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When Does Feature Search Fail to Protect Against Attentional Capture?

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Abstract

When participants search for a shape (e.g., a circle) among a set of homogenous shapes (e.g., triangles) they are subject to distraction by color singletons that are more salient than the target. However, when participants search for a shape among heterogeneous shapes, the presence of a non-target color singleton does not slow responses to the target. Attempts have been made to explain these results from both bottom-up and top-down perspectives. What both accounts have in common is that they do not predict the occurrence of attentional capture on typical feature search displays. Here, we present a case where manipulating selection history, rather than the displays themselves, leads to attentional capture on feature search trials. The ability to map specific colors to the target and distractor appears to be what enables resistance to capture during feature search.

Keywords

attentional capture; attentional control; feature search; search modes; selection history

The control of visual attention has been the subject of intensive investigation in recent years. Particular emphasis has been placed on the analysis of situations in which attention seems to be "captured" by task-irrelevant stimuli. Theeuwes (1991) found that when observers searched for a pop-out singleton target along a particular dimension, response times were slower in the presence of a more salient singleton along another dimension. That is, pop-out singletons along the irrelevant dimension captured attention. It did not appear that the initial guidance of attention could be controlled by top-down selection of a particular dimension. A follow-up experiment by Theeuwes (1992) found a lack of top-down selectivity even with practice. Theeuwes has argued (see especially Theeuwes, 2004, 2010) that capture by the most salient stimulus in the display is automatic, that is, not under top-down control.

Several studies that took place around the same time as Theeuwes's initial studies came to essentially the opposite conclusion—that the initial orientation of attention depends on an observer's top-down attentional control settings. Folk, Remington, & Johnston (1992) used a spatial cuing paradigm in which a search display was preceded by a cue display (the cue actually had no predictive value). They found that when participants searched for a target defined by color, a color cue could misdirect attention, but a sudden onset cue did not.

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Conversely, when participants searched for an onset target, an onset cue could misdirect attention, but a color cue did not. That is, the top-down control setting (e.g., “search for red”) determined whether an irrelevant stimulus captured attention or not.

How can the strikingly different outcomes of the Theeuwes (1991, 1992) and Folk, Remington, and Johnston studies be reconciled? Bacon and Egeth (1994) suggested that the notion of top-down sets could explain the results found in Theeuwes's additional singleton paradigm. They pointed out that participants were instructed to search for a circle among diamonds, but they may not have followed those instructions; instead they may have searched for a distinctive item. That is, following a suggestion of Pashler (1988), they argued that the trials in Theeuwes's task could actually be handled in one of two different ways by participants. Consider a participant looking for a circle in a display of diamonds. The participant could monitor an appropriate map (as in Treisman & Souther, 1985) that codes for the presence of a relevant feature. Alternatively, an observer may rely on a mode of processing that identifies elements that differ from their backgrounds. These two ways of processing were referred to as *feature search mode* and *singleton detection mode*, respectively. Singleton detection mode is based purely on local salience; the highest priority for selection is accorded to the most salient information in the display (e.g., a singleton). Feature search mode takes advantage of observers' abilities to impose top-down selectivity; participants using this mode are able to resist capture by stimuli that do not match the attentional set.

Bacon and Egeth (1994) were able to replicate the findings of Theeuwes but disagreed with the conclusion that top-down selectivity was impossible. They argued that participants in the Theeuwes studies were employing top-down attention in order to detect singletons in general. Attentional capture resulted from a failure to be selective for singletons along a particular feature dimension, not a failure of all top-down selectivity. They created a modified version of the paradigm in which participants still searched for a known target (a circle), but now with one, two, or three unique forms in each display, so that a singleton detection strategy would not lead participants directly to the target.

With these more heterogeneous displays, participants no longer experienced capture, presumably because they were forced to use feature search mode. Critically, this was the case even on trials where the target was the only shape singleton, as long as such trials were randomly mixed into blocks containing heterogeneous displays. In another experiment participants also did not experience capture by the irrelevant singleton when there were multiple identical targets in the display, again because the design of the displays presumably prevented the use of singleton detection mode. In short, Bacon and Egeth (1994) argued that when participants were in ‘singleton detection mode’ they were open to distraction even by a singleton in a task-irrelevant dimension. When they were in feature search mode irrelevant singletons would not capture attention. Note that search mode theory argues that participants *can* use feature search mode when the identity of the target is known, but participants aren't necessarily going to as long as other search strategies are available.

The critical assumption in search mode theory is that participants are capable of selectively monitoring a relevant feature map and can thus avoid capture by a stimulus that is salient in an irrelevant feature map. Is this a reasonable assumption? Based on previous research that has directly examined such selectivity, the answer is not obvious. Consider, for example, a comparison of selectivity in speeded-classification tasks and same-different comparison tasks (Santee & Egeth, 1980). Garner and his colleagues (e.g., Garner, 1974) presented stimuli one-at-a-time to participants and measured the time to classify test stimuli according to a single experimenter-defined dimension. Two critical conditions were (a) when the stimuli varied along only that dimension and other dimensions remained fixed and (b) when stimuli varied along two dimensions orthogonally. For a variety of pairs of stimulus dimensions that Garner referred to as *separable* there was no difference in reaction time between these conditions. (Color and form, as used in many attention capture experiments, would exemplify separability.) For other combinations of dimensions referred to as *integral* (e.g., hue and saturation), orthogonal variation led to slowed reaction time. However, separability did not prevent dimensions from interfering with one another in a different task —deciding whether two multidimensional stimuli were the same or different. For example when comparing a square and circle, the "different" judgment is faster when one is red and one is green than when they are both the same color. Similarly, when comparing a square and a square, the "same" judgment is faster when both are green than when they are different colors (Santee & Egeth, 1980). Based on the different behavior of separable dimensions in speeded classification and comparison tasks, it does not seem possible, *a priori*, to say with certainty whether dimensions should be able to interfere with one another or not in some other task, such as the additional singleton task. However, there is some recent empirical evidence that does speak to this issue and suggests that participants may *not* be able to selectively monitor the relevant dimension in the additional singleton task, at least not in the way that search mode theory would predict. These studies have to do with what has been called *selection history,* which can be seen as a third possible determinant of attentional control in addition to bottom-up and top-down guidance (e.g., Awh, Belopolsky, & Theeuwes, 2012).

Selection History

Selection history encompasses various phenomena such as priming, perceptual learning, and value-driven attentional capture that result from factors outside the physical stimuli on a given trial but at the same time are different from explicit goals and search strategies. Whether these are all considered top-down is partly a matter of semantics, but it does seem theoretically useful to distinguish between influences that result purely from an observers goal state combined with current task demands and those that do not and that will, at least in some circumstances, work against the observer's current goals.

