subjects included within this analysis (see text).

one-saccade trials, suggesting that performance was optimized when the second saccade to the distractor was inhibited: one-saccade trials were significantly faster than two-saccade trials overall (Figure 4;  $F(1,7) = 23.6$ ,  $p < 0.005$ )<sup>1</sup> and there were significantly fewer two-saccade trials when the distractor was salient ( $t(9) = 5.3$ ,  $p < 0.0005$ ; proportion of one-saccade trials: distractor-salient = 0.58; neutral = 0.32; Figure 4). While RTs were shorter on one-saccade than two-saccade trials, they were still slower than target-alone trials (both  $t(7) > 3.3$ ,  $p < 0.05$ ; gray line in Figure 4), suggesting that the presence of a distractor slowed processing even when no overt eye movement was made. More importantly, however, the degree of interference afforded by the distractor varied as a function of its salience such there were more one-saccade trials when the distractor was salient compared to non-salient and these trials resulted in shorter RTs.

Analysis of fixation durations on the target suggest that the reason two-saccade trials resulted in longer RTs was due to truncated processing of the target: fixation durations on the target were significantly shorter when a second saccade was executed (neutral condition: one-saccade = 436.5 ms, two = 194.8 ms; distractor-salient condition: one = 443.3 ms, two = 235.5 ms). In fact, fixation durations on one-saccade trials were similar to that on target-alone trials (469.5 ms), suggesting that the longer fixation duration reflected the time needed to discriminate and make a decision regarding the orientation of the target. Fixation durations on target-alone trials were not different

from one-saccade trials in either condition (both  $t(7) < 0.96$ ) and were significantly longer than two-saccade trials in both conditions (both  $t(7) > 8.4$ ,  $p < 0.0001$ ).

In addition to fewer second saccades, there was still an RT benefit on two-saccade trials when the distractor was salient, suggesting that a second mechanism contributed to the pattern of shorter RTs when the distractor was fixated (see Figure 4). The difference in RT between one- and two-saccade trials was smaller when the distractor was salient and the interaction between the number of saccades and salience was significant ( $F(1,7) = 9.2$ ,  $p < 0.05$ ; see Figure 4); analyses of the simple effects demonstrated that in addition to one-saccade trials being faster than two-saccade trials in both salience conditions (both  $t(7) > 3.1$ ,  $p < 0.05$ ), RTs on two-saccade trials were shorter when the distractor was salient compared to non-salient ( $t(7) = 3.0$ ,  $p < 0.05$ ).

Facilitation on two-saccade trials is likely due to a second strategy of *rapid rejection* in which processing of the salient distractor was terminated more rapidly based on its surface feature (see Distractor-first trials section below). Consistent with that notion, fixation durations on salient distractors were significantly shorter than fixations on non-salient distractors ( $t(7) = 3.2$ ,  $p < 0.05$ ; fixation duration: neutral = 350.0 ms, distractor-salient = 261.2), indicating that less time was spent processing the salient distractor before making a saccade away.

In sum, among *target-first* trials, performance was facilitated when the distractor was salient compared to non-salient. Knowledge that the salient feature was never a property of the target increased the likelihood that inefficient second saccades were inhibited when a salient distractor was present and also by allowing *rapid rejection* of salient distractors once they were fixated. This result is opposite to that in Experiment 1, when salience was not informative and salient distractors interfered with responses.

### Distractor-first trials

Overall performance suffered when the first saccade went to the distractor instead of the target: RTs were longer on *distractor-first* compared to *target-first* trials ( $F(1,9) = 14.6$ ,  $p < 0.005$ ), and accuracy was lower ( $F(1,9) = 20.0$ ,  $p < 0.005$ ). Despite the fact that performance declined when the first saccade was directed to the distractor and subjects knew that the salient object was never the target, there were still more *distractor-first* trials in the distractor-salient condition than the neutral condition (57% vs. 45%; see Figure 3A). The larger proportion of distractor-first trials was driven by bottom-up attentional and oculomotor capture: saccade latencies were faster to a salient compared to non-salient distractor ( $t(9) = 4.3$ ,  $p < 0.005$ ; neutral = 213.4 ms; salient = 199.1 ms). Thus, despite knowledge that the salient item was never the target,

bottom-up capture still won the competition for selection more often than not.

