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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 colour singletons that are more salient than the target. However, when participants search for a shape among heterogeneous shapes, the presence of a non-target colour 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 colours to the target and distractor appears to be what enables resistance to capture during feature search.

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**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.

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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, and 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 colour, a colour cue could misdirect attention but a sudden onset cue did not. Conversely, when participants searched for an onset target, an onset cue could misdirect attention but a colour 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, 1976) 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. (Colour 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 colour. Similarly, when comparing a square and a square, the "same" judgment is faster when both are green than when they are different colours (Santee & Egeth, 1980). Based on the different behaviour 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, Laurent, & Yantis, 2011; Anderson & Yantis, 2013). In the value-driven attentional capture paradigm, there is a training phase during which participants search for a colour-defined target. Participants are given a high monetary reward after correct responses to targets of one colour and a lower monetary reward after correct responses to targets of another colour. 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 colour, so there is no colour singleton. If one of the non-targets is in a previously rewarded colour, it will capture attention as if it gained salience through having been previously rewarded. This does not happen if participants merely searched for those colours 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 colour more strongly captures attention, which is further evidence that learned associations between reward and colour 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 colour of the colour 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 colour, otherwise changing the singleton colour 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, 2006b) 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 colour of the singleton at test was different from the colour 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 colour singleton distractor, and possibly even whether colour 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 Experiment 1 we avoid this by randomly swapping, from trial to trial, the singleton colour and the colour 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 colour uncertainty under conditions where an association between specific colours 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 colours with the target and salient distractor. One group of participants experienced the typical fixed colour condition and one experienced a colour-swapping condition, in which the colour of the majority of the items could switch with the singleton colour 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 colour-swapping and the typical fixed-colour 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 colour condition, not the colour-swapping condition because in the colour-swapping condition participants would not be able to associate a particular feature value with the colour singleton. Any learning that occurred over a few trials would presumably be wiped out when a colour switch occurred, as it was in Vatterott and Vecera's (2012) experiment after a change in the colour of the colour singleton. One could also imagine an experience-based model under which top-down control is more difficult in the colour-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 colour 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 colour singleton targets when the colours 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.

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

In the colour-swapping condition, we will examine both the influence of the colour 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 colour. Consideration of trial history effects leads us to expect that participants will experience more capture on such a trial than on a trial (such as the second trial) that follows a trial with the same majority colour. This is because the previous trial's majority colour (which is, of course, also the target colour) 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 colour.

We will also look at whether significant capture occurs on trials that were preceded by trials with the same majority colour. This is to determine whether, on trials where participants have had immediately previous experience with that colour 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 colour 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

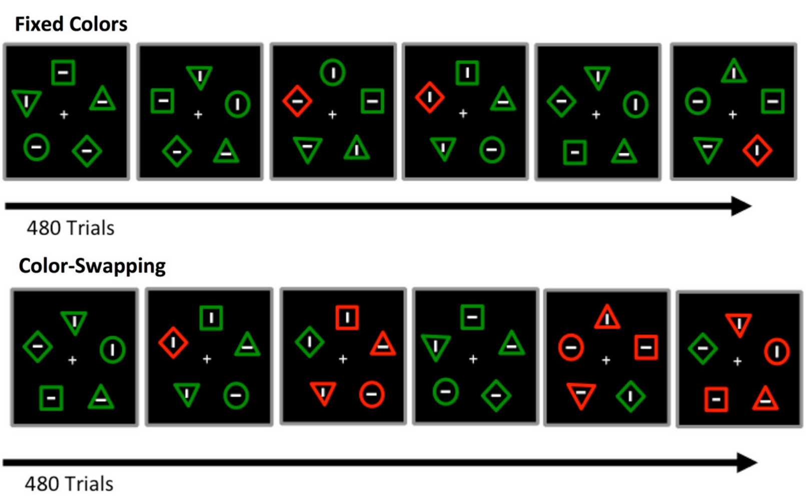


**Figure 1.** Example trials for Experiment 1, where the target was always the circle. In the fixed condition the displays were always a particular colour throughout the experiment (green majority colour, as here, or red majority colour), although there could be a colour singleton distractor present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