In terms of attentional capture, it is now a well-known phenomenon that features previously associated with reward will capture attention during a search task when that feature is no longer rewarded (Anderson & Yantis, 2013; Anderson, Laurent, & Yantis, 2011). In the value-driven attentional capture paradigm, there is a training phase during which participants search for a color-defined target. Participants are given a high monetary reward after correct responses to targets of one color and a lower monetary reward after correct responses to targets of another color. During the test phase, participants search for a unique shape such as a diamond among circles. However, in this paradigm each shape is a different color, so there is no color singleton. If one of the non-targets is in a previously rewarded color, it will capture attention as if it gained salience through having been previously rewarded. This does not happen if participants merely searched for those colors without receiving rewards in the training phase, so it is not simply an effect of previously attended/selected items receiving priority. The magnitude of capture is also modulated by the level of reward, such that the highly-rewarded color more strongly captures attention, which is further evidence that learned associations between reward and color are driving attentional capture.

The present research is particularly concerned with the ability to resist capture by irrelevant distractors. There are recent findings that shed light on the importance of past experience on attentional capture, even in the absence of reward. These findings provide evidence against both the idea that top-down selectivity is impossible in the initial stages of visual processing, and the idea that that search mode theory as originally envisioned serves as a full explanation for the resistance to capture seen in feature search.

To start with, Vatterott and Vecera (2012) found that resistance to capture does not occur immediately during a feature search. In Experiment 1, the color of the color singleton was changed after each 48-trial block. If only search mode and not distractor experience mattered, one would expect resistance to capture to be immediate. If only bottom-up factors mattered, one would not expect a difference between initial trials and later trials within a block. They analyzed the first and second halves of each block and found that there was a significant amount of capture on the first half, but not on the second half. Experiment 2 was similar except that they eliminated rest breaks, and showed the same result. There are two important conclusions to be drawn from these findings. The first is that the lack of capture during feature search is not automatic or the result of a single trial, though it does develop relatively quickly. The second is that the experience that allows resistance to capture to develop has to be with a specific color, otherwise changing the singleton color would not result in a period of measurable attentional capture. Vatterott and Vecera proposed an experience-dependent account of resistance to capture.

There is also evidence of the influence of selection history in experiments that explore transfer of training from one trial block to another. Leber and Egeth (2006a,b) gave two groups of participants different kinds of initial training, but identical test trials. The training trials for one group consisted of singleton detection trials, which were similar to the typical additional singleton displays used previously, but in which the target singleton could be one of either a circle, diamond, or triangle among non-target squares, in order to ensure that participants could only find the target through a singleton-detection strategy and not through a feature-search strategy. The other group received heterogeneous feature-search displays as in Bacon and Egeth (1994) as the training.

The test displays were like the typical Theeuwes (1991,1992) additional singleton paradigm displays in that the target was always a singleton circle among diamonds. These were referred to these as *option trials*, since participants could find the target either through singleton detection (since the target was a shape singleton) or feature search (since the target was known to be a circle), although the previous findings of attentional capture with these displays pointed to singleton detection as the default search mode used for option trials.

They found that participants who received singleton detection training experienced capture on the test trials, while those who received feature search training did not. They concluded that search modes could transfer from training to test.

In an important recent study, the transfer of resistance to capture from feature search training to option test trials was shown to occur only under specific conditions. Transfer did not occur if there was no distractor present during feature search training, or when the color of the singleton at test was different from the color of the singleton used during training (Zehetleitner, Goschy & Müller, 2012). In both cases participants experienced a similar magnitude of capture at test, regardless of the training type. This indicates that a lack of experience with a distractor, and specifically the salient feature of that distractor, might lead to a lack of attentional control. If it was feature search mode that was transferring, then the identity of the color singleton distractor, and possibly even whether color singleton distractors were ever present during training, should not have mattered. One thing that is unclear is the extent to which novelty or surprise is an important factor in transfer experiments or experiments in which stimuli change after a block of trials, as participants will have built up an expectation of what stimuli will look like during the course of the training phase or block. It is possible that a sudden violation of expectancy captures attention and eliminates whatever resistance to capture was present. (Of course even such an explanation implies that participants are not completely “blind” to the variation on what is still an irrelevant feature.)

Goals of the current study

The purpose of this study is to explore the resistance to attentional capture that has (sometimes) been found under conditions that promote feature search. Existing evidence (e.g., Vatterott & Vecera, 2012; Zehetleitner et al., 2012) already suggests that both strong bottom-up and top-down models are incomplete and that selection history must be taken into account. However, these experimental designs have involved making changes in stimuli across blocks of trials, and thus involve the violation of fairly stable expectancies. In our Experiment 1 we avoid this by randomly swapping, from trial to trial, the singleton color and the color of the rest of the items in the display (for a similar manipulation carried out in conditions that promote singleton detection, see Hickey, Olivers, Meeter, & Theeuwes, 2011). We ask whether resistance to capture can be observed under such conditions. We also perform several follow-up experiments to determine the effect of color uncertainty under conditions where an association between specific colors and the distractor and the target can be formed.

Experiment 1

We wanted to create a paradigm in which even fairly slowly developing resistance to capture would have an opportunity to be observed. If capture persists even after hundreds of feature search trials this would place an important constraint on search mode theory. In order to do so, the current study uses feature search trials where the task was to look for a circle, but the trials in one condition are arranged in such a way that participants cannot learn to associate particular colors with the target and salient distractor. One group of participants experienced the typical fixed color condition and one experienced a color-swapping condition, in which the color of the majority of the items could switch with the singleton color between trials[1]. That is, on one trial the majority of items could be green and the distractor red, and on the next trial, the majority could be red and the distractor could be green.

Search mode theory would predict resistance to capture in both the color-swapping and the typical fixed-color versions of feature search, since in both cases the target is known to be a circle and can only be found based on top-down attentional settings. However, if the experience-dependent account is correct, resistance to attentional capture should occur only in the fixed color condition, not the color-swapping condition because in the color-swapping condition participants would not be able to associate a particular feature value with the color singleton. Any learning that occurred over a few trials would presumably be wiped out when a color switch occurred, as it was in Vatterott and Vecera's (2012) experiment after a change in the color of the color singleton. One could also imagine an experience-based model under which top-down control is more difficult in the color-swapping condition, but increases over time. Participants receive hundreds of trials, so that if resistance to capture does develop, but slowly, this should be detectable with the current paradigm.

Our design avoids the problem of surprise when there are “macro changes” in stimuli between blocks of trials. However, like all studies, it cannot avoid the problem of “micro-changes” from trial to trial. If we assume that subjects are, in fact, not blind to the nature of the irrelevant color dimension, then it is likely that the characteristics of the previous trial could have an effect on the response times (e.g., Fox, 1995; Maljkovic & Nakayama, 1994) and the magnitude of capture of a given trial (e.g., Hickey et al., 2011; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Töllner, Müller, & Zehetleitner, 2012).

Maljkovic and Nakayama (1994) found a cumulative priming effect whereby observers are faster to find color singleton targets when the colors of the target and distractors match those on previous trials, referred to as priming of popout (PoP). However, in that case the specific target feature on each trial was unpredictable. We are focusing on priming effects from the immediately previous trial because previous research has shown that when observers search for a target with a known identity, as they do during the feature search version of the additional singleton task, repetition of the target feature speeds search, but a longer run of preceding trials with the same target feature does not provide an additional benefit (Leonard & Egeth, 2008). In the same study, when the target feature was not known in advance there was a benefit of additional preceding trials with the same target feature, as in typical PoP studies.

