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Memory for Found Targets Interferes With Subsequent Performance in Multiple-Target Visual Search

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Multiple-target visual searches—when more than 1 target can appear in a given search display—are commonplace in radiology, airport security screening, and the military. Whereas 1 target is often found accurately, additional targets are more likely to be missed in multiple-target searches. To better understand this decrement in 2nd-target detection, here we examined 2 potential forms of interference that can arise from finding a 1st target: interference from the perceptual salience of the 1st target (a now highly relevant distractor in a known location) and interference from a newly created memory representation for the 1st target. Here, we found that removing found targets from the display or making them salient and easily segregated color singletons improved subsequent search accuracy. However, replacing found targets with random distractor items did not improve subsequent search accuracy. Removing and highlighting found targets likely reduced both a target's visual salience and its memory load, whereas replacing a target removed its visual salience but not its representation in memory. Collectively, the current experiments suggest that the working memory load of a found target has a larger effect on subsequent search accuracy than does its perceptual salience.

Keywords: visual search, working memory, satisfaction of search, visual salience

Visual search, the act of finding target objects among distractors, is a ubiquitous human activity. Whereas many everyday searches are easy and innocuous (e.g., looking for a pen on a desk), searches in a professional context can often have life-or-death consequences (e.g., a radiologist looking for tumors in medical X-rays). Extensive research has focused on the nature of visual search and has provided detailed insight into the processes involved and related cognitive abilities (e.g., see Eckstein, 2011; Nakayama & Martini, 2011, for recent reviews). Despite a few notable exceptions (e.g., Horowitz & Wolfe, 2001; Körner & Gilchrist, 2008), a commonality of laboratory research is a focus on single-target search—visual search tasks in which there is either zero or one target present. However, an important aspect of many real-world visual searches is the possibility of *multiple-target* searches, in which more than one target can be present in a given display (e.g., both a water bottle and a gun could be present in a baggage X-ray).

Multiple-target visual searches have long been known to be especially error prone; after having found one target, an additional target in the display is often less likely to be found than if that same target had been the only target in the display, a phenomenon known as *satisfaction of search* (SOS; Smith, 1967; Tuddenham, 1962). In addition, second targets are more vulnerable than first targets to influences such as anxiety (Cain, Dunsmoor, LaBar, & Mitroff, 2011), motivation (Clark, Cain, Adcock, & Mitroff, 2012a, 2012b), and visual clutter (Adamo, Cain, & Mitroff, 2012). SOS is not mitigated by expertise, as both novice and professional searchers have been found to commit SOS errors in laboratory multiple-target search tasks (Biggs, Cain, Clark, Darling, & Mitroff, 2012; Clark, Samei, Baker, & Mitroff, 2011, 2012; Fleck, Samei, & Mitroff, 2010). In real-world searches, radiologists have been aware of SOS for at least 50 years, but one third of misses still arise from this problem (see Berbaum, Franklin, Caldwell, & Schartz, 2010, for a review); this suggests that SOS is a deep-rooted issue that likely has a multitude of underlying causes.

From a cognitive psychology perspective, multiple-target visual search provides a means to examine questions that single-target searches cannot address: Multiple-target searches are more intricate than a simple series of single-target searches as they involve additional attention, memory, and decision-making aspects. In a single-target search with zero or one targets present, the decision about when to quit searching is relatively straightforward: If a target is found, the searcher can move on to the next trial, and if a target is not found, the searcher continues until the search has continued "long enough" (Chun & Wolfe, 1996). The dynamics of such searches have been modeled extensively (e.g., Wolfe, 2007).

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With the seemingly simple addition of two-target trials alongside zero- and one-target trials, search parameters become exceedingly more complex. If the searcher finds two targets, the searcher can confidently move on to the next trial, but what additional factors might affect a searcher's feeling that the search has continued "long enough" after finding one target when there may or may not be a second? One complicating feature common to all multiple-target searches that does not affect any single-target search is the presence of found targets in the display. Here, we investigate how the presence of found targets might contribute to SOS errors.

There is a clear consensus that SOS is a major cause of miss errors in multiple-target search, but there is no consensus on why. Support has been offered for a variety of explanations of SOS, suggesting that there are likely a number of factors involved in second-target miss errors (see Cain, Adamo, & Mitroff, 2012a, 2012b). The original theory of SOS was that searchers become "satisfied" that they have searched exhaustively after finding one target and thus terminate search too early (Smith, 1967; Tuddenham, 1962). However, premature termination of search is not likely the primary cause of SOS as numerous studies have failed to find evidence supporting this theory (e.g., Berbaum et al., 2010; Fleck et al., 2010). One compelling alternative explanation is the *perceptual set hypothesis* (Berbaum et al., 2010; but see Ashman, Yu, & Wolfman, 2000): When one target is found (e.g., a broken bone), a searcher is more likely to recognize additional targets that are perceptually similar to the found target (e.g., another fracture) and is less likely to recognize additional, perceptually dissimilar targets (e.g., a tumor). Fleck et al. (2010) found evidence outside of radiology that was consistent with the perceptual set hypothesis but also demonstrated that it cannot be the sole explanation of SOS. In addition, the perceptual set hypothesis cannot explain SOS errors in displays in which the targets are perceptually similar (e.g., Cain, Vul, Clark, & Mitroff, 2012). These hypothesized mechanisms and others (see Berbaum et al., 2010; Cain et al., 2012b; Cain, Adamo, et al., 2012a) offer some insight but also demonstrate that much more work is needed to better understand the causes of SOS.

