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“Satisfaction” in search: Individuals’ own search expectations predict their errors in multiple-target search

Cary Stothart[1] • James R. Brockmole[2]

Abstract

When people search for multiple targets in a display, finding one target hinders their ability to find additional targets. These errors were originally proposed to stem from a “satisfaction” with finding a first target that leads people to prematurely stop searching. However, empirical evidence for this premise has been elusive, prompting consideration of other theories. We returned to the satisfaction proposal and assessed whether people generate expectations regarding the likelihood of multiple targets that lead to search biases that, in turn, predict the rates at which additional targets are missed. Participants searched for one or two targets among distractors. To measure accuracy, most trials allowed search to progress to completion. The remaining trials terminated when participants had found their first target. In these cases, participants guessed whether an additional (unfound) target was present. The time needed to find a first target was inversely related to the searchers’ expectations that a second target would be present. These expectations underestimated objective reality, and the strength of an individual’s one-target bias was directly related to his or her likelihood of missing subsequent targets. Thus, people’s expectations—based on their own behavior—likely impacted search performance, providing a novel mechanistic explanation for the previously posited “satisfaction-of-search” errors.

Keywords Visual search · Satisfaction of search · Subsequent search misses · Expectations

Visual search is an activity that can be found almost anywhere. Examples range from someone searching for her car keys at home to security agents searching for explosives at an airport. Success finding a search target can vary as a function of environmental factors such as the target’s prevalence (e.g., Wolfe et al., 2007), value (e.g., Anderson, Laurent, & Yantis, 2011), and visual distinctiveness (e.g., Duncan & Humphreys, 1989), as well as due to individual factors such as concurrent mental workload (e.g., Recarte & Nunes, 2003), expertise (Biggs & Mitroff, 2015), personality (e.g., Biggs, Clark, & Mitroff, 2017), and affect (e.g., Öhman, Flykt, & Esteves, 2001). But not all searches involve only a single target. Perhaps counterintuitively, when multiple targets are in a display, people are more likely to miss a particular target if they have already found another one in the same search. These errors were first examined in the context of radiology, in which one X-ray might reveal multiple abnormalities and the costs of missing targets are high. The first hypothesis proffered to account for these errors suggested that they occur because searchers become “satisfied” after finding a first target, prompting them to discontinue their effort at finding other targets in a display (Smith, 1967; Tuddenham, 1962).

Although the term *satisfaction of search* would be used to refer to these errors for nearly 50 years, lab-based experimental work aimed at determining the circumstances under which they are most likely to occur, as well as the ways in which they could be reduced, has generally failed to support the satisfaction hypothesis (see Berbaum, 2012, for a review). A stream of articles, for example, demonstrated that although radiologists are more likely to miss a particular abnormality following detection of another abnormality, they search radiographs containing single and multiple abnormalities for similar amounts of time (e.g., Berbaum et al., 1991), and misses are rarely due to a failure to fully scan the image (e.g., Berbaum et al., 1998; Samuel, Kundel, Nodine, & Toto, 1995; but see Franken et al., 1994). Instead, follow-up attempts to account for the cause(s) of satisfaction-of-search errors in both radiology and other contexts have brought two broad explanations

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to light. First, the identified search targets might lead observers to adopt particular *perceptual sets* that bias them toward the processing of other perceptually similar items. Thus, in cases in which a fracture is found first, a dissimilar abnormality such as a tumor could become more difficult to identify (Berbaum et al., 1991; Fleck, Samei, & Mitroff, 2010). Second, searching for multiple targets can lead to *resource depletion*. At the group level, this work has implicated diminished attentional control (Adamo, Cain, & Mitroff, 2013, 2017, 2018) and memory resources (Cain & Mitroff, 2013; Stothart, Clement, & Brockmole, 2017) that accompany the need to process and remember multiple targets and, at the level of individual differences, variations in the ability to modulate attention to stimuli and vigilantly attend to ongoing tasks (Adamo et al., 2017).