Although prior knowledge failed to prevent the first saccade from being captured by the salient distractor, performance was still better on *distractor-first* trials when the distractor was salient: RTs were shorter for distractor-salient compared to neutral trials ( $t(9) = 3.78, p < 0.01$ ) and accuracy was higher ( $t(9) = 2.8, p < 0.05^2$ ; see Figure 3B). The facilitation by salient distractors was similar to *target-first* trials (see above). Again, these results were opposite to those from Experiment 1 where performance was worse on *distractor-first* trials when the distractor was salient.

Analysis of fixation dwell times suggests that performance was bootstrapped by the strategy of rapid rejection once the salient object was fixated. Mean fixation dwell times were shorter on the salient-distractor compared to the non-salient distractor ( $t(9) = 3.2, p < 0.01$ ; neutral = 252.5 ms, distractor-salient = 158.8 ms). Additional analyses of the distribution of fixation dwell times further shows that there were a greater proportion of trials with short fixation dwell times (at 100 and 150 ms) in the distractor-salient condition and a greater proportion of trials with longer fixation dwell times (at 250–450 ms) in the neutral condition (Figure 5; all  $t(9) > 2.2, p < 0.05$ ). Subjects spent less time examining the salient distractor and this led to faster saccades to the target and shorter RTs.

To rule out the possibility that salient distractors were rejected more rapidly because high contrast stimuli are easier to perceive than lower contrast stimuli, we compared fixation durations on distractors from *distractor-first* trials from Experiments 1 and 2. Fixation durations on identical salient distractors were significantly shorter in Experiment 2 ( $F(1,19) = 35.0, p < 0.0005$ ; Experiment 1 = 235.3 ms, Experiment 2 = 158.8 ms). In contrast, fixation durations

on neutral distractors from the two experiments did not differ ( $F(1,19) = 0.2$ ; Experiment 1 = 249.3 ms, Experiment 2 = 252.5). This demonstrates that the short fixation durations on salient distractors in Experiment 2 could not be due to the perceptual processing of high and low contrast stimuli *per se* but must have been due to the experimental context.

Although the salient distractor captured the first saccade on more than half of trials, performance was facilitated by the *rapid rejection* of the salient distractor once it was fixated. Knowledge that a salient item could never be the target-influenced processing even after inhibition of the prepotent response to the salient item initially failed. This suggests that top-down selection responded to the presence of bottom-up capture by initiating a response to *rapidly reject* the distractor and generate a second saccade immediately to the target.

### Experiment 3

In order to establish the degree to which *inhibition* and *rapid rejection* relied specifically on bottom-up processing of a perceptually salient feature, we next tested whether a distractor that differs reliably from the target in color, but does not produce strong attentional capture, will also facilitate target detection in our paradigm. A critical role for perceptual salience in producing the results from Experiment 2 would suggest that behavioral facilitation was due to interactions between top-down and bottom-up attentional processes. If perceptual salience is not critical, however, it would suggest that top-down selection mechanisms were sufficient for generating *inhibition* and *rapid rejection* within a single trial.

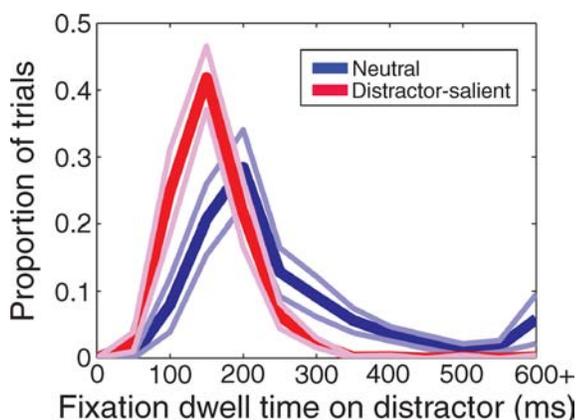


Figure 5. Experiment 2. Distribution of fixation dwell times on the distractor during *distractor-first* trials. There were a greater number of trials with short fixation durations when the distractor was salient (red) and a greater number of trials with longer fixation durations when the distractor was neutral (blue). Time values on x-axis represent bin centers. Lighter boundary lines are standard error of the mean.