In the color-swapping condition, we will examine both the influence of the color mapping of the previous trial and distractor presence on the previous trial. As an example of the kind of effect we will be looking for, consider a trial (for example, the fifth trial shown in the lower panel of Figure 1) that follows a trial with a different majority color. Consideration of trial history effects leads us to expect that participants will experience more capture on such a

[1]We use “majority” color to refer to the color of the items in the display that are not a color singleton. For example, in the lower (color-swapping) panel of Figure 1, on the second trial the majority color is green and on the third trial the majority color is red. Note that the target is always in the majority color. Indeed, we could even replace the term “majority color” with “target color.”

trial than on a trial (such the second trial) that follows a trial with the same majority color. This is because the previous trial's majority color (which is, of course, also the target color) will be associated with having successfully found the target on the previous trial, and attention will be even more strongly drawn to the distractor on the current trial because it now possesses that color.

We will also look at whether significant capture occurs on trials that were preceded by trials with the same majority color. This is to determine whether, on trials where participants have had immediately previous experience with that color mapping, participants will be able to resist capture or whether they will experience capture due to the fact that in the overall context of the experiment there is no reliable association between a particular color and either the target or the distractor. If significant capture did not occur on such trials, it would indicate that any overall capture effect found in the color-swapping condition resulted only from trial-to-trial changes rather than a more long-term effect of trial history.

Distractor presence on the previous trial may also have an effect on the current trial. The presence of a distractor on the previous that was the same color as a distractor on the current trial might lead to decreased capture because participants are now inhibiting that color. It is also possible that the presence of a distractor on the previous trial might lead to reduced capture by a distractor of any color due to expectancy effects.

Several studies have examined target uncertainty and priming in the additional singleton paradigm, but have reached very different conclusions about its importance. Pinto, Olivers, and Theeuwes (2005) argued that when the target shape in singleton detection changed from trial to trial, an increased magnitude of capture resulted from the priming-related switch cost on trials preceded by trials with a different target shape, but that target uncertainty had no effect on its own. In contrast, Lamy, Carmel, Leber & Egeth (2006; see also Lamy & Yashar, 2008) came to the conclusion that differences between the magnitude of capture when the target shape was fixed or varied were more likely due to differences in search strategy than to priming because increasing the length of runs of same shape target trials did not lead to reduced attentional capture. Here, the target will always be a circle, so such studies are important to consider but may not be directly relevant.

Method

Participants—Twenty-four (ten male) Johns Hopkins University undergraduates with a mean age of 19.5 years participated in exchange for extra course credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. Half were assigned to the color-swapping condition and half were assigned to the fixed color condition.

Apparatus—Stimuli were presented in a testing room with ambient lighting on an LCD monitor with a 1920 × 1080 resolution and a screen refresh rate of 60 Hz that was controlled by a PC running Microsoft Windows, Matlab, and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The viewing distance was approximately 76 cm. All stimuli were presented against a black background. Participants reported the orientation of the line inside the target by pressing the ‘h’ keyboard key for horizontal or ‘v’ key for vertical.

Stimuli—Each display consisted of five outline shapes equally spaced around an imaginary circle with a radius of 3° from the center of the display to the center of the shapes, each of which contained a horizontal or vertical white line in the center. Each shape outline was .1° thick and the line inside was .5° in length and .05° in thickness. The fixation cross at the center of the screen was white and drawn using two lines that had the same height, width, and thickness of the lines inside the shapes. The shapes were a circle (diameter 1.5°), diamond (sides 1.3°), square (sides 1.3°), upward pointing equilateral triangle (sides 1.5°), and downward pointing equilateral triangle (sides 1.5°). The outline shapes could be either red (RGB: 255, 0, 0) or green (RGB: 0, 255, 0) in color. If a color singleton was present in the display, it was always the diamond, while the circle was always the target.

Design—Half the trials in all conditions were distractor-absent and half were distractor-present. These trials were randomly intermixed. On distractor-absent trials, all items were the same color, referred to here as the majority color, which could be either green or red. On distractor-present trials one items was a color singleton, which would be green if the majority color was red or red if the majority color was green. In the fixed color condition, half of the participants were given trials where the majority color was green throughout the experiment and half were given trials where the majority color was red throughout the experiment. In the color-swapping condition, half the trials had a red majority color and half had a green majority color. Each trial in the color-swapping condition was equally likely to have the same or different majority color as the one before it. This means that in the color-swapping condition, green could sometimes be the majority color and sometimes the singleton color, as could red. In both conditions, the lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five possible locations was randomized.

Procedure—Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 480 trials long, which took most participants about 20 minutes.

Results and Discussion

Trials with an incorrect response or no response were excluded from the main analyses. The trials were divided into four quarters in order to examine the effects of practice. We did not examine smaller time scales due to the variability in RT and the fact that, since the experiment was not originally designed with an analysis over time in mind, the ratio of distractor present to distractor-absent trials in bins with a small number of trials would not be controlled. Mean RTs were entered into a 2 (color mapping group) × 4 (quarter) × 2 (distractor present or absent) mixed ANOVA. All *p* values reported were Geisser-Greenhouse corrected when appropriate. There was no main effect of color mapping, $F(1, 22) = 1.40$, $p = .251$, $\eta_p^2 = .06$. There was a main effect of color singleton distractor, indicative of attentional capture, $F(1, 22) = 16.74$, $p < .001$, $\eta_p^2 = .43$, which was driven by the significant interaction between the color mapping condition and presence of the distractor, $F(1, 22) = 6.85$, $p = .016$, $\eta_p^2 = .24$, such that the distractor slowed response times more in the color-swapping condition than in the fixed condition, as predicted. Accuracy data were entered into a similar ANOVA and there were no significant results, so the difference in response times cannot be explained by a speed-accuracy tradeoff.

The mean amount of capture (distractor-present response time minus distractor-absent response time) in the fixed condition was 12 ms, $t(11) = 1.78$, $p = .103$, which was not significant, as expected from classical feature search trials. In the swapping condition it was 45 ms, $t(11) = 3.77$, $p = .003$. This is actually quite similar to the amount of capture typically found on option trials with absent or ineffective training, for example, 40 ms in Experiment 2 of Zehetleitner, et al. (2012) where the training phase did not include any color singleton distractors. Figure 2 depicts the difference in the amount of capture in the fixed condition and in the color-swapping condition.

There was a main effect of practice, $F(3, 66) = 7.31$, $p = .001$, $\eta_p^2 = .26$, which means that RTs varied with the amount of practice. The mean RT in the first quarter was 733 ms, in the second quarter 745 ms, in the third quarter 695 ms, and in the last quarter 687 ms. Despite a slight increase in RT from the first to the second quarter, the most likely explanation is that response times became faster as participants became more experienced at the task. There was a significant linear trend, $F_L = 9.27$, $p = .006$, $\eta_p^2 = .30$.