To further explore SOS, it is helpful to consider the steps involved in a multiple-target search scenario. In a single-target search (or in search for a first target in a multiple-target search), the searcher is simply engaged in target detection. However, search for a second target is different: The searcher has just found a target and, moreover, that target is still present in the very same array. The goal of the current article is to explore how such a found target can act as a distractor during subsequent multiple-target search.

Previous evidence from eye-tracking studies supports the hypothesis that found targets can act as a form of distraction. For example, in single-target searches, individual distractors are rarely examined more than once (e.g., McCarley et al., 2006; Peterson, Kramer, Wang, Irwin, & McCarley, 2001), but in a recent eye-tracking investigation of multiple-target search, we revealed that refixations on distractors accounted for nearly a quarter of all fixations after a target had been found (Cain et al., 2012b; Cain, Adamo, et al., 2012a). Moreover, found targets were refixated on nearly a quarter of all dual-target trials, and were refixated more often when the second target was missed than when it was subsequently found (Cain et al., 2012b; Cain, Adamo, et al., 2012a). This suggests that the presence of a found target may be misdirecting attention or diverting cognitive resources away from subsequent search.

In the present experiments, we tested two hypotheses to better understand how a found target could interfere with subsequent search: *perceptual salience* and *resource depletion*. According to the perceptual salience hypothesis, found targets interfere with subsequent search because their perceptual characteristics always match those of a target. As such, they may continue to attract attention during search even after they have been found and reported. For example, in a search for *X*s among other letters, any previously found *X* will always have the same shape as the *X* being searched for, and this shape match may attract searchers' attention back to found *X*s as they look for additional targets. This is complementary to the perceptual set hypothesis. For example, in a search for either *X*s and *O*s among other letters (with, say, 0–2 of each target possible per display), the perceptual set hypothesis suggests that, after finding an *X*, searchers would be in "*X* search mode" and, thus, it should be easier for them to find additional *X*s than to find *O*s. It is important to note that the perceptual set hypothesis does not speak to whether finding a second *X* while in "*X* search mode" is easier or harder than finding the first *X*. In contrast, the perceptual salience hypothesis suggests that the first found *X* would distract from subsequent search for both *X*s and *O*s but does not make a prediction about whether subsequent *X*s would be easier or harder to find than *O*s.

Alternatively, according to the resource depletion hypothesis, found targets interfere with subsequent search by consuming memory resources that could otherwise aid search; for example, if the location or identity of a found target is retained in working memory for the rest of search, then those resources are not available to other search processes. Whether and how such a memory load interacts with visual search have been the subject of much debate in the literature. Some have argued that visual search itself does not require memory (Horowitz & Wolfe, 1998, 2003), and others have argued that visual search involves memory for three or four items (e.g., Emrich, Al-Aidroos, Pratt, & Ferber, 2009; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). Visual search has been demonstrated to be more adversely affected by location-based memory loads than by item feature-based memory loads (Beck, Peterson, & Vomela, 2006; Oh & Kim, 2004; Woodman & Luck, 2004), but memory may be extensive for both the locations (e.g., Dickinson & Zelinsky, 2005, 2007; Takeda, 2004) and features (e.g., Hollingworth, Williams, & Henderson, 2001) of items encountered during search. Similarly, keeping multiple categories of potential targets in memory while searching (e.g., looking for both guns and bombs in a baggage X-ray) has been shown to decrease search accuracy compared with searching for only one category of target (e.g., looking for only guns or bombs; Menneer, Barrett, Phillips, Donnelly, & Cave, 2007).

Beyond the general role of memory in search, there is evidence that found targets in multiple-target search may have a privileged representation in memory (e.g., Williams, Henderson, & Zacks, 2005). For example, when searching displays with one or two targets—compared with searching displays with zero or one—the first target appears to consume memory resources even before it has been found (Körner & Gilchrist, 2008). The most direct evidence about the memory load of found targets comes from a multiple-target search paradigm in which participants were asked to report whether more than a certain number of targets were present in a given display, with both the criterion number and the actual number of targets present manipulated (Horowitz & Wolfe, 2001). Results from this paradigm were initially interpreted as supporting a memory-free model of visual search. However, further work with this paradigm has suggested that keeping track of the locations of found targets produces an increasing load on search performance (McCarley et al., 2006; Takeda, 2004). In addition, evidence for search deficits due to impairments in remembering the locations of previously found targets has been observed in patients with simultagnosia (Dehaene & Cohen, 1994) and hemispatial neglect (Wojciulik, Rorden, Clarke, Husain, & Driver, 2004). Together, these findings suggest that found targets consume some form of memory resources and that reducing the mnemonic load of found targets may improve search for subsequent targets.