in the colour-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 colour as a distractor on the current trial might lead to decreased capture because participants are now inhibiting that colour. It is also possible that the presence of a distractor on the previous trial might lead to reduced capture by a distractor of any colour 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, Egeth, and Leber (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 (10 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 colour-swapping condition and half were assigned to the fixed colour 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 centre of the display to the centre of the shapes, each of which contained a horizontal or vertical white line in the centre. Each shape outline was .1° thick and the line inside was .5° in length and .05° in thickness. The fixation cross at the centre 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 colour. If a colour 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 colour, referred to here as the majority colour, which could be either green or red. On distractor-present trials one item was a colour singleton, which would be green if the majority colour was red or red if the majority colour was green. In the fixed colour condition, half of the participants were given trials where the majority colour was green throughout the experiment and half were given trials where the majority colour was red throughout the experiment. In the colour-swapping condition, half the trials had a red majority colour and half had a green majority colour. Each trial in the colour-swapping condition was equally likely to have the same or different majority colour as the one before it. This means that in the colour-swapping condition, green could sometimes be the majority colour and sometimes the singleton colour, 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 colours of the items were irrelevant to the task. Each participant was given 24 practice trials without colour 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 2000 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 response times and error rates are shown in Table 1. Mean RTs were entered into a 2 (colour 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 colour mapping, $F(1, 22) = 1.40$, $p = .251$, $\eta_p^2 = .06$. There was a main effect of colour 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 colour 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 colour-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 colour singleton distractors. Figure 2 depicts the difference in the amount of capture in the fixed condition and in the colour-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 colour mapping and practice, $F(3, 66) = .31$, $p = .756$, $\eta_p^2 = .01$, or distractor and practice, $F(3, 66) = .70$,

**Table 1.** Mean colour 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 (%) | |
|---|---|---|---|---|
| | Fixed Colour | Colour-swapping | Fixed Colour | Colour-swapping |
| *First Quarter* | | | | |
| Colour Singleton Absent | 699(113) | 733(121) | 4.2 | 4.4 |
| Colour Singleton Present | 720(114) | 782(138) | 4.5 | 4.9 |
| *Second Quarter* | | | | |
| Colour Singleton Absent | 709(110) | 753(136) | 5.7 | 3.9 |
| Colour Singleton Present | 729(143) | 789(166) | 5.3 | 4.1 |
| *Third Quarter* | | | | |
| Colour Singleton Absent | 661(107) | 701(106) | 4.2 | 4.1 |
| Colour Singleton Present | 660(89) | 758(132) | 4.5 | 4.3 |
| *Fourth Quarter* | | | | |
| Colour Singleton Absent | 666(79) | 689(115) | 6.1 | 4.6 |
| Colour Singleton Present | 667(81) | 728(137) | 4.7 | 4.5 |

$p = .536$, $\eta_p^2 = .03$. We were particularly interested in the three-way interaction between colour mapping group, practice, and distractor presence in order to see if the capture that occurred in the colour-swapping condition decreased over time, however, it did not, $F(3, 66) = 1.38$, $p = .258$, $\eta_p^2 = .06$.