There was no significant interaction between color mapping and practice, $F(3, 66) = .31$, $p = .756$, $\eta_p^2 = .01$, or distractor and practice, $F(3, 66) = .70$, $p = .536$, $\eta_p^2 = .03$. We were particularly interested in the three-way interaction between color mapping group, practice, and distractor presence in order to see if the capture that occurred in the color-swapping condition decreased over time, however, it did not, $F(3, 66) = 1.38$, $p = .258$, $\eta_p^2 = .06$.

Further analysis of the color-swapping condition—In order to assess the effect of the previous trial in the color-swapping condition, we divided the trials in that condition based on whether there was a color singleton present, whether the majority color on that trial was the same or different as the majority color on the previous trial, and whether a distractor had been present on the previous trial or not. Mean RTs (see Table 2) were entered into a 2 (current trial distractor presence) × 2 (previous trial majority color) × 2 (previous trial distractor presence) repeated-measures ANOVA.

There was a main effect of distractor presence in the current trial, $F(1, 11) = 14.34$, $p = .003$, $\eta_p^2 = .57$, indicating robust attentional capture, as expected from the preceding analysis. There was also a main effect of the previous majority color such that response times were slower on trials where the previous majority color was different, $F(1, 11) = 16.57$, $p = .002$, $\eta_p^2 = .60$. This effect was almost certainly due to color priming.

Several papers have discussed intertrial priming in the context of ambiguity resolution theory (Meeter & Olivers, 2006, Olivers & Hickey, 2010) The idea here is that priming is increased in magnitude by any factor that increases competition for selection. Several experiments have shown that the presence of an additional singleton increases priming compared to a no-singleton condition, presumably because the singleton increases competition (vis a vis the target) for selection. The present study does not provide—and was not intended to provide—a critical test of ambiguity resolution theory. However, the large majority-color priming effect we observed the color-swapping condition is consistent with that theory because feature search displays, due to their high heterogeneity, are high in ambiguity and thus are ripe ground for priming. To be clear, the effect we are referring to here is the main effect of previous majority color (same or different) on response time, and not its effect on the magnitude of capture.

There was also a significant interaction between the previous majority color and the presence of the distractor such that participants experienced a greater magnitude of capture after a different majority color trial, $F(1, 11) = 5.32$, $p = .042$, $\eta_p^2 = .33$. This indicates that the magnitude of capture was affected by a priming effect possibly similar to that examined in past additional singleton experiments (Pinto et al., 2005; Lamy et al., 2006). This is the starred difference shown in Figure 3.

There was no significant main effect of whether the previous trial had a distractor or not, $F(1, 11) = .78$, $p = .397$, $\eta_p^2 = .07$, no interaction of the presence of the distractor on the previous trial with the previous majority color, $F(1, 11) = .43$, $p = .526$, $\eta_p^2 = .04$, and no interaction of the presence of a distractor on the previous trial with presence of a distractor on the current trial, $F(1,11) = .76$, $p = .403$, $\eta_p^2 = .06$.

There was no three-way interaction of the previous distractor, previous majority color, and current presence of a distractor, $F(1, 11) = .14$, $p = .717$, $\eta_p^2 = .01$. A significant interaction might have indicated that participants experienced the least capture on trials where the current majority color matched the previous majority color and there was a distractor on the previous trial, that is, when the current distractor is the same color as the distractor on the previous trial. A three-way interaction would have indicated that a substantial degree of resistance to capture was able to develop after a single trial of experience with a particular distractor color as compared to after a trial with the same majority color but no distractor, but this was not the case.

Although there was significantly more capture after trials with a different majority color trial than after trials with the same majority color, we were interested in whether there was still significant capture after same majority color trials. The magnitude of capture on such trials was 29 ms, $t(11) = 2.38$, $p = .037$. The fact that there was significant capture in the color-swapping condition on trials that were not preceded by a swap, in contrast with the non-significant capture in the fixed color condition where swaps never occurred, indicates that the effect of color swapping on capture extends beyond the trial immediately after a swap.

This experiment demonstrates that attentional capture can occur on feature search trials with heterogeneous displays, which is not what search mode theory predicts. In both the fixed condition and the swapping condition, the target was a circle and participants needed a strategy of searching for circles in order to find the target. In the color-swapping condition, the color singleton distractor did not share the defining feature of the target, and yet it was able to capture attention. The magnitude of capture in the swapping condition was reduced but not eliminated when the previous trial had the same color mapping, indicating that not all capture in this condition resulted from a change in the majority color from the previous trial. In addition, the overall amount of experience with the search task did not lead to any reduction in the magnitude of capture.

Experiment 2

In Experiment 2 we wanted to rule out the possibility that the capture found in the color-swapping condition of Experiment 1 was due only to target feature uncertainty or switch costs resulting from changes in the majority color from trial to trial. Search mode theory does not generally predict capture on feature search trials, but perhaps it is easier to direct attention to the target and avoid capture if the template is 'green circle' instead of simply 'circle.' The target in Experiment 2 was always a circle, but unlike in the fixed color condition of Experiment 1, the majority color could be one of two colors (blue or green). When the target template only has one feature, perhaps observers are less efficient in locating the target and thus vulnerable to attentional capture. On the other hand, in Experiment 2, unlike in the color-swapping condition of Experiment 1, the color singleton did not vary in color. An experience-dependent theory under which distractor features are critical would predict a lack of capture in this experiment because the distractor color was always red, as seen in Figure 4A, and participants should have the experience they need in order to resist capture by that distractor.

Method

Participants—Sixteen (seven male) Johns Hopkins University undergraduates with a mean age of 19.5 participated in exchange for extra credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. Data from the first four participants was discarded due to a programming error and one participant was excluded from further analysis due to having an overall accuracy of less that 70%.

Apparatus—See Experiment 1.

Stimuli—The stimuli were similar to those in Experiment 1, but each display consisted of five or nine outline shapes. When there were five items one of each shape was present, when there were nine items the additional shapes were all diamonds. The outline shapes could be red (RGB: 255, 0, 0), green (RGB: 0, 255, 0), or blue (RGB: 0, 0, 255) in color.

Design—In this experiment, the majority color had an equal probability of being green or blue. A color singleton was present on half the trials and was always red. Half the trials had five items and half had nine. The lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five or nine possible locations was randomized.

Procedure—Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 1440 trials long, which took most participants about 50 minutes.

Results and Discussion

The mean RTs (see Table 3) were entered into a 2 (majority color) × 2 (color singleton distractor present or absent) × 2 (display size) repeated-measures ANOVA. There was a main effect of majority color such that participants were slower when the majority color was blue, $F(1, 10) = 6.73$, $p = .027$, $\eta_p^2 = .40$. This was almost certainly due to the fact that colors were not matched in luminance and the blue subjectively did not stand out as well against the black background as the green. There was no main effect of the presence of the distractor, $F(1, 10) = .87$, $p = .372$, $\eta_p^2 = .08$, which means that participants were able to resist capture. The main effect of display size was significant, $F(1, 10) = 13.38$, $p = .004$, $\eta_p^2 = .57$, which shows that this was not a perfectly parallel search, which is typical of these types of displays. However, the difference between conditions was only 21 ms, which represents a very efficient 5 ms/item cost. Error rates were similar across all conditions, and no significant main effects or interactions were found when accuracy data were entered into a similar repeated-measures ANOVA, so the differences in response time are not reflective of a speed-accuracy tradeoff.