Here, we tested the perceptual salience and resource depletion hypotheses across three experiments. In Experiment 1, found targets were removed from the screen, improving subsequent search accuracy, consistent with both hypotheses. In Experiment 2, found targets were highlighted in yellow to make them a color singleton, which also improved subsequent search accuracy, arguing against the perceptual salience hypothesis but consistent with the resource depletion hypothesis. Finally in Experiment 3, found targets were replaced by new, randomly generated distractors, which did not improve subsequent search accuracy, again arguing against the perceptual salience hypothesis but consistent with the resource depletion hypothesis.

Experiment 1—Target Removal

Experiment 1 was designed as a simultaneous first test of both hypotheses. The perceptual salience hypothesis predicts that removing a found target from the search display should lead to more accurate second-target search, as the found target is no longer a perceptual distraction; if the features of the found target are not visible, they cannot capture attention. If removing a found target from the search display also allows it to be removed from searchers' working memory, then the resource depletion hypothesis would also predict improved second-target search. For example, if the primary utility of maintaining a working memory representation of a found target is to inhibit re-searching the item, then observing a target disappearing may serve as a strong cue that such a representation is not necessary. Thus, improved second-target search due to found-target removal would be consistent with both hypotheses, whereas no change in performance would be strong evidence against the perceptual salience hypothesis, but would not entirely rule out the resource depletion hypothesis if found targets are obligatorily retained in working memory.

Method

Participants. Eighteen members of the Duke University community participated for $10 or partial fulfillment of a class requirement. Three participants were excluded from analysis because of poor overall search performance: two for committing false alarms on more than 20% of trials and one for finding the low-salience target on less than 10% of the trials on which it was present; both cutoffs were more than 2.5 standard deviations below their respective means. The 15 participants remaining in the analysis ranged in age from 18 to 32 years ($M = 22.3$ years) and included eight men and seven women.

Stimuli and apparatus. The stimuli and apparatus were based on two prior studies (Cain et al., 2011; Fleck et al., 2010). Each display contained 25 total items arranged within an invisible 8 × 7 grid, with each item randomly offset 0–10 pixels from perfect grid alignment (see Figure 1). Targets were perfect T shapes and appeared in one of two salience levels (high salience: 57–65% black; low salience: 22–45% black). Two different salience levels were employed to mimic real-world search scenarios, such as when a baggage X-ray contains both an obvious banned item, such as a water bottle, and a harder-to-spot threat, such as a component of a bomb, or when a medical X-ray contains a relatively easy-to-spot but benign abnormality and a more subtle, more dangerous abnormality (e.g., Berbaum et al., 2007). In addition, the presence of high-salience targets allows for a better test of the perceptual salience hypothesis than would, say, all low-salience targets, as a found high-salience target would likely be more perceptually distracting than a found low-salience target. Distractors were non-T shapes drawn from the same salience ranges; 5% of distractors were high salience, and 95% were low salience. Each item was composed of two rectangles (width = 0.3° of visual angle; participants were seated approximately 57 cm from the screen) oriented perpendicularly and slightly separated; each item was 1.3° × 1.3° at its widest point. Each item appeared in one of four possible rotations, and all were on a background of gray "clouds" (4–37% black). The distribution of target prevalence was designed to elicit an SOS effect (Fleck et al., 2010): 52% of displays had a single, high-salience target; 14% of trials had a single, low-salience target; 14% had both a low-salience and a high-salience target; and the remaining 20% of trials had no targets.

Procedure. Participants were instructed to make a mouse click on each of the targets they found and then click a button marked "Done" when they had completed their search. The *Done* button appeared once an item had been clicked or after 3 s had elapsed without a click. This delay was introduced to minimize motor-based miss errors (i.e., to prevent the target-absent response from becoming prepotent and executed habitually; Fleck & Mitroff, 2007; Rich et al., 2008). If the *Done* button was not clicked within 15 s, the trial was terminated, and a message appeared encouraging the participant to search faster. Feedback on

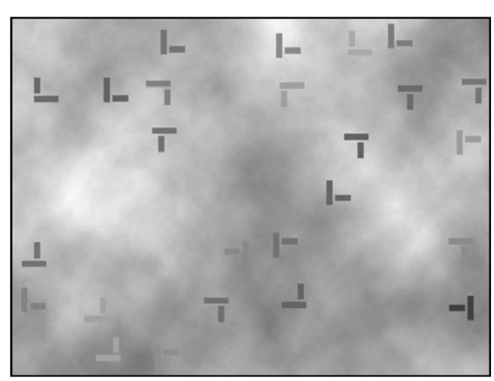

Figure 1. Example stimulus display for all three experiments. Targets were perfect T shapes, and two are present here (one high-salience target in the lower right and one low-salience target in the upper right).

misses and false alarms was given during an unanalyzed 25-item practice block, but no feedback was given during experimental blocks.