The focus on the perceptual-set and resource-depletion accounts has had the positive impact of bringing several new mechanistic explanations for multiple-target search errors to light (see Cain, Adamo, & Mitroff, 2013, for a full taxonomy of these errors). Indeed, because of the multiple mechanisms involved, less theory-laden terminology has recently emerged for these search errors within the psychological literature, where they are now more commonly referred to as *subsequent search misses* (SSMs; Adamo et al., 2013). A question remains, however, concerning whether the shift in focus away from "satisfaction" has overlooked explanatory mechanisms related to observer search strategies akin to those originally proposed for SSMs. Using an individual-differences approach, our goal in this article was to explore the possibility that, despite the identified role of perceptual sets and depleted resources in SSM errors, observers' strategies and predictions also bias them to terminate their searches too soon and, if so, to identify a particular mechanism by which observers might come to be "satisfied" with their search.

Recently, Adamo et al. (2018) provided the first empirical evidence for a satisfaction account of SSMs. In their study, participants searched for one or more target letters among a set of distractor items. Their key finding was that the time spent searching for a second target after locating a first target was negatively correlated with SSMs: Participants who searched longer were simply less likely to miss second targets. In an effort to begin decoding the reasons for the variation observed in search times, the authors further showed that posttarget search times were positively correlated with conscientiousness (as measured by the NEO-FFI personality test; Costa & McCrae, 1992). This suggests that conscientious people are more likely to search longer and more effectively for multiple targets (i.e., they are less satisfied with their task performance after finding a first target) and, as a result, are less prone to SSMs.

The link that Adamo et al. (2018) established between search times, personality traits, and SSMs has reopened discussion of these errors in terms of the satisfaction-of-search hypothesis, and, more importantly, has highlighted a need to further explore the mechanistic causes of these errors. In an effort to identify additional mechanisms by which observers might come to be prematurely "satisfied" with their searches, our goal in this article was to explore the possibility that, aside from their own personality characteristics, individual observers' strategies and predictions also bias them to terminate their searches too soon.

Our focus was on the expectations that searchers have for the likelihood that multiple targets are present in a display. In both single- and multiple-target search, the across-trial rates at which targets appear influence search success: More misses occur when targets are rare, and more false alarms when targets are common (e.g., Fleck & Mitroff, 2007; Wolfe et al., 2007). Similarly, observers search for longer periods of time when targets are more likely (Cain, Vul, Clark, & Mitroff, 2012). Our interest is not, however, in across-trial expectations based on encountered target frequencies *in the environment*, but in within-trial search expectations derived from *observers' own behavior*. We hypothesized that the more time it takes a searcher to find the first target, the less likely it is that the searcher will believe subsequent targets are present. This premise is based on the assumption that the more targets there are in a search, the less time one should need to first find one. If searchers use this assumption to guide their expectations for subsequent targets, the likelihood of SSM errors would be determined by the extent to which their expected probabilities of subsequent targets match the actual probabilities. That is, a searcher who tends to underestimate the probability of subsequent targets would be more likely to end searches earlier than they should be ended, thus giving the searcher less time to find subsequent targets, and in turn making an SSM error more likely. Thus, we assessed (1) whether the time it takes searchers to find a first target in a search is related to their expectations regarding the likelihood that subsequent targets are present, and (2) whether these expectations are in turn related to SSM errors. If so, we may conclude that SSM errors are associated, at least in part, with a "satisfaction" that a second target is absent and that additional searching would probably be fruitless.

Method

Participants

Ninety-six University of Notre Dame undergraduates (56 females, 40 males) participated for course credit. The sample size was primarily determined by a commitment to test as many participants as possible prior to the lab moving to a new building and refreshing all testing equipment. That said, a power analysis[1] indicates that such a sample achieves 80% power for effect sizes as small as .085.

Materials, design, and procedure

Participants completed a visual search task in which they searched for perfect Ts (targets) hidden among imperfect Ts (distractors) presented within in a 20.5 × 15.5 cm bounding box; they were asked to click on any targets found (see Fig. 1). Participants were seated comfortably in front of the display, and their viewing distance was not constrained. Each trial consisted of 20 objects (1 × 1 cm) randomly positioned in the display (their edges had to be at least 0.5 cm apart). Either one or two targets were present. Experiment-level expectations regarding second-target prevalence were established by (accurately) informing participants at the beginning of the experiment that 50% of the trials would involve one target, and 50% would involve two targets.