There was no significant interaction between majority color and distractor presence, $F(1, 10) = .43$, $p = .527$, $\eta_p^2 = .04$, so it was not the case that the distractor was able to capture attention when presented among items of one color but not the other due to contract effects. The interaction between distractor presence and display size was not significant, $F(1, 10) = .33$, $p = .577$, $\eta_p^2 = .03$, nor was the interaction between majority color and display size, $F(1, 10) = .43$, $p = .527$, $\eta_p^2 = .04$. There was no three-way interaction between majority color, distractor presence, and display size, $F(1, 10) = .22$, $p = .651$, $\eta_p^2 = .02$.

To analyze the effects of practice, the trials were grouped into 12 bins of 120 trials (since the practice analysis of Experiment 1 used bins of 120 trials). The data were entered into a 2 (color singleton distractor present or absent) × 12 (practice) repeated-measures ANOVA, which did not show any significant main effects or interactions.

This experiment demonstrates that the attentional capture found in the color-swapping condition of Experiment 1 was not due to uncertainty about the target color. Although participants could not predict the target's color on a given trial, they might have been able to learn to associate both colors with the target. More importantly, they were able to associate a single color with the distractor, which fits in nicely with an account of attentional capture that is driven by experience with the salient feature of the distractor.

Intertrial analysis—For Experiment 2, the intertrial effects were analyzed similarly to how they were analyzed in Experiment 1. The current trial could have a color singleton distractor present or absent. The previous trials had either the same majority color or a different majority color, and the previous trial could have had a distractor present or not. The main difference was that, unlike in Experiment 1, where a distractor-present trial that had been preceded by a distractor-present trial could have had the same or different distractor color depending on whether the previous majority color was different or the same, in Experiment 2 all the color singletons were the same color.

Mean RTs were entered into a 2 (current trial distractor presence) × 2 (previous trial majority color) × 2 (previous trial distractor presence) repeated-measures ANOVA. The only significant result was the three-way interaction, $F(1, 10) = 9.07$, $p = .01$, $\eta_p^2 = .48$. The capture effect was -13 ms when the previous trial had the same majority color and did not contain a distractor and -5 ms (effectively no capture) when the previous had the same majority color and contained a distractor. Capture was 11 ms on trials when the previous trial had a different majority color and did not contain a distractor and -13 ms when the previous trial had a different majority color and contained a distractor. We do not have a meaningful way to interpret negative capture and therefore have no explanation to offer for those results.

Experiment 3

The purpose of Experiment 3 was to determine whether observers would be able to resist capture even if they were uncertain about the distractor color on a given trial. Again, search mode theory would predict no capture on these feature search trials, but because capture was found in the color-swapping condition of Experiment 1, this is an important control experiment. Here we test the robustness of experience-dependent, color-based resistance to capture. In this experiment we use two different singleton colors, while the majority color is always a third color, as seen in Figure 4B, which means that the singleton distractor colors are never used as target colors.

Method

Participants—Twenty (seven male) Johns Hopkins University undergraduates with a mean age of 20 years participated in exchange for extra course credit. All participants had normal or corrected-to-normal vision, were over 18 years of age, and provided written consent. One participant was excluded from further analysis due to having an overall accuracy of less than 70%.

Apparatus—See Experiment 1.

Stimuli—See Experiment 2.

Design—In this experiment, the majority color was always blue. A color singleton was present on half the trials and had an equal probability of being green or red. Half the trials had five items and half had nine. The lines inside of the shapes each had an equal probability of being horizontal or vertical. The positioning of the different shapes in the five or nine possible locations was randomized.

Procedure—Participants received both written and oral instructions. They were told to keep their gaze on the fixation cross, search for the circle without moving their eyes, and report the orientation of the line inside the circle as quickly and accurately as possible. They were instructed that the colors of the items were irrelevant to the task. Each participant was given 24 practice trials without color singletons before proceeding to the experiment, and they were given several breaks. Before each break participants were informed of their accuracy so far in order to encourage a high level of performance.

Each trial began with the appearance of the fixation cross for 500 ms, after which the stimulus display appeared. The display remained until the participant made a response or for 2,000 ms. If the participant made an incorrect response, a low beep played, while there was no feedback after a correct response. The next trial began after an ISI of 500 ms. The experimental phase was 1440 trials long, which took most participants about 50 minutes.

Results and Discussion

All p values reported were Geisser-Greenhouse corrected when appropriate. The mean RTs (see Table 4) were entered into a 3 (color singleton type) × 2 (display size) repeated-measures ANOVA. There was no main effect of distractor, $F(2, 36) = .89$, $p = .400$, $\eta_p^2 = .05$. Since there was no difference between the distractor-absent trials, the green distractor trials, and the red distractor trials, it is evident that capture did not occur in this experiment. There was a main effect of display size such that participants were 41 ms slower when there were 9 items than when there were 5, $F(1, 18) = 24.24$, $p < .001$, $\eta_p^2 = .57$. This is a 10 ms/item cost, which indicates that while search was not perfectly parallel, it was still quite efficient, which is typical for feature search trials. There was no interaction between distractor presence and number of items in the display, $F(2, 36) = 1.83$, $p = .175$, $\eta_p^2 = .09$. Participants had consistent error rates across all conditions, with no significant effects when the data were entered into a repeated-measures ANOVA, so the results do not reflect a speed-accuracy tradeoff.

As in Experiment 2, the data were also entered into a 2 (color singleton distractor present or absent) × 12 (practice) repeated-measures ANOVA in order to determine the effect of practice. The only significant effect was a main effect of practice, $F(1, 11) = 5.74$, $p < .001$, $\eta_p^2 = .24$, such that participants responded faster as they had more practice with the task.

Participants were able to resist attentional capture even when the color of the distractor could not be predicted on a trial-by-trial basis. The key difference between this experiment and the color-swapping condition of Experiment 1 is that here the two singleton colors were never the target color and any change in how participants responded to the singleton colors, in order to resist capture by those colors, could have remained throughout the experiment. This experiment demonstrates that participants can learn to resist capture by more than one color at a time.

Intertrial analysis—Intertrial effects could not be analyzed in the same way for Experiment 3 as for Experiments 1 and 2. Here, only distractor-present trials were analyzed to see whether there was any difference between those preceded by a distractor-absent trial, a trial with a distractor of the same color, or a trial with a distractor of a different color. If there were any difference it would make sense for response times to be slowest when the previous trial did not contain a distractor and fastest on those where the previous trial contained a same color distractor.

Data were entered into a one-way repeated-measures ANOVA with three levels (previous trial type). The effect of previous trial type was not significant, $F(2, 36) = .91$, $p = .40$, $\eta_p^2 = .05$. Here, the characteristics of the previous trial had no effect on response times.