There were two conditions, presented in two blocks of 204 trials each, with the order of blocks counterbalanced across participants. In the control condition, a small, blue, unfilled circle (0.3° diameter, the same size as the circular mouse cursor) appeared at the location clicked (see Figure 2A). In the remove condition, no mark was made, but whenever an item was clicked (regardless of whether it was a target or not), the item immediately disappeared and remained hidden for the rest of the trial (see Figure 2B). A click within a 35-pixel radius of the center of an item was considered a click on that item.

Results and Discussion

Accuracy was the primary dependent variable of interest; responses were made with mouse clicks and, thus, response times were mostly uninformative but are reported in Appendix A and B. Trials with false alarms (defined as mouse clicks not made on target items, i.e., on distractor items or empty space) accounted for 4.3% of all trials, with no difference in occurrences by condition, $t(14) = 1.56$, $p = .141$, and were not analyzed further. For low-salience target analysis on dual-target trials, we considered only those dual-target trials in which the high-salience target was correctly found first (87% of dual-target trials), allowing for a cleaner examination of the target removal manipulation: When the high-salience target was not identified at all, it is difficult to discern what effect, if any, it had on search and the low-salience target was not identified first often enough to allow for robust analysis (e.g., on only 3.0% of dual-target trials was the low-salience target found but the high-salience target subsequently missed).

High-salience targets. High-salience targets were found with 94.8% accuracy across all trial types. A 2 × 2 repeated measures analysis of variance (ANOVA) with condition (remove vs. control) and number of targets (single vs. dual) as within-subject factors revealed no significant main effects or interaction ($ps > .5$). This lack of difference across conditions was expected, as the high-salience target was usually found first and the visual consequences of a click and the presence or absence of a second target and should not have affected first-target accuracy.

Low-salience targets. Low-salience accuracy results are summarized in Figure 3A. Low-salience target accuracy data were submitted to the same 2 × 2 repeated measures ANOVA as the high-salience target accuracy data. A significant main effect of condition, $F(1, 14) = 6.98$, $p = .019$, corresponded to higher accuracy in the remove condition than in the control condition (54.8% vs. 47.7%). A significant main effect of number of targets, $F(1, 14) = 23.07$, $p < .001$, corresponded to an overall SOS effect, with higher accuracy for low-salience targets in single-target trials than in dual-target trials (57.5% vs. 44.1%). There was no interaction between the factors, $F(1, 14) = 0.58$, $p = .461$, indicating that the SOS effect was present in both conditions (10.9% in the remove condition and 11.3% in the control condition).

The critical comparison is the difference in second-target accuracy between the two conditions. Despite the presence of an SOS effect in both conditions, second-target accuracy significantly improved when found targets were removed from the display compared with when left in place (48.8% in the remove condition vs. 39.9% in the control condition), $t(14) = 2.55$, $p = .023$. This provides evidence that the mere presence of a found target does impair search for a subsequent target. Removing a found target removes any potential distraction due to perceptual similarity with subsequent targets; thus, the improvement in second-target search performance is consistent with the perceptual salience hypothesis. Similarly, the location of a removed target does not need to be kept in working memory to avoid accidentally re-searching it; thus, the results are also consistent with the resource depletion hypotheses. Experiment 2 was designed to tease apart these hypotheses, as well as to address a potential concern inherent in this design that removing a found item from the screen also reduces the set size, which alone could speed search (albeit somewhat negligibly here given that the set size went from 25 to 24).

Experiment 2—Target Highlighting

Because removing a found target from the search display reduces its visual impact and perhaps its memory impact as well, the improvement in second-target performance in Experiment 1 was

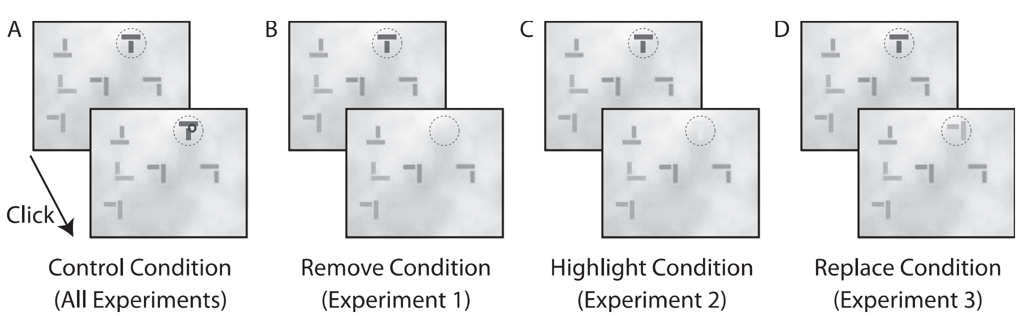

Figure 2. Conditions for all three experiments, demonstrating the effect of a mouse click on a target item (marked with a dashed circle that was not present on actual displays). (A) In the control condition (for all three experiments), the location of a click was marked with a small blue circle (shown here in gray and thickened for visibility). (B) In the remove condition, the clicked item disappeared. (C) In the highlight condition, the clicked item turned yellow, shown here in light gray. (D) In the replace condition, the clicked item was replaced with a random distractor item. All changes occurred immediately after a click was made.