### *Further analysis of the colour-swapping condition*

In order to assess the effect of the previous trial in the colour-swapping condition, we divided the trials in that condition based on whether there was a colour singleton present, whether the majority colour on that trial was the same or different as the majority colour 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

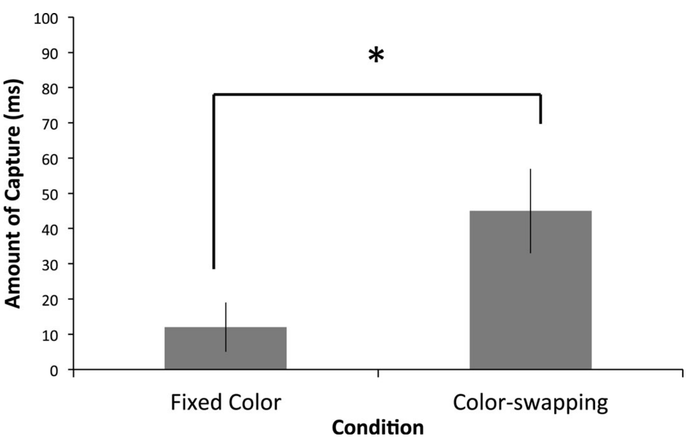


**Figure 2.** Amount of capture in the fixed colour condition and the colour-swapping condition of Experiment 1. Error bars represent the standard error of the mean.

trial majority colour) × 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 colour such that response times were slower on trials where the previous majority colour was different, $F(1, 11) = 16.57$, $p = .002$, $\eta_p^2 = .60$. This effect was almost certainly due to colour 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 (in relation to 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-colour priming effect we observed the colour-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 colour (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 colour and the presence of the distractor such that participants experienced a greater magnitude of capture after a different majority colour 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 (Lamy et al., 2006; Pinto et al., 2005). 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 colour, $F(1, 11) = .43$, $p = .526$, $\eta_p^2 = .04$, and no interaction of the presence of a distractor on

**Table 2.** Mean colour singleton present and absent reaction times and standard deviations in milliseconds for the different priming conditions of Experiment 1.

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

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 colour, 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 colour matched the previous majority colour and there was a distractor on the previous trial, that is, when the current distractor is the same colour 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 colour as compared to after a trial with the same majority colour but no distractor, but this was not the case.

Although there was significantly more capture after trials with a different majority colour trial than after trials with the same majority colour, we were interested in whether there was still significant capture after same majority colour 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 colour-swapping condition on trials that were not preceded by a swap, in contrast with the non-significant capture in the fixed colour condition where swaps never occurred, indicates that the effect of colour swapping on capture extends beyond the trial immediately after a swap.

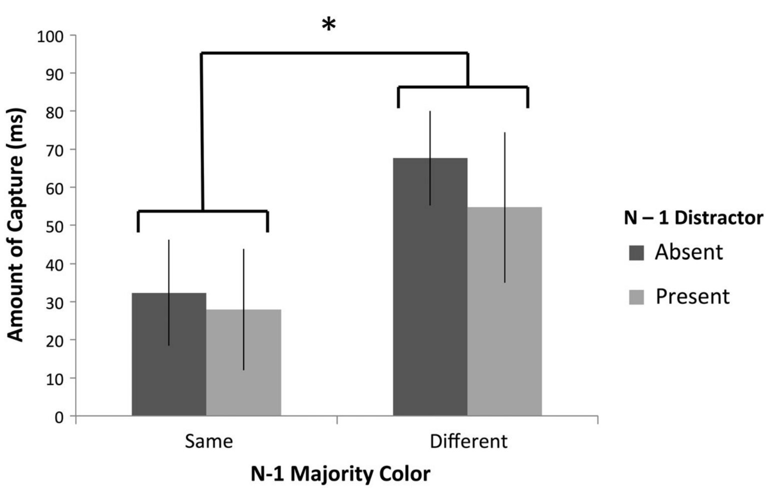


**Figure 3.** Amount of capture based on the similarity of the previous trial, which could have had either the same or different majority colour from the preceding trial, and could have had a distractor on the preceding trial or not. Error bars represent the standard error of the mean.

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 colour-swapping condition, the colour 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 colour mapping, indicating that not all capture in this condition resulted from a change in the majority colour 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 colour-swapping condition of Experiment 1 was due only to target feature uncertainty or switch costs resulting from changes in the majority colour 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 colour condition of Experiment 1, the majority colour could be one of two colours (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 colour-swapping condition of Experiment 1, the colour singleton did not vary in colour. An experience-dependent theory under which distractor features are critical would predict a lack of capture in this experiment because the distractor colour was always red, as seen in Figure 4(A), 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.