General Discussion

The results of Experiment 1 show that capture can occur on feature search trials with heterogeneous displays under conditions that prevent the learning of an association between singleton status and a particular color or colors. When the trials had a fixed color mapping, that is, the majority of items were always one specific color and the color singleton was always another specific color, the typical lack of capture was obtained. In the color-swapping condition, where a trial could have either one of two majority colors and the singleton, if present, had the other of those colors, there was a significant amount of capture. In Experiments 2 and 3, participants were able to resist capture even when the majority color or singleton color had two possible values, as long as there was no overlap between the set of majority colors and the set of singleton colors. This is in conflict with search mode theory, which predicts that attentional capture should never occur on feature search trials. It is clear that color can interfere with the ability to find a shape target, despite the separability of these features, even under conditions where shape information has far more top-down importance.

These results are also problematic for the bottom-up salience model. Theeuwes (2004) argued for an alternative explanation for the lack of capture in Bacon and Egeth (1994). According to Theeuwes, the reason that the color singleton did not capture attention on feature search displays could have been due to their addition of more unique shapes leading to both the target and the distractor decreasing in salience compared to the situation in the singleton detection condition. A less salient singleton would fail to capture attention. A less salient target could also have explained Bacon and Egeth's finding of slightly less efficient search for a non-singleton target than a shape singleton target. If uniqueness in general, not along a particular dimension, leads to attentional capture, then adding more heterogeneity of any kind could reduce the salience of individual items overall. If the target was not salient enough, then participants could not find it by means of a strictly parallel search. In short, Theeuwes (2004) argued that what Bacon and Egeth (1994) had referred to as feature search and singleton detection modes were actually just two different sizes of attentional window, respectively small and large. For a more detailed discussion and critique of the attentional window hypothesis see Leber and Egeth (2006b).

For now it is sufficient to note that the present results cannot be explained by the attentional window theory as originally put forth, since the physical stimuli on individual trials in the fixed and swapping conditions were essentially the same and should have affected the attentional window in the same way. If the attentional window in feature search mode is small enough that it results in a slower, more serial search and usually does not encompass both the color singleton and the target, then capture should not be found in either the fixed or the swapped conditions. Instead, these results appear to support an explanation of attentional capture that is neither fully bottom-up or top-down, but that takes selection history into account.

It is clear the previous trial has a strong influence on the current trial. It makes sense that importance would be placed on features of the previous trial's target that are truly predictive of the target, but it seems that importance is placed on the previous trial's target color—the majority color--even though the target is not defined by its color and the target color on one trial is not predictive of target color on the next trial. Although some theories of priming posit that priming affects distinct feature representations (Maljkovic & Nakayama, 1994), there is also evidence that features of the target are bound when it comes to priming effects (Huang, Holcombe, & Pashler, 2004), as seems to be the case here. On the current trial, attention is drawn even more strongly to a color singleton that has the previous trial's majority color than it would otherwise be, leading to increased attentional capture. Inhibition of the previous trial's distractor color appears not to have been an important intertrial factor because the presence of a distractor on the previous trial had no effect on the current trial, whether or not it was the same or different color than the current target. Therefore, it appears that intertrial color priming can influence the magnitude of capture, but resistance to capture by particular colors is not fully explained by priming of the previous target's features.

The finding of capture on trials in the color-swapping condition where the previous trial had the same color mapping, for example a trial with green items and a red distractor preceded by a trial with all green items, can be interpreted in one of two ways. We believe that it is because bottom-up capture is to be expected when no color associations can be made. However, there is a possibility that this attentional capture effect resulted from observers being distracted by a color that had recently (several trials back) been the color of the target. Based on the findings of Vatterott and Vecera (2012), where capture was obtained until participants had sufficient experience with a specific color distractor and where distractor colors had never been target colors, it seems unlikely that capture here resulted purely from the influence of attention drawn to the irrelevant color of the target several trials back in the sequence. We suspect it resulted from participants being unable to associate the singleton distractor with a particular color, and that it takes longer than a single trial's worth of experience to form such an association.

The fact that participants do not experience capture when only the color singleton distractor color varies across trials and the majority color is constant suggests that whatever it is that allows observers to resist capture (de-weighting, inhibition, etc.) can occur for multiple colors simultaneously. However, further experiments will be needed to discover how many colors can successfully be resisted at once, and whether there are ever conditions using similar displays under which all color information can be discounted by the visual system.

The current results are compatible with either a feature weighting account or a dimensional weighting account. Under a feature weighting account (e.g. Wolfe, 2007) there is a master saliency map and top-down attention can only assign more or less weight to specific feature values (or a feature category, in the case of Guided Search 4.0). A dimensional weighting account could also explain the results (Müller, Reimann, & Krummenacher, 2003), though only the version under which color categories are treated as separate dimensions rather than only being treated as values under the general dimension of color, at least if one takes into consideration the findings of Vatterott and Vecera (2012) and Zehetleitner et al. (2012). Dimensional weighting is hierarchical, and posits that observers use top-down weightings to bias attention toward different feature dimensions, or in the case of color, sub-dimensions. Each dimension has its own saliency map. Whether an item with a certain feature value captures attention is determined both by whether it has the highest physical salience along its dimension and by the weighting given to that dimension. Under either account, in the fixed condition participants would be assigning more weight to the majority color and less to the singleton color over time. In the swapping condition, participants might begin to adjust color weightings after every switch trial, but on average weight the two colors the same, leading to capture by whichever color had more physical salience on a given trial.

In the fixed majority/switching singleton experiment (Experiment 3) participants might add more weight to the majority color category while de-weighting both singleton color categories. It is possible that the maximum de-weighting of the two distractor colors took longer than for a single color, but in any case it was effective. In the switching majority/fixed singleton experiment (Experiment 2), participants might have similarly added weight to both majority colors, while de-weighting the singleton color. It is also possible that most of the dimensional weighting only affected the features related to the target or to the color singleton.

Based on the evidence from Zehetleitner et al. as well as Vatterott and Vecera (2012) it is likely that the weighting mainly affects the singleton color, since introducing a new singleton color while the majority color remains the same results in attentional capture when it was not previously occurring. If the weighting of the majority/target color rather than the weighting of the singleton color was primarily affected by experience, we would not expect this to be the case. This makes sense given that the presence of the majority color is not a very good predictor of whether the item is a target, since many non-targets share that color, while the singleton color is perfectly predictive of that item being a non-target, therefore the singleton color is more informative. However, it remains possible that changes in the majority color might lead to capture in some conditions, and perhaps the weight assigned to the majority color is important in explaining cases in which capture does or does not occur depending on past experience.

Although the current findings cannot be explained by search mode theory, one aspect of search mode theory that does appear to be justified is its emphasis on search strategy.

Although Experiment 1 has demonstrated that resistance to capture does not always arise during feature search, it does appear to be the only type of search where complete resistance to capture will arise when distractor prevalence is moderate. Participants who receive trials of either the singleton detection or option version of the additional singleton paradigm also receive substantial experience with the salient feature of the distractor, yet they experience significant attentional capture, sometimes with a far greater magnitude that that obtained here in the color-swapping condition. Even though resistance to capture does not arise during option trials, resistance to capture can transfer from feature search trials to option trials as long as the distractor has the same salient feature during training and test (Leber & Egeth, 2006b; Zehetleitner et al., 2012). We will not truly understand attentional capture or resistance to capture until we understand why that is the case.