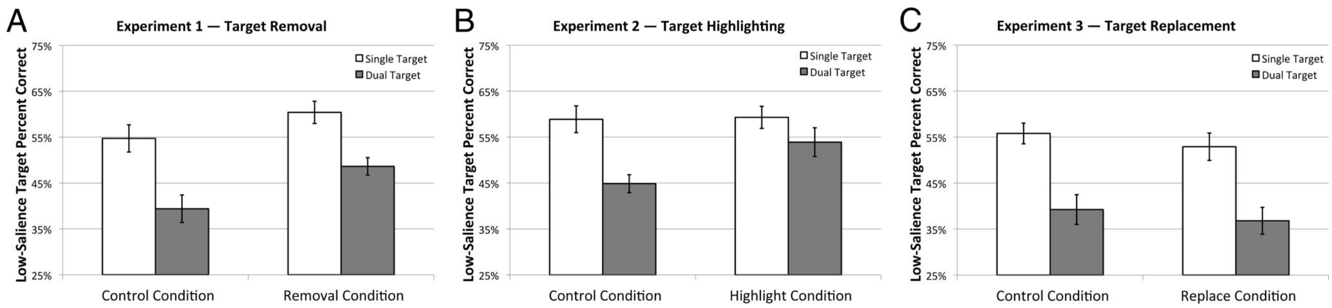

Figure 3. Results for (A) Experiment 1, (B) Experiment 2, and (C) Experiment 3. White bars depict accuracy for low-salience single targets and gray bars depict accuracy for low-salience targets on dual-target trials after the high-salience target was successfully found. Error bars represent within-participants confidence intervals (Morey, 2008).

consistent with both the perceptual salience and resource depletion hypotheses. Experiment 2 sought to differentiate between these hypotheses by leaving the found target visible, but highlighting it in a contrasting color. According to the perceptual salience hypothesis, this manipulation should not lead to improvements in search, and search performance may even worsen if the color change produces additional visual distraction. In contrast, the resource depletion hypothesis predicts improved performance, as highlighting a found target would make it easily distinguishable from the rest of the search array, and thus its location and other details would not need to be remembered (or at least remembered as much).

Method

Participants. Fifteen members of the Duke University community volunteered to participate in return for $10 or partial fulfillment of a course requirement. No participants had taken part in Experiment 1 nor were any excluded for poor performance. The participants ranged in age from 18 to 24 years ($M = 19.8$ years) and included eight men and seven women.

Stimuli and procedure. The stimuli and procedure were identical to those in Experiment 1, except that the remove condition was replaced by a highlight condition in which no marker appeared when an item was clicked, but each clicked item (regardless of whether it was a target or a distractor) immediately became bright yellow (100% red, 100% green, 30% blue; see Figure 2C) and remained this color for the remainder of the trial. The number of items visible in the display remained constant throughout each trial.

Results and Discussion

Trials with false alarms were excluded from analysis (4.0% of total trials), with more false alarm trials in the highlight condition than the control condition (5.6% vs. 2.5%), $t(14) = 2.87$, $p = .012$. For low-salience target accuracy on dual-target trials, as in Experiment 1, only dual-target trials in which the high-salience target was found correctly and first were considered. Response time data are reported in Appendix A and B.

High-salience targets. High-salience targets were found with 96.4% accuracy overall, and a 2×2 repeated measures ANOVA with condition (highlight vs. control) and number of targets (single vs. dual) as within-subject factors found no significant main effects or interaction ($ps > .2$). As in Experiment 1, no differences were predicted.

Low-salience targets. Low-salience accuracy results are summarized in Figure 3B. Low-salience target accuracy data were submitted to the same 2×2 repeated measures ANOVA as the high-salience target data. No significant main effect of condition, $F(1, 14) = 3.24$, $p = .094$, indicated no overall accuracy improvement in the highlight condition. A significant main effect of number of targets, $F(1, 14) = 9.78$, $p = .007$, corresponded to an overall SOS effect, with higher low-salience target accuracy in single-target trials than in dual-target trials (59.1% vs. 49.3%). A significant interaction between the factors, $F(1, 14) = 4.32$, $p = .056$, corresponds with a reduction in the SOS effect in highlight trials compared with control trials (5.4% vs. 14.0%).