Two trial types were randomly intermixed. One third of trials were *probe trials*. These trials terminated immediately after participants' first response to a target (i.e., participants were not given the opportunity to search for/identify a second target, even if one was present). Participants were then asked to (a) guess whether there was a second target in the trial and (b) report whether they had actually seen a second target (half of the probe trials included two targets). The first question allowed us to measure participants' within-trial expectations regarding the probability that a second target would be present, as a function of the time it took them to find their first target (cf. Peltier & Becker, 2017, who had used similar search interruption and guessing methods to assess participant expectations regarding the likelihood that a single target was present in a low-prevalence search task). The second question enabled us to exclude trials on which participants had actually seen two targets before clicking on their first one. The questions were asked on separate screens, and the responses were collected via button presses. The remaining two thirds of trials were *no-probe trials*. These trials were used to measure each participant's susceptibility to SSMs. Participants were given up to 15 s to find and click on the search target(s). These trials then ended when participants indicated that they had completed their search, by clicking a "Done" button located below the search display. Regardless of the trial type, as participants completed the search task, the clicked objects were not highlighted or marked in any way. Additionally, on all trials, if no responses had been registered after 15 s of elapsed search time, the trial self-terminated and participants were shown a message that encouraged them to search faster on future trials (in the case of probe trials, no postsearch questions were asked). Participants completed ten no-probe practice trials before completing 252 experimental trials.

Results

Target set size expectations

Prior to the analysis, we removed probe trials in which participants failed to click a target (2.6%) and trials on which participants reported they had seen a second target in the display (20%). For these analyses, we defined a response variable that we refer to as *second-target presence* (0 for *no second target present*, 1 for *second target present*). Our first predictor variable was second target presence type (actual presence or guessed presence): *Actual presence* refers to whether or not a second target was indeed in the display, and *guessed presence* refers to whether or not the participant predicted a second target was present. Our second predictor variable was first-target search time (the elapsed time from the onset of the trial to the participant's first click on a target).

We first considered whether the amount of time participants took to find their first target predicted actual second-target presence. To do this, we regressed second-target presence on first-target search time when the second-target presence type was selected for "actual presence," using a mixed-effects logistic regression with a random intercept for participant ID. As is shown in Fig. 2 (upper curves), the overall probability of a second target actually being in a search display decreased with the amount of time participants took to find their first target, $b = 0.77$ [95% CI: 0.83–0.70], $z = 23.79$, $p < .001$. Thus, first-target search time indeed predicted actual second-target presence.

We next determined whether first-target search time also predicted participants' expectations regarding the likely presence of a second target, by conducting the same mixed-effects logistic regression as above, but when the second-target presence type was "guessed presence." The outcome of this analysis paralleled the previous outcome: The longer participants took to find their first target, the less likely they were to predict that a second target was in the display, $b = 2.09$ [95% CI: 1.95–2.33], $z = 29.30$, $p < .001$ (Fig. 2, lower curves). However, participants' predictions did not mirror reality—their expectations for second targets declined more quickly over time than they should have. That is, participants were biased to expect one target. To characterize this expectancy bias, we regressed second-target presence on second-target presence type (actual vs. guessed), first-target search time, and the interaction between second-target presence type and first-target search time using a mixed-effects logistic regression with participant ID and trial ID as random intercepts. We found that, overall, the longer participants took to find their

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[1] Many of our statistical tests used mixed-effects logistic regression analyses that pose inherent challenges to a priori power analysis. We therefore based this power analysis on the linear regression methods used in this report.