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Figure 1.

Example trials for Experiment 1, where the target was always the circle. In the fixed condition the displays were always a particular color throughout the experiment (green majority color, as here, or red majority color), although there could be a color singleton distractor present in the display. In the color-swapping condition displays could be either red or green, as could the color singleton distractors. Some trials in the color-swapping condition could have a completely different color mapping, as in the second and third displays, while some were the same, as in the fifth and sixth displays.

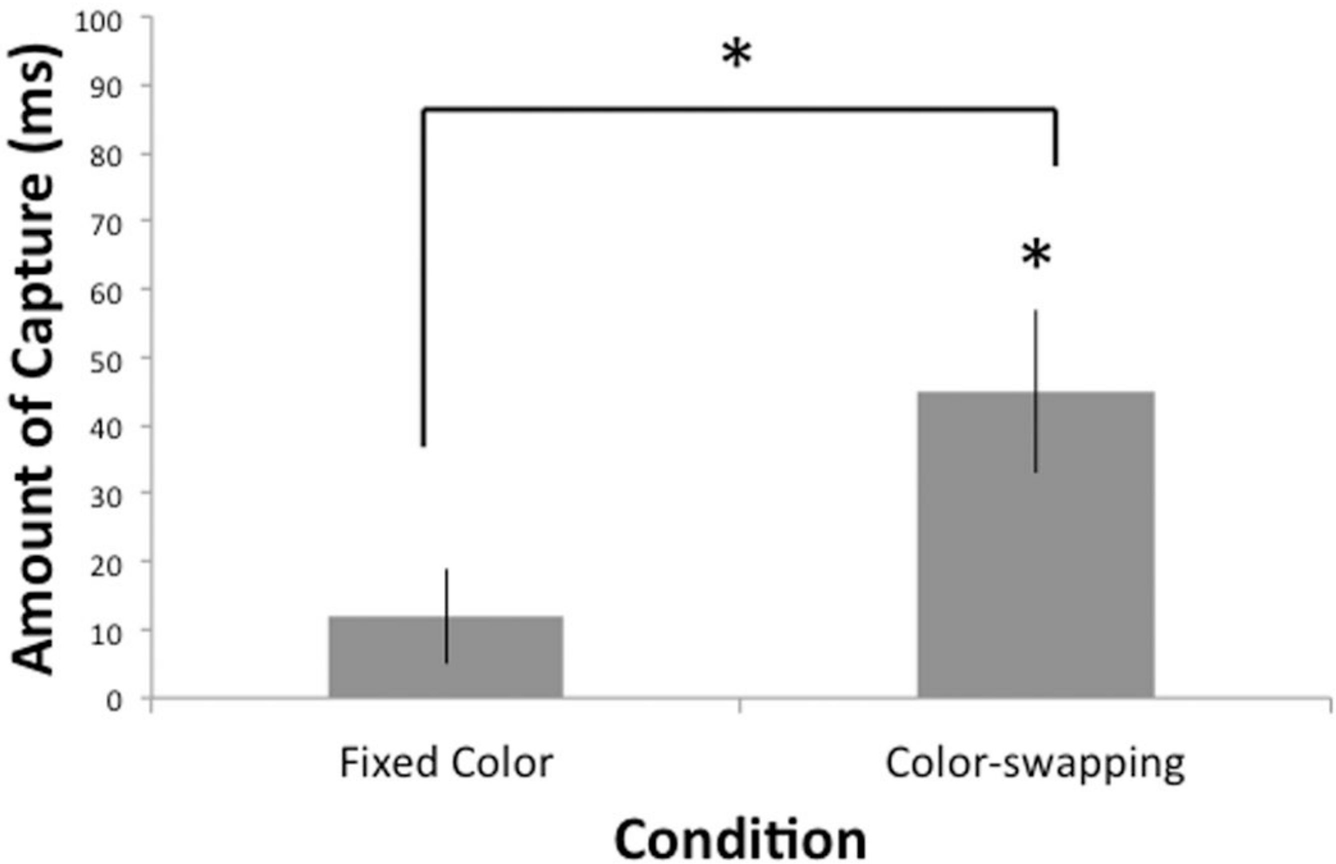

Figure 2.
Amount of capture in the fixed color condition and the color-swapping condition of Experiment 1. Error bars represent the standard error of the mean.