Again, the critical comparison is the difference in second-target accuracy between the two conditions. As suggested by the reduction in SOS in the highlight condition, second-target accuracy was significantly improved in the highlight condition relative to the control condition (53.9% vs. 44.9%), $t(14) = 2.75$, $p = .016$. This result presents a challenge for the perceptual salience hypothesis: This improvement in accuracy occurred even though the found targets were still present on the screen and were, by virtue of their unique color, even more perceptually salient than distractors. This may initially seem surprising, as color singletons usually strongly capture attention (e.g., Theeuwes & Burger, 1998), but they do not always do so when searchers are looking for specific features (e.g., a particular shape) rather than salience per se (Leber & Egeth, 2006). Note also that no attentional capture would be expected here because the color change (like the changes in the other experiments described here) occurred immediately once an item was clicked, when, presumably, visual attention was already directed at the target item. The increase in false alarms between the control and highlight conditions was disproportionately due to nontarget clicks after a first target had been found (from 0.33% of control condition trials to 1.27% of highlight condition trials). This increase could be a subtle indication of the color singleton interfering with subsequent search.

One mechanism that may be at play in this experiment is that, with a color change, the found target was able to be perceptually segregated from the rest of the display. Thus, searchers may have been able to effectively filter out the yellow object while searching the rest of the gray display. Such a mechanism would be consistent with the resource depletion hypothesis; here, color, rather than working memory, could be used to avoid the found target in subsequent search. However, the possibility of early color-based segregation also prevents the perceptual salience hypothesis from being ruled out entirely: If searchers are able to perceptually filter out the found target early in visual processing, the target's shape may not get processed and, thus, may not be available to capture attention. Experiment 3 addressed this color-segregation issue by replacing found targets with random distractors that were not easily distinguishable from other items in the display.

Experiment 3—Target Replacement

The results of Experiments 1 and 2 clearly demonstrate that the presence of a found target disrupts subsequent search. However, the findings thus far do not fully differentiate between the perceptual salience and resource depletion hypotheses. In this experiment, found targets were replaced with random distractors (see Figure 2D). The perceptual salience hypothesis predicts that this replacement would improve performance by removing the distracting target shape from the display during subsequent search. Conversely, the resource depletion hypothesis does not necessarily predict improved performance. If the replacement item is considered a new object, then performance would improve, as the memory representation of the found target could be discarded. However, if the replacement item is interpreted as a change to the found target, performance would not improve, as the memory representation of the found target would be updated and retained (e.g., Kahneman, Treisman, & Gibbs, 1992).

Method

Participants. Twenty-one members of the Duke University community who did not take part in Experiments 1 or 2 participated for $10 or partial fulfillment of a class requirement. One participant was excluded for committing false alarms on more than 20% of trials, the same criterion used in Experiment 1. The participants remaining in the analysis ranged in age from 18 to 46 years (M = 23.1 years) and included nine men and 11 women.[1]

Stimuli and procedure. The stimuli and procedure were identical to those in Experiment 1 except that the remove condition was substituted with a replace condition in which no marker appeared when an item was clicked, but each clicked item (regardless of whether it was a target or a distractor) was immediately replaced with a randomly generated distractor. These replacement distractors had all of the same properties as the other distractors.

Results and Discussion

Trials with false alarms were excluded from analysis (3.7% of total trials), with no difference between conditions, $t(19) = 0.73$, $p = .473$. For low-salience target accuracy on dual-target trials, as in Experiments 1 and 2, only dual-target trials in which the high-salience target was found correctly and first were considered. Response time data are reported in Appendix A and B.

High-salience targets. High-salience targets were found with 91.4% accuracy overall. A 2×2 repeated measures ANOVA with condition (replace vs. control) and number of targets (single vs. dual) as within-subject factors found no significant main effects or interaction ($ps > .15$). As in Experiments 1 and 2, no differences were predicted.

Low-salience targets. Low-salience accuracy results are summarized in Figure 3C. Low-salience target accuracy was submitted to the same 2×2 repeated measures ANOVA as the high-salience target accuracy data. There was no significant main effect of condition, $F(1, 19) = 3.44$, $p = .564$, indicating no overall accuracy improvement in the replace condition. A significant main effect of number of targets, $F(1, 19) = 39.34$, $p < .001$, corresponded to an overall SOS effect, with higher low-salience single-target accuracy than dual-target accuracy (54.3% vs. 38.0%). There was also no interaction between factors, $F(1, 19) = 2.71$, $p = .609$, indicating no reduction in SOS in replacement trials compared with control trials (16.1% vs. 16.6%).