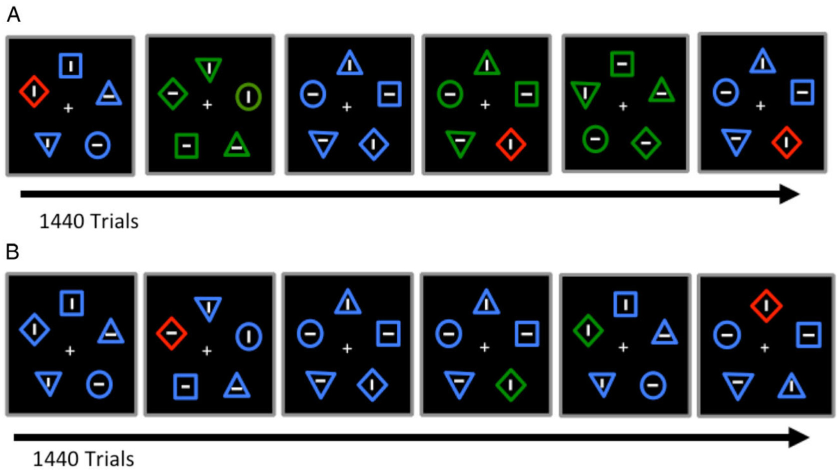


**Figure 4.** (A) Example trials for Experiment 2, where the target was always the circle. The majority colour was randomly either green or blue. Colour singletons distractors were present on half of all trials and were always red. (B) Example trials for Experiment 3, where the target was always the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

### *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 colour.

### *Design*

In this experiment, the majority colour had an equal probability of being green or blue. A colour 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 colours of the items were irrelevant to the task. Each participant was given 24 practice trials without colour 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 2000 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 colour) × 2 (colour singleton distractor present or absent) × 2 (display size) repeated-measures ANOVA. There was a main effect of majority colour such that participants were slower when the majority colour was blue, $F(1, 10) = 6.73$, $p = .027$, $\eta_p^2 = .40$. This was almost certainly due to the fact that colours 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 colour 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 colour 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

**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* | | | | |
| Colour Singleton Absent | 690(136) | 710(128) | 5.6 | 4.9 |
| Colour Singleton Present | 694(147) | 712(126) | 5.1 | 5.4 |
| *Blue Majority* | | | | |
| Colour Singleton Absent | 670(131) | 721(135) | 5.0 | 5.2 |
| Colour Singleton Present | 704(134) | 730(137) | 4.8 | 4.5 |

colour and display size, $F(1, 10) = .43$, $p = .527$, $\eta_p^2 = .04$. There was no three-way interaction between majority colour, 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 (colour singleton distractor present or absent) x 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 colour-swapping condition of Experiment 1 was not due to uncertainty about the target colour. Although participants could not predict the target's colour on a given trial, they might have been able to learn to associate both colours with the target. More importantly, they were able to associate a single colour 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 colour singleton distractor present or absent. The previous trials had either the same majority colour or a different majority colour, 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 colour depending on whether the previous majority colour was different or the same, in Experiment 2 all the colour singletons were the same colour.

Mean RTs were entered into a 2 (current trial distractor presence) × 2 (previous trial majority colour) × 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 colour and did not contain a distractor and −5 ms (effectively no capture) when the previous trial had the same majority colour and contained a distractor. Capture was 11 ms on trials when the previous trial had a different majority colour and did not contain a distractor and −13 ms when the previous trial had a different majority colour 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 colour on a given trial. Again, search mode theory would predict no capture on these feature search trials, but because capture was found in the colour-swapping condition of Experiment 1, this is an important control experiment. Here we test the robustness of experience-dependent, colour-based resistance to capture. In this experiment we use two different singleton colours, while the majority colour is always a third colour, as seen in Figure 4(B), which means that the singleton distractor colours are never used as target colours.