### Methods

Sixteen new volunteers participated (11 females, 18–34 years, 16 right-handed). Data from six participants were excluded due to poor signal to noise in the eye-position signal or accuracy lower than 50% in one or more conditions. The procedure was identical to that of Experiment 2. The stimuli were modified so that the target and distractor now differed in color rather than in luminance or contrast (as in Experiments 1 and 2). The colors were chosen such that neither was inherently more perceptually salient than the other, but yet were still clearly distinguishable from each other. To do so, the background of the non-salient stimulus from the previous experiments was changed to light blue ( $19.6 \text{ cd/m}^2$ ) or pink ( $13.1 \text{ cd/m}^2$ ); the foreground gray value was not changed. The contrast between the blue and pink stimuli was similar (blue = 0.56, pink = 0.41) and appeared subjectively near equiluminance. As in Experiment 2, subjects were explicitly told that sometimes the non-target would be a different color and that the target would never be that color (either pink or light blue).

The discriminability of these stimuli at fixation were tested separately to be sure that it was possible to distinguish between the blue and pink items while fixating the central fixation diamond (see [Supplemental materials](#)). Without moving their eyes, subjects were clearly able to determine whether the two objects were the same or different in color and when different, identify which of the two was pink or blue. Any differences in performance from [Experiment 2](#) therefore could not be due to an inability to perceive which stimulus was “different” at the beginning of the trial. As before, the stimuli were  $6.3^\circ$  of visual angle from central fixation.

Target color (light blue, pink) was counterbalanced between participants and the distractor was randomly light blue or pink on 50% of trials each. Subjects were told to be as accurate as possible.

## Results and discussion

Overall accuracy was high: 6.4% of the data were excluded based on behavioral errors and an average of 10.5% of trials was excluded based on eye-position criteria. A repeated measures ANOVA with the factors target color (pink, blue), target location (left, right), and distractor similarity (target-alone, same, different) was used to test the effect of target color and location on our primary condition of interest involving distractor similarity. There were no significant effects associated with target color in RT or accuracy (main effects:  $F(1,8) = 0.4$ ;  $F(1,8) < 0.001$ ; interaction with distractor condition:  $F(2,16) = 1.3$ ;  $F(2,16) = 0.02$ ), nor with target location (main effect:  $F(1,8) = 0.27$ ,  $F(1,8) = 2.4$ ; interaction with distractor condition:  $F(2,16) = 1.1$ ,  $F(1,16) = 0.02$ ). This demonstrated

that the same pattern of effects was found irrespective of target color and location. All subsequent analyses therefore collapse across both target color and location.

As before, the data were first divided into *target-first* and *distractor-first* trials. Analyses of the proportion of *target-first* trials in each distractor condition revealed no significant difference between same and different distractors ( $t(9) = 0.5$ ,  $p = 0.6$ ); there were an equal number of *target-first* saccades when the distractor was the same color as the target (58.0%) and when it was a different color (58.2%; [Figure 6A](#)). This is in contrast to both [Experiments 1](#) and [2](#), where the salient distractor was more likely to capture the first saccade (see [Figures 2A](#) and [3A](#)). Similar to previous experiments, however, RTs were slower on *distractor-first* compared to *target-first* trials ( $F(1,9) = 12.0$ ,  $p < 0.01$ ), but there was no difference in accuracy ( $F(1,9) = 3.2$ ).

Importantly, there were no significant differences in manual RT or accuracy between same and different distractor conditions for *target-first* trials (RT:  $t(9) = 0.03$ ,  $p = 0.9$ ; accuracy:  $t(9) = 0.4$ ,  $p = 0.7$ ; [Figure 6B](#)). As expected, however, there was a difference in RT between target-alone and both distractor present conditions for *target-first* trials (both  $t(9) > 4.8$ ,  $p < 0.001$ ). There was no difference in accuracy (both  $t(9) < 0.9$ ). Performance was faster and more accurate when no distractor competition was present, but there was no difference in performance based on distractor color.

Similar to the manual RT data, fixation durations on the target differed based on distractor conditions ( $F(2,19) = 9.3$ ,  $p < 0.005$ ), but this was entirely due to longer target fixation dwell times in the target-alone compared to the two distractor conditions (same:  $t(9) = 3.1$ ,  $p < 0.05$ ; different:  $t(9) = 3.0$ ,  $p < 0.05$ ); there was no difference in target fixation times based on whether the distractor was the same