Most important, there was no significant difference in low-salience second-target accuracy between conditions (39.1% in the control condition and 38.2% in the replace condition), $t(19) = 0.19$, $p = .852$. Whereas physically removing a found target (Experiment 1) and making a found target easily distinguishable from all others (Experiment 2) improved accuracy for finding a second target, replacing a found target with a random distractor did not change performance. This result provides strong evidence against the perceptual salience hypothesis, which predicts that changing the perceptual features of the found target—including the search-relevant feature of shape—should prevent it from interfering with subsequent search. According to the resource depletion hypothesis, low-salience second-target performance would have improved in the replace condition if searchers considered the found target to have been removed, as in Experiment 1. If, as we argue below, participants processed the found target as a persisting object that underwent a change in shape, then the target may still have consumed the same level of working memory resources as if no change had occurred.

General Discussion

In professional visual searches, the number of potential targets is unknown, and the cost of missing a target can be high, but several factors conspire to limit accuracy in multiple-target search once a first target has been found. In the present studies, we examined the role that such a found target plays in subsequent search. We demonstrated that the presence of a previously found target in a search display had a powerful, negative impact on search for subsequent targets, but this impact was mitigated by removing the found item from the search array (Experiment 1) or by perceptually segregating it from the rest of the display (Experiment 2). Notably, changing the search-relevant visual features of a found target did not improve subsequent search accuracy (Experiment 3).

To understand the effects of a found target on subsequent performance, we proposed two possible explanations: the perceptual salience and resource depletion hypotheses. The perceptual salience hypothesis posits that the visual features that define a

[1] There were more participants in this experiment than the previous experiments because the first five were initially thought to have unanalyzable data because of a programming error, but their data were later able to be analyzed; excluding them does not change the pattern of results.

found target (e.g., its T shape) are perceptually salient, as they perfectly match the search criteria and attract attention during subsequent search, degrading performance. Experiment 1 provided initial support for this hypothesis, as removing all the visual features of a found target from the search display improved subsequent search performance, but Experiment 3 argued against the perceptual salience hypothesis, as changing all the visual features of a found target did not alter subsequent search performance.

The resource depletion hypothesis proposes that found targets take up working memory resources (e.g., memory for the location of the target to avoid searching that area again) that would otherwise be devoted to further search. Experiments 1 and 2 are consistent with this hypothesis, as the improved performance seen when the found target became either invisible or highly visible could be ascribed to searchers not devoting memory resources to those items, as they were easily avoided in subsequent search. The results of Experiment 3 suggest that searchers might treat the replacement distractor not as a new object but as a change in, or update to, the original target object, which would still consume memory resources.

The idea that a found target could be interpreted as changed rather than replaced is supported by object file theory (Kahneman et al., 1992). Object file theory suggests that an object representation is formed when an object is attended to and that this representation is maintained, and updated, as long as the spatiotemporal parameters of the object provide a reasonable expectation that the object is the same entity (e.g., Mitroff, Scholl, & Wynn, 2004; Moore, Mordkoff, & Enns, 2007; Noles, Scholl, & Mitroff, 2005). When objects cease to exist, as in Experiment 1, their persisting, midlevel visual representations are discarded (e.g., Scholl & Feigenson, 2004). However, an object can change its features (e.g., Moore et al., 2007), but as long as it has a consistent spatiotemporal history, it is treated as the same memory representation. Thus, in Experiment 3, when a found target immediately changed its features, it likely maintained its identity as the same persisting object.

The second-target search interference that is proposed by the resource depletion hypothesis has several potential sources. Given the important role of spatial location memory in visual search (e.g., Oh & Kim, 2004; Woodman & Luck, 2004), if searchers remember the location or features of a found target in order to avoid unnecessarily revisiting it, this may limit the number of visited distractor locations that can be remembered in subsequent search. Previous work from our lab has demonstrated that memory span for similar stimuli as those employed here is approximately 1.3 items (Cain, Vul, et al., 2012, Supplementary Experiment 1), suggesting that the features of a found target could produce a heavy working memory load. Recent work has demonstrated that item memory load does not affect search rate (i.e., search slope) but does lead to a slowing of general search processes, less optimal selection of fixation targets, and increased distractor refixations (Solman, Cheyne, & Smilek, 2011). Thus, if searchers encode either the location of a found target, its features, or both, the resulting memory load could have a negative impact on subsequent search performance.

One possible mechanism for this negative impact of memory load is a decreased *perceptual span* (McCarley et al., 2006) or *visual lobe* (e.g., Chan & Courtney, 1995; Chan, Courtney, & Ma, 2002). That is, as memory load increases, the amount of information (or effective area) that a searcher can process during a given fixation decreases. This reduction in useful field of view due to finding a first target in visual search could help explain why SOS studies have found decreases in accuracy for second targets without finding obvious time-on-task differences. If participants develop an intuitive sense of "how long" they should search for a low-salience target that is based on their search efficacy when conducting single-target search, then searching that long with reduced efficacy after finding a first target may lead them to feel as if they have conducted a more thorough search than they actually have. A similar explanation comes from eye-tracking data that show that distractors that have already been visited are rarely revisited in single-target search (e.g., McCarley et al., 2006; Peterson et al., 2001) but are often revisited in multiple-target search (Cain et al., 2012b; Cain, Adamo, et al., 2012a). If participants mistake some or all of these refixations for fixations on previously unsearched objects, they may mistakenly feel that they have exhaustively searched the display before they have actually done so. Thus, by consuming working memory resources, a found target may both decrease the information that can be processed during each fixation and increase the likelihood of refixating a previously examined item, leading searchers who do not take these effects into account to feel satisfied that they have conducted a thorough search before they have truly done so.

