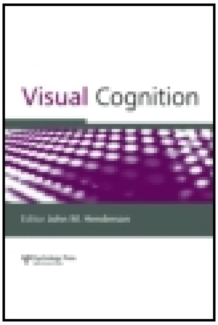

Visual Cognition
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pvis20

A taxonomy of errors in multiple-target visual search

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Published online: 09 Oct 2013.

Visual Cognition, 2013
http://dx.doi.org/10.1080/13506285.2013.843627

A taxonomy of errors in multiple-target visual search

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(*Received 1 March 2013; accepted 5 September 2013*)

Multiple-target visual searches are especially error prone; once one target is found, additional targets are likely to be missed. This phenomenon, often called *satisfaction of search* (which we refer to here as *subsequent search misses*; SSMs), is well known in radiology, despite no existing consensus about the underlying cause(s). Taking a cognitive laboratory approach, we propose that there are multiple causes of SSMs and present a taxonomy of SSMs based on searchers' eye movements during a multiple-target search task, including both previously identified and novel sources of SSMs. The types and distributions of SSMs revealed effects of working memory load, search strategy, and additional causal factors, suggesting that there is no single cause of SSMs. A multifaceted approach is likely needed to understand the psychological causes of SSMs and then to mitigate them in applied settings such as radiology and baggage screening.

Keywords: Visual search; Satisfaction of search; Eye tracking.

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We thank Elise Darling for assistance with conducting the experiment and the Duke Visual Cognition Lab for helpful feedback. This work was partially supported by the Army Research Office [grant number 54528LS] and partially through a subcontract with the Institute for Homeland Security Solutions, a research consortium sponsored by the Resilient Systems Division in the Department of Homeland Security (DHS). This material is based upon work supported by the DHS under Contract No. HSHQDC-08-C-00100. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the official policy or position of DHS or of the US Government. The study is approved for public release. SHA was supported by a National Science Foundation predoctoral fellowship and a Ford Foundation predoctoral fellowship.

Visual search, the act of looking for target objects among distractors, is an important task in daily life, but unfortunately can be quite error prone. Errors are especially common in multiple-target visual searches—searches where more than one target can be present in a given display. Multiple-target searches are common in professional contexts, such as radiology, baggage screening, and military searches, so it is vital to understand how errors arise and how they can be overcome. In particular, it has been well established that once one target is found in a display, additional targets are more likely to be missed, a phenomenon known as *satisfaction of search* (Smith, 1967; Tuddenham, 1962). The satisfaction of search effect has been demonstrated in both radiology (see, for recent reviews, Berbaum, Franklin, Caldwell, & Schartz, 2010; Berbaum, 2012) and cognitive psychology (Fleck, Samei, & Mitroff, 2010) and is particularly sensitive to outside influences, such as searcher anxiety (Cain, Dunsmoor, LaBar, & Mitroff, 2011), visual clutter (Adamo, Cain, & Mitroff, 2012), and even the framing of task instructions (Clark, Cain, Adcock, & Mitroff, in press).

Satisfaction of search has been known to be responsible for missed abnormalities in radiology for over 50 years, but, despite the existence of a number of influential theories, there is no consensus on its root cause. Here we argue that there is no single root cause, and, as such, we also suggest that the term "satisfaction of search" is problematic as it presupposes a specific mechanism. Namely, "satisfaction of search" suggests that searchers become "satisfied" after having found a first target in a display and do not complete an exhaustive search for other potential targets (Smith, 1967; Tuddenham, 1962). Given that previous research has found evidence inconsistent with a satisfaction explanation (e.g., Berbaum, 2012; Berbaum et al., 1990, 1991; Samuel, Kundel, Nodine, & Toto, 1995), and that we demonstrate several simultaneous causes here, we prefer to use a more neutral label. As such, we will use the term "subsequent search misses" (SSMs) to describe miss errors that occur in multiple target trials when at least one target has been successfully found, but without suggesting any particular cause for these errors (Adamo, Cain, & Mitroff, in press).