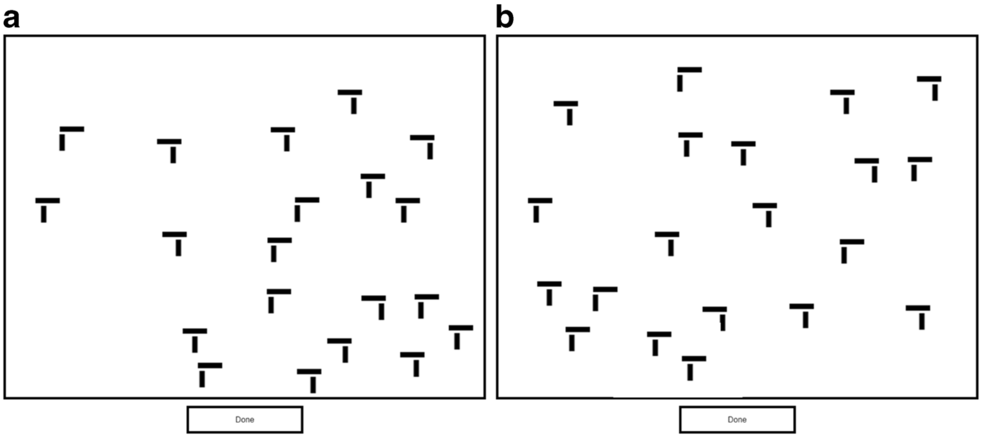

Fig. 1 (A) A one-target trial from the visual search task. (B) A two-target trial. The targets were perfect Ts, and the distractors were misaligned Ts. Participants clicked on targets as they found them, and clicked "Done" when they thought all targets had been found

first target, the larger their expectancy bias was for one target, $b = 1.12$ [95% CI: 0.99–1.25], $z = 16.50$, $p < .001$.

Subsequent search misses

Participants tended to have an expectancy bias for one target, but did this bias impact the rates at which participants made SSM errors? To answer this question, we first calculated an overall expectancy bias score and SSM rate for each participant (see Fleck et al., 2010). We calculated the expectancy bias scores using the filtered probe trials from the previous analysis, by taking the overall expected probability for one target and subtracting the overall actual probability for one target. To calculate the SSM rates, we first restricted the dataset to nonprobe trials on which participants (1) pressed the "Done" button to end the trial (2.2% excluded) and (2) made no false-positive errors, by clicking on either a

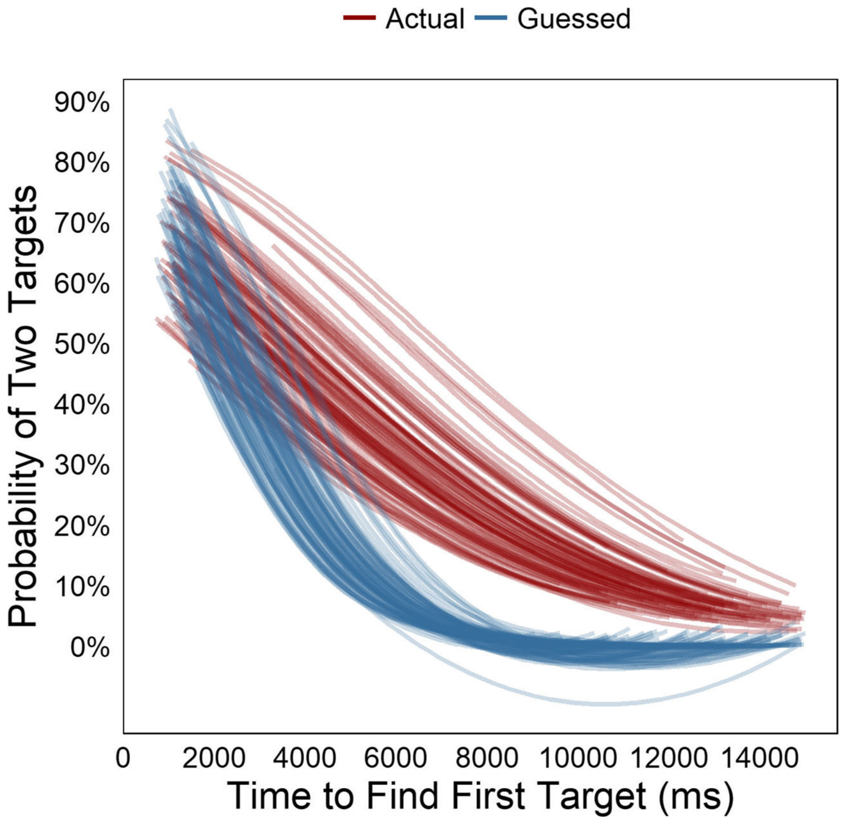

Fig. 2 Probability of participants guessing the presence of two targets, along with the actual probability of two targets being in the display, as a function of time to find the first target. Each line represents the model fit for one participant