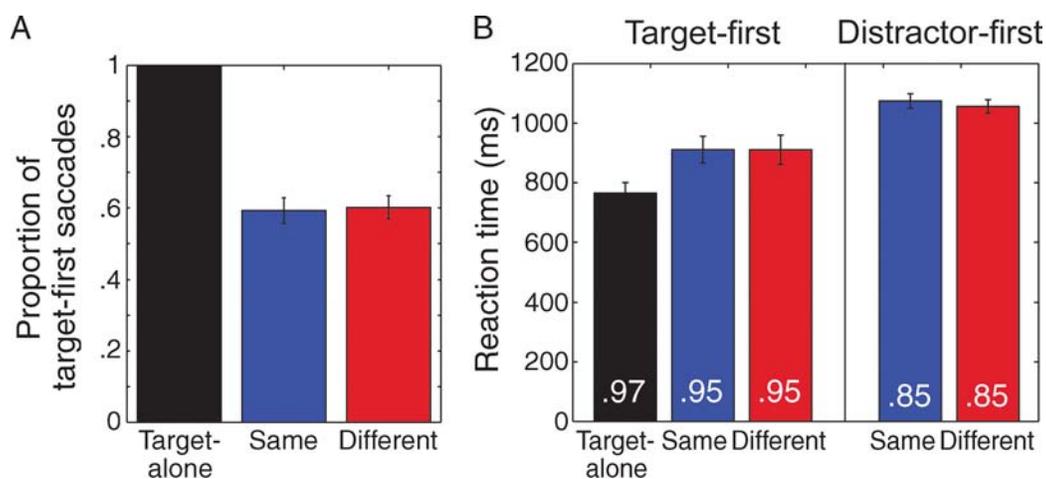


Figure 6. [Experiment 3](#). (A) Proportion of *target-first* saccades in the three distractor conditions. There was no difference based on whether the distractor was in the same or different condition. (B) RT in each of the distractor salience conditions was divided into *target-first* trials (left panel) or *distractor-first* trials (right panel). There were again no significant differences based on whether the distractor was the same or different. Error bars are standard error of the mean.

or a different color ( $t(9) = 0.7$ ). There was now also no difference between same and different distractor conditions in the likelihood of additional second saccades to the distractor ( $t(9) = 0.4$ ; same = 40.6%, different = 39.7%).

Similarly, there were also no significant differences in performance between same and different distractor conditions on *distractor-first* trials (RT:  $t(9) = 1.5$ ; accuracy:  $t(9) = 0.7$ ). There were also no differences in distractor fixation dwell times ( $t(9) = 0.4$ ), suggesting that subjects did not use *rapid rejection* as a strategy to facilitate behavior when the distractor was different in color (cf. Figure 3B).

In contrast to Experiments 1 and 2, different colored distractors did not facilitate performance in this experiment. The results demonstrate a boundary condition in which a distractor that is clearly perceptually different, but not salient, does not produce the same pattern of inhibition and rapid rejection seen in the previous experiment (see General discussion section). These data suggest that the results from Experiments 1 and 2 depended on top-down selection in response to a perceptually salient distractor that captured bottom-up attention. Perceptual difference was not sufficient to produce bottom-up attentional capture and initiate these top-down attentional strategies.

## General discussion

Perceptually salient non-targets are most commonly thought of as interfering with target detection and discrimination. Here we report the result that a perceptually salient distractor that captures attention can facilitate behavior when it is predictably the non-target (Experiment 2). The same results were not found for a perceptually distinct but non-salient distractor. Eye-movement data demonstrated that the facilitation was mediated by parallel mechanisms of *inhibition* and *rapid rejection*. *Inhibition* occurred on *target-first* trials and was evident in significantly fewer additional saccades to the distractor once the target had been fixated.

Inhibition was seen most clearly late in the trial as fewer additional saccades to the salient distractor. Although it may seem odd that there should be second saccades to the distractor after the target had already been fixated at all, subjects may have developed a default strategy of planning saccades to both locations in order to maximize the likelihood of finding the target within the limited 600-ms exposure duration. The interesting difference between experiments, however, was the frequency with which second saccades to the distractor were executed on *target-first* trials: in Experiment 1, the salient distractor elicited more additional saccades whereas in Experiment 2, the salient distractor elicited fewer additional saccades compared to neutral distractors. Although it may be surprising that a salient object could elicit fewer second saccades late in a trial, we would suggest that inhibition was successful

precisely because top-down selection mechanisms used the strong bottom-up salience to “mark” the object as a non-target. When the non-target was not perceptually salient in Experiment 3, bottom-up capture would be too weak to be used as a trigger for initiating a top-down strategy of inhibition.