Because the current experiments always used identically shaped targets they cannot directly speak to the merits of the perceptual set hypothesis for SOS (i.e., the perceptual match between targets was not manipulated). However, the results are more consistent with a memory mechanism than a purely perceptual one; the contents of working memory have been shown to bias search, with searchers more likely to fixate items that match items in working memory (e.g., Olivers, Meijer, & Theeuwes, 2006; Wong & Peterson, 2011). Moreover, such memory influences have been found to be strong enough to overcome effects of salience in similar displays as those used here (Dowd & Mitroff, 2012) and subject to explicit instructions (Moher & Egeth, 2012). This suggests that found targets in working memory might bias subsequent search in favor of similar items. In the present experiments, this bias would overall help subsequent search performance, but could be detrimental for multiple-target searches with dissimilar targets. This suggests that the working memory representation of a found target might serve as a mechanism for the previously proposed perceptual set hypothesis (cf. Vickery, King, & Jiang, 2005).

Multiple-target searches with targets of unequal salience are common in professional searches, such as radiology and airport security screening, and the present results make direct predictions for how to improve such searches. For example, in computer-aided detection in radiology, once an abnormality has been identified, it should be removed from the display or highlighted in an easily visually separable color. Although such manipulations would have been difficult with traditional X-ray films, concealing an area containing a suspected abnormality would be relatively easy to test and implement on modern viewing systems. Similarly, these findings support the current airport security practice of removing a found threat item from a bag and then searching that bag anew rather than continuing search on the first X-ray image.

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(*Appendices follow*)

Appendix A

Time Taken to Correctly Find Targets, by Experiment, Trial Type, and Condition

Experiment	Target	Single- or dual-target trial	Condition	Average time (s) to find target (*SD*)
1	High salience	Single	Remove	2.80 (0.80)
			Control	2.83 (0.96)
		Dual	Remove	2.78 (0.80)
			Control	2.93 (1.07)
	Low salience	Single	Remove	5.47 (1.14)
			Control	5.20 (1.18)
		Dual	Remove	5.33 (0.82)
			Control	5.74 (0.88)
2	High salience	Single	Highlight	2.46 (0.57)
			Control	2.55 (0.91)
		Dual	Highlight	2.56 (0.66)
			Control	2.57 (1.02)
	Low salience	Single	Highlight	5.00 (1.01)
			Control	4.63 (1.00)
		Dual	Highlight	5.46 (0.92)
			Control	5.55 (1.08)
3	High salience	Single	Replace	3.04 (1.28)
			Control	3.34 (1.08)
		Dual	Replace	3.21 (1.57)
			Control	3.37 (1.26)
	Low salience	Single	Replace	5.42 (0.98)
			Control	5.05 (1.00)
		Dual	Replace	5.56 (1.34)
			Control	5.45 (1.26)

(*Appendices continue*)

Appendix B

Time to Click "Done" on Trials Without Targets and Trials in Which Exactly One Target Was Found, by Experiment, Trial Type, and Condition

Experiment	Target	Single- or dual-target trial	Condition	Average time (s) to click "Done" (*SD*)
1	None		Remove	8.87 (1.63)
			Control	8.61 (1.95)
	High salience	Single	Remove	8.51 (1.73)
			Control	8.15 (2.11)
		Dual	Remove	7.38 (1.21)
			Control	7.41 (1.86)
	Low salience	Single	Remove	7.57 (1.65)
			Control	8.17 (1.24)
		Dual	Remove	7.60 (1.66)
			Control	8.16 (1.34)
2	None		Highlight	8.25 (1.70)
			Control	7.89 (2.15)
	High salience	Single	Highlight	8.36 (1.57)
			Control	7.95 (2.02)
		Dual	Highlight	7.49 (1.54)
			Control	7.27 (1.92)
	Low salience	Single	Highlight	8.62 (1.75)
			Control	8.07 (2.17)
		Dual	Highlight	7.70 (2.00)
			Control	8.26 (2.76)
3	None		Replace	8.38 (2.21)
			Control	8.46 (1.69)
	High salience	Single	Replace	7.94 (2.17)
			Control	8.38 (1.76)
		Dual	Replace	7.44 (2.14)
			Control	7.86 (1.70)
	Low salience	Single	Replace	8.32 (2.16)
			Control	8.54 (1.68)
		Dual	Replace	7.80 (2.03)
			Control	7.48 (2.89)

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