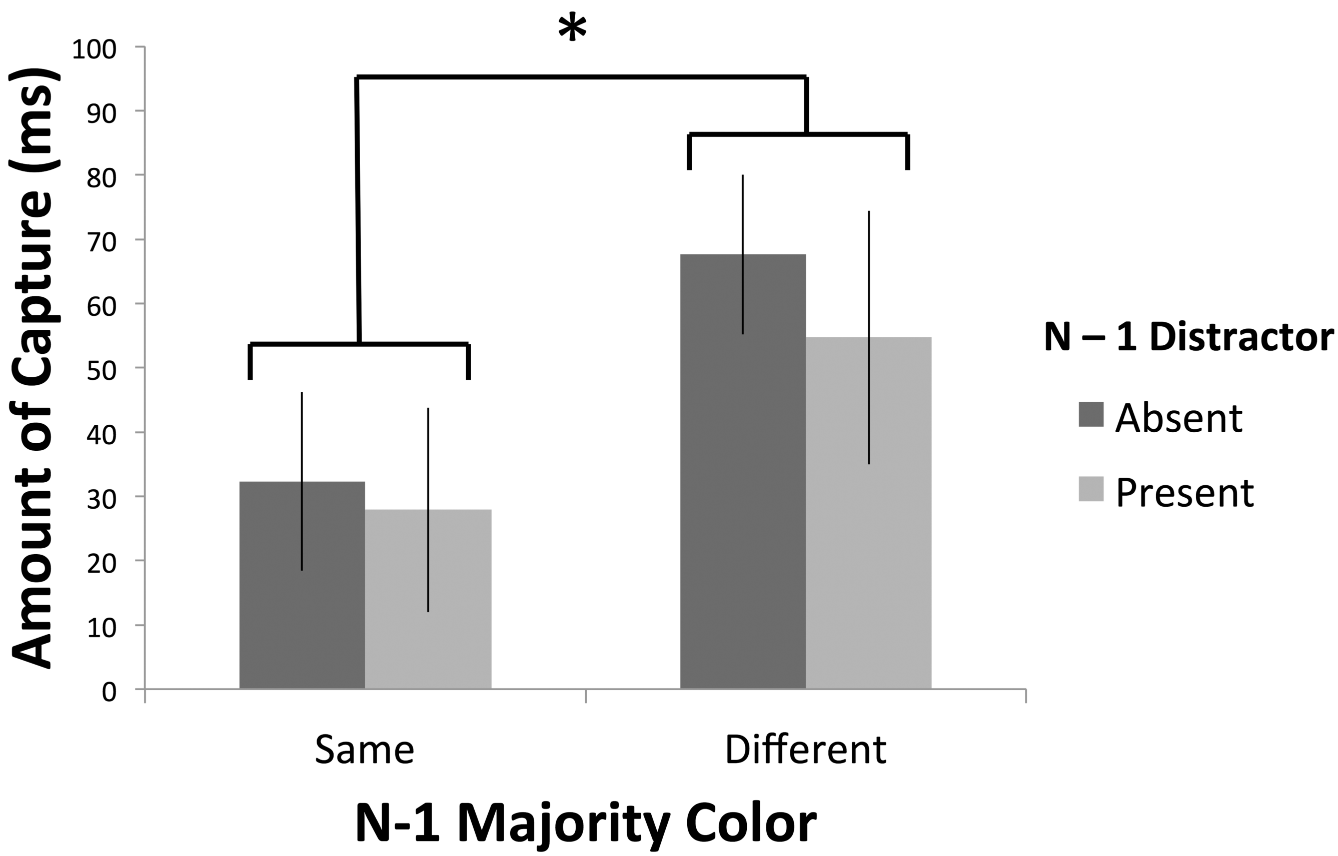

Figure 3.

Amount of capture based on the similarity of the previous trial, which could have had either the same or different majority color from the preceding trial, and could have had a distractor on the preceding trial or not. Error bars represent the standard error of the mean.

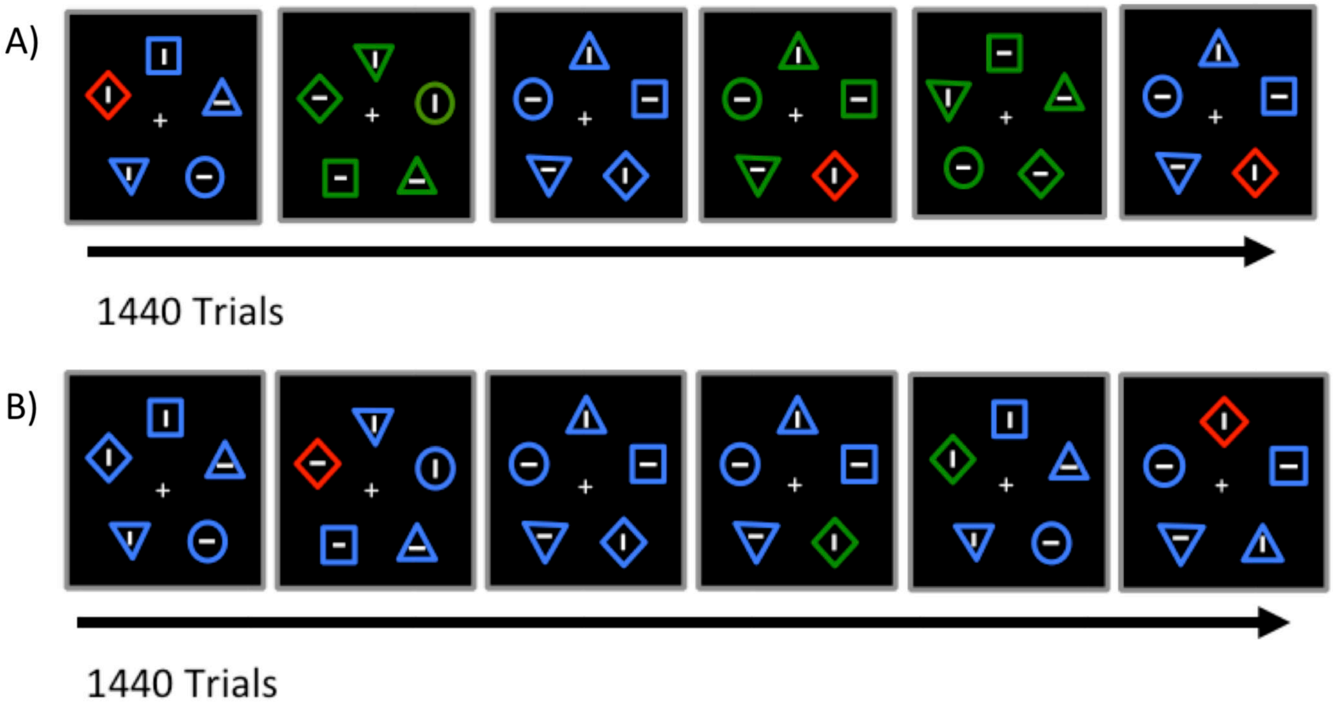

Figure 4.
A) Example trials for Experiment 2, where the target was always the circle. The majority color was randomly either green or blue. Color singletons distractors were present on half of all trials and were always red. B) Example trials for Experiment 3, where the target was always the circle. Displays always had a blue majority color. Color singletons distractors were present on half of all trials and could randomly be either red or green.

Table 1

Mean color singleton present and absent reaction times and standard deviations in milliseconds, as well as percent error rates for the four levels of practice of Experiment 1

	Response Time (ms)		Error Rate (%)	
First Quarter	**Fixed Color**	**Color-swapping**	**Fixed Color**	**Color-swapping**
Color Singleton Absent	699(113)	733(121)	4.2	4.4
Color Singleton Present	720(114)	782(138)	4.5	4.9
Second Quarter				
Color Singleton Absent	709(110)	753(136)	5.7	3.9
Color Singleton Present	729(143)	789(166)	5.3	4.1
Third Quarter				
Color Singleton Absent	661(107)	701(106)	4.2	4.1
Color Singleton Present	660(89)	758(132)	4.5	4.3
Fourth Quarter				
Color Singleton Absent	666(79)	689(115)	6.1	4.6
Color Singleton Present	667(81)	728(137)	4.7	4.5

Table 2

Mean color singleton present and absent reaction times and standard deviations in milliseconds for the different priming conditions of Experiment 1

	Previous Majority Color			
	Same		*Different*	
	Previous Distractor			
	Absent	*Present*	*Absent*	*Present*
Color Singleton Absent	708(114)	721(123)	750(132)	725(112)
Color Singleton Present	740(124)	750(132)	784(129)	780(165)

Table 3

Mean reaction times and standard deviations in milliseconds, along with percent error rates for each condition of Experiment 2

	Response Time (ms)		Error Rate (%)	
	5 Items	9 Items	5 Items	9 Items
Green Majority				
Color Singleton Absent	690(136)	710(128)	5.6	4.9
Color Singleton Present	694(147)	712(126)	5.1	5.4
Blue Majority				
Color Singleton Absent	670(131)	721(135)	5.0	5.2
Color Singleton Present	704(134)	730(137)	4.8	4.5

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Table 4

Mean reaction times and standard deviations in milliseconds, along with error rates for each condition of Experiment 3

	Response Time (ms)		Error Rate (%)	
Color Singleton	**5 Items**	**9 Items**	**5 Items**	**9 Items**
Absent	721(83)	752(99)	4.3	3.9
Red	717(83)	761(100)	4.3	4.3
Green	719(81)	765(107)	4.2	4.3