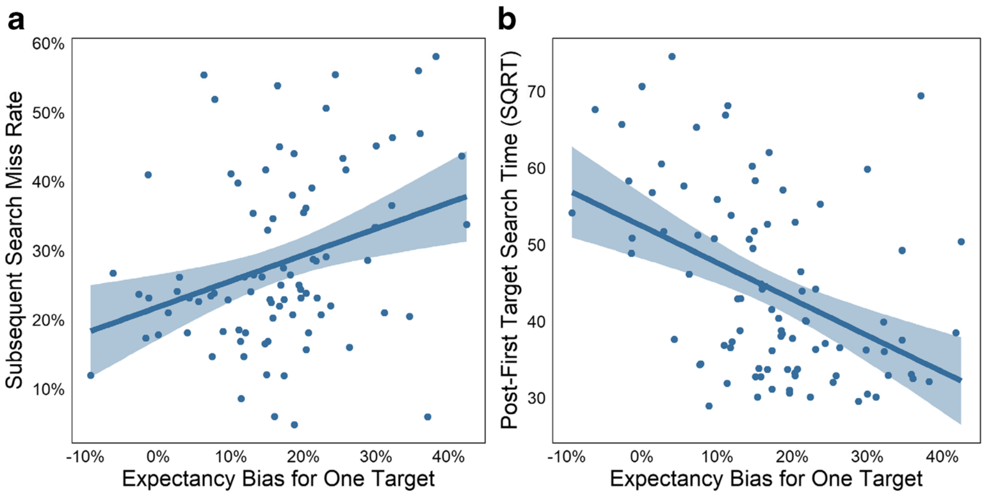

Fig. 3 (A) Subsequent search misses by expectancy bias for one target. (B) Post-first-target search times by expectancy bias for one target. Shaded areas represent 95% confidence bands

distractor or a previously identified target (2.8% excluded). We then calculated two probabilities for each participant. First, we calculated the participant's probability of finding a target after having found another target, by dividing the number of two-target trials on which the participant found both targets by the number of two-target trials on which the participant found at least one target. Second, we calculated the participant's probability of finding a target after having found no other targets by dividing the number of one-target trials on which the participant found the target by the total number of one-target trials.[2] We then calculated an SSM rate for each participant by subtracting the participant's probability of finding a target after having found another target from his or her probability of finding a target after having found no other targets. We then regressed the SSM rates on the expectancy bias scores. This analysis revealed that participants' expectancy biases for one target can be used to predict their likelihood of committing SSM errors (Fig. 3A), $b = 0.38$ [95% CI: 0.14–0.61], $t(86) = 3.17$, $p = .002$.

What is the mechanism for this relationship? We hypothesized that participants with larger expectancy biases would terminate their search earlier than those with lower expectancy biases, thus giving themselves less time to find subsequent targets. Indeed, this hypothesis is in line with previous research that had found a negative relationship between post-first-target search times (i.e., the elapsed time between the identification of a first target and the participants' termination of search prior to the detection of a second target) and SSM error rates (Adamo et al., 2018). We focused on nonprobe trials on which participants pressed the "Done" button to end the trial (2.2% excluded), found only one target (37% excluded), and made no false alarms by clicking on a distractor or reclicking on an already-identified target (2.8% excluded). We then regressed the square root of participants' median post-first-target search times on their expectancy bias scores while also controlling for the median time it took participants to find their first target on nonprobe trials on which the participants found at least one target (participants who took longer to find their first target likely ended their searches earlier, as they had less time to find subsequent targets).[3] Participants with larger expectancy biases indeed terminated the search earlier than those with lower expectancy biases (Fig. 3B), $b = 44.67$ [95% CI: 25.58–63.76], $t(87) = 4.65$, $p < .001$.