Interestingly, despite prior knowledge that the target was never salient, 57% of distractor-salient trials in Experiment 2 resulted in oculomotor capture. On these trials, the first saccade was captured by the salient distractor (as indicated by rapid saccade latencies), but a compensatory strategy was used to rapidly reject the distractor once it was fixated: fixation dwell times were shorter on salient than non-salient distractors, allowing for a more rapid saccade to the target. There are at least three possible explanations for *rapid rejection*: the first is that the “t” discrimination was simply easier to make with a high contrast stimulus and therefore it could be completed earlier. This is unlikely because fixation times on the same salient distractor in Experiment 1 were not faster than fixation times on non-salient objects. A second possibility is that the second saccade plan was initiated even while the first saccade to the distractor was captured. This could happen if processing associated with oculomotor capture could be used as an early error signal to trigger a second oculomotor plan to be initiated before the first one was even completed. A third possibility is that rapid bottom-up processing of the salient surface feature (high contrast and luminance) led to faster disengagement from the salient distractor before a full discrimination was made. The latter two possibilities are not mutually exclusive since they operate at different processing points and could have both contributed to our current results.

It may seem surprising that we did not find any effects in Experiment 3 based on the color dissimilarity of the distractor to the target. Results from previous findings reviewed in the Introduction section may seem to suggest that differently colored distractors should be inhibited more effectively. Our paradigm differed from those studies in several ways. First only two objects were present at once, and therefore, any simultaneous contextual pop-out effects would be reduced (e.g., a pink object is not by default more salient than a blue one whereas a high contrast stimulus is always more salient than a lower contrast stimulus). Additionally, it may be that the degree of effort required to maintain and use near equiluminant color information in working memory for selection was too great given the relatively low cost of simply making more saccades. A top-down response strategy may only be worthwhile when the strength of a salient stimulus is sufficient to produce automatic capture as in Experiment 2. Thus, we argue that our results in Experiment 2 are due to bottom-up attentional capture constraining top-down selection.

Although we did not find effects for clearly dissimilarly colored distractors, one might argue that our RT results were due to greater target–distractor dissimilarity in Experiment 2 than in Experiment 3. While salience may indeed be defined

by a threshold in the magnitude of difference between stimuli along a continuous dimension, our effects cannot be due simply to the fact that the distractor was just more different from the target in [Experiment 2](#) than in [Experiment 3](#). First in [Experiment 2](#), there were still more first saccades to the salient distractor than to the target (see [Figure 3A](#); indeed more than in [Experiment 3](#), see [Figure 6A](#)). This indicates that subjects were not able to use the fact that the distractor was very different from the target template to avoid making a saccade to the salient distractor (as one would expect if attention were only directed to the stimuli that are similar to the target). Second, saccade latencies on *distractor-first* trials indicate that salient distractors produced oculomotor capture, an involuntary saccade to a salient stimulus that is thought to follow attentional capture. This argues against the idea that RT facilitation for salient distractors was a result of more dissimilar distractors being less likely to capture attention. Third, there was no pattern of rapid rejection in [Experiment 3](#), even after the distractor had been fixated. If rapid rejection was a mechanism that can be used for any dissimilar distractors, then one would expect that a clearly differently colored distractor could be rapidly rejected after being fixated even when it could not be inhibited initially, but this is not what was found (there was no trend in this direction). This rather suggests that rapid rejection in [Experiment 2](#) was due to a rapid top-down response to the signal of bottom-up attentional and oculomotor capture by a known non-target.

In summary, our results demonstrate the flexibility and speed with which prior knowledge guides top-down attention in response to the presence of a salient bottom-up signal. Our results showed that prior knowledge of stimulus statistics led to the use of mechanisms that improved performance at multiple stages of processing. The strategies of *inhibition* and *rapid rejection* could not have been distinguished without eye-tracking data since RTs were shorter for distractor-salient than neutral trials on both *target-first* and *distractor-first* trials. The oculomotor data provided finer discrimination of attentional processes that can only be assumed to occur during covert measurements. These data highlight the continuous and interactive dynamics between knowledge of stimulus statistics and on-going interactions between top-down and bottom-up attentional selection.

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## Footnotes

<sup>1</sup>The decrease in degrees of freedom due to the fact that two subjects always made two saccades in the neutral condition therefore was excluded from these statistical analyses.

<sup>2</sup>Accuracy remains significantly different even when only considering neutral trials in which the target was successfully fixated after a second saccade ( $t(9) = 2.9$ ,  $p < 0.05$ ).

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