## 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 colour was always blue. A colour 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 colours of the items were irrelevant to the task. Each participant was given 24 practice trials without colour 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 2000 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 (colour 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 nine items than when there were five, $F(1, 18) = 24.24$, $p < .001$, $\eta_p^2 = .57$. 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 (colour 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 colour of the distractor could not be predicted on a trial-by-trial basis. The key difference between this experiment and the colour-swapping condition of Experiment 1 is that here the two singleton colours were never the target colour and any change in how participants responded to the singleton colours, in order to resist capture by those colours, could have remained throughout the experiment. This experiment demonstrates that participants can learn to resist capture by more than one colour at a time.

**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 (%) | |
|---|---|---|---|---|
| Colour 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 |

### *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 colour, or a trial with a distractor of a different colour. 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 colour 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 colour or colours. When the trials had a fixed colour mapping, that is, the majority of items were always one specific colour and the colour singleton was always another specific colour, the typical lack of capture was obtained. In the colour-swapping condition, where a trial could have either one of two majority colours and the singleton, if present, had the other of those colours, there was a significant amount of capture. In Experiments 2 and 3, participants were able to resist capture even when the majority colour or singleton colour had two possible values, as long as there was no overlap between the set of majority colours and the set of singleton colours. This is in conflict with search mode theory, which predicts that attentional capture should never occur on feature search trials. It is clear that colour 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 colour 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 colour 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 colour—the majority colour—even though the target is not defined by its colour and the target colour on one trial is not predictive of target colour 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 colour singleton that has the previous trial's majority colour than it would otherwise be, leading to increased attentional capture. Inhibition of the previous trial's distractor colour 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 colour than the current target. Therefore, it appears that intertrial colour priming can influence the magnitude of capture, but resistance to capture by particular colours is not fully explained by priming of the previous target's features.

The finding of capture on trials in the colour-swapping condition where the previous trial had the same colour 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 colour associations can be made. However, there is a possibility that this attentional capture effect resulted from observers being distracted by a colour that had recently (several trials back) been the colour of the target. Based on the findings of Vatterott and Vecera (2012), where capture was obtained until participants had sufficient experience with a specific colour distractor and where distractor colours had never been target colours, it seems unlikely that capture here resulted purely from the influence of attention drawn to the irrelevant colour 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 colour, 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 colour singleton distractor colour varies across trials and the majority colour is constant suggests that whatever it is that allows observers to resist capture (de-weighting, inhibition, etc.) can occur for multiple colours simultaneously. However, further experiments will be needed to discover how many colours can successfully be resisted at once, and whether there are ever conditions using similar displays under which all colour 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 colour categories are treated as separate dimensions rather than only being treated as values under the general dimension of colour, 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 colour, 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 colour and less to the singleton colour over time. In the swapping condition, participants might begin to adjust colour weightings after every switch trial, but on average weight the two colours the same, leading to capture by whichever colour 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 colour category while de-weighting both singleton colour categories. It is possible that the maximum de-weighting of the two distractor colours took longer than for a single colour, 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 colours, while de-weighting the singleton colour. It is also possible that most of the dimensional weighting only affected the features related to the target or to the colour 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 colour, since introducing a new singleton colour while the majority colour remains the same results in attentional capture when it was not previously occurring. If the weighting of the majority/target colour rather than the weighting of the singleton colour was primarily affected by experience, we would not expect this to be the case. This makes sense given that the presence of the majority colour is not a very good predictor of whether the item is a target, since many non-targets share that colour, while the singleton colour is perfectly predictive of that item being a non-target, therefore the singleton colour is more informative. However, it remains possible that changes in the majority colour might lead to capture in some conditions, and perhaps the weight assigned to the majority colour 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 colour-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.

## Disclosure statement

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