Both expectancy bias and post-first-target search times were related to SSMs. So a final question to ask was whether one's expectancy bias for one target explained variance in SSM error rates above and beyond his or her post-first-target search times. To answer this, we used a model comparison approach in which we hierarchically calculated two regression models. The first model regressed the SSM error rates on the post-first-target search times ($R^2 = .09$), and the second model regressed the SSM error rates on both the post-first-target search times and the expectancy bias scores ($R^2 = .13$). The comparison revealed that a searcher's expectancy bias for one target can predict SSM errors even after accounting for post-first-target search times, $F(1, 85) = 4.76$, $p = .032$. Thus, although expectancy bias for one target and post-first-target search times were related, they were not redundant. Expectancy independently predicted SSM error rates.

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[2] The difference between the mean probability of finding a target after having found another target (69.13%, $SD = 14.79\%$) and the mean probability of finding a target after having found no other targets (98.46%, $SD = 3.74\%$) was significant, 29.33% [95% CI: 26.45%–32.20%], $t(95) = 20.22$, $p < .001$. Thus, an overall SSM effect was present.

[3] We used square roots to normalize the distribution of the post-first-target search times because the raw distribution was positively skewed and resulted in a positive regression residual distribution.

Discussion

Our study is among the first to provide a mechanistic account of the long-ago-proposed satisfaction-of-search account of SSM errors (Smith, 1967; Tuddenham, 1962). This account supposes that SSM errors result because searchers prematurely terminate their searches after becoming "satisfied" with the search after finding a target. In our study, the time a person needed to find a first target was inversely related to his or her expectations that a second target would be present. These resulting second-target expectations underestimated objective reality, especially late in search, and greater underestimation was correlated with shorter searches and more SSM errors. That is, when participants believed the likelihood of a second target was low, they afforded themselves less time to find subsequent targets. They, in short, became "satisfied" with their efforts and, as a result, abandoned their task too soon.

In addition to providing novel mechanistic support for the satisfaction-of-search account of SSM errors, our findings open new avenues for future research. In the context of multiple-target search, consideration of the potential intersection of search expectations and cognitive resources may be particularly fruitful. For example, the availability of attentional resources modulates the effects of expected target frequency on search efficiency (e.g., Hon & Tan, 2013). It is possible that cognitive resources may similarly influence expectations regarding target presence. Indeed, evaluating this possibility may be a way to evaluate the degree to which the satisfaction-of-search and resource-depletion hypotheses of SSM errors (Cain & Mitroff, 2013) may be placed within a common theoretical account. Our understanding of the role that cognitive resources play in SSM errors might also be broadened by considering contexts in which multiple different targets are possible. In low-prevalence search contexts, for example, the need to search for multiple types of targets often leads to more missed targets than in situations in which a single target type is known in advance, because multiple target representations demand more visual working memory resources (e.g., Mestry, Menneer, Cave, Godwin, & Donnelly, 2016). As memory resources are consumed, individual representations are weakened (e.g., Schneegans & Bays, 2016), and this weakening can lead searchers to over-rely (incorrectly at times) on external search aids such as computer-aided detection (e.g., Kunar, Watson, Taylor-Phillips, & Wolska, 2017). It is possible that greater cognitive demands could also prompt searchers to over-rely (again sometimes incorrectly) on internally generated heuristics such as their own beliefs and expectations. If true, higher cognitive demands might exacerbate SSMs via the satisfaction mechanisms identified in our study. Hence, future research should consider the generalizability of the satisfaction mechanism identified here to circumstances in which second-target prevalence is unknown and/or rare. Not only will doing so clarify the theoretical issues identified above, it could also elucidate the degree to which satisfaction explanations of SSMs apply to real-world settings in which these aspects of search vary.

More generally, our results also extend prior work linking search success and experiment-level expectations regarding target frequency, by showing that observers construct within-search expectations regarding target presence. Hence, both the object properties of the environment and the subjective experiences of the observer play important roles in visual search. This leads to a potential application of our findings. Although environmental constraints are generally fixed, personal expectations are likely more modifiable through training. In fact, the search biases we observed in our study are likely more modifiable than other individual difference factors that impact SSM (modulation of attention, vigilance, and conscientiousness). Whether it is possible for professional searchers to be trained to reduce their expectancy biases, and thereby reduce the likelihood of SSM errors, in real-world contexts is an interesting avenue for future research.

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