In the present study, we used eye tracking in a laboratory-based abstract multiple-target visual search to present a taxonomy of SSM errors. Most previous studies have looked at measures such as accuracy and response time to detect SSMs (e.g., Berbaum et al., 1990; Fleck et al., 2010). However, with these measures it is difficult to differentiate between various possible causes of SSMs: One can readily determine that an error has been made, but not *why* a given target was missed. Eye tracking allows for the measurement of more variables than just accuracy and response time, and thus can give a more nuanced understanding of multiple-target search errors. This application of eye tracking has proven useful, for example, in examining the causes of errors in rare-target visual search (Rich et al., 2008) and in demonstrating that items in visual working memory interfere with search (Solman, Cheyne, & Smilek, 2011) where response time data had not been able to detect interference (Woodman, Vogel, & Luck, 2001).

A primary goal of the current study is to take a cognitive psychology approach to a problem predominantly studied in the field of radiology to provide a descriptive taxonomy of SSM errors. In particular, we build upon previous radiological eye tracking studies of SSMs (e.g., Berbaum et al., 1996; Samuel et al., 1995) by using displays with highly controlled stimuli to investigate a broader range of error types than is possible with typical medical images. This is an important step in the study of multiple-target visual search errors, given that establishing the distribution of different types of errors can directly inform theories about the underlying mechanisms of SSMs. As discussed later, a variety of theories have been proposed (e.g., Berbaum et al., 1991; Smith, 1967), and more are arising (e.g., Cain & Mitroff, 2012), but there is no clear consensus. The current data can help to determine what support there is for and against each of the existing theories.

Existing theories of subsequent search misses

Satisfaction. The original theory from radiology (that gave the satisfaction of search phenomenon its name) proposed that searchers, upon having found a first target, become "satisfied" with the "meaning" of the display (i.e., what diagnosis can be made) and terminate their search too early (Smith, 1967; Tuddenham, 1962). However, numerous studies have failed to support this theory, suggesting that premature termination of search is not the primary cause of SSMs in radiology (Berbaum et al., 1990) or in more abstract search tasks (Fleck et al., 2010). However, under the right circumstances, searchers may strategically terminate search early when they believe the likelihood of finding a target is not high enough to justify additional time to search (Cain, Vul, Clark, & Mitroff, 2012).

Perceptual set. According to the perceptual set hypothesis, when one target is found (e.g., a broken bone), searchers are more likely to recognize additional targets that are perceptually similar to the found target (e.g., another broken bone) and are less likely to recognize additional, perceptually dissimilar targets (e.g., a tumor; Berbaum et al., 1990, 1991). In an abstract search task with parameters similar to those employed in the current experiment, Fleck et al. (2010) found evidence consistent with the perceptual set hypothesis: Finding a dark-coloured target reduced searchers' chances of finding an additional, light-coloured target. However, the same study also found SSMs when all targets were similar colours, demonstrating that perceptual set cannot be the sole explanation of SSMs.

Resource depletion. Another cause of SSM errors may be the targets themselves; a target that has already been found could interfere with subsequent performance by depleting cognitive resources, thereby creating more second target search errors (Adamo et al., in press; Berbaum et al., 1991; Cain & Mitroff, 2012). In particular, remembering the identity (Solman et al., 2011) or location (Oh & Kim, 2004; Woodman & Luck, 2004) of a found target may consume working memory resources that would otherwise be used for further search. Recent evidence suggests that searchers may automatically encode this information—even when found targets are clearly marked—leading to decreased second-target accuracy. However, performance can be improved by removing the found target from the display or making it perceptually separable from the other items in the display (Cain & Mitroff, 2012). Importantly, these manipulations do not completely erase SSMs, suggesting that resource depletion is also not the sole cause of these errors. Interestingly, the mere knowledge that two targets might need to be found (as compared with one) constrains available memory resources, even before the first target is found, as if searchers are "preallocating" memory for the location of the first target (Körner & Gilchrist, 2008), implying that dual-target searches may always be at a disadvantage compared to single-target searchers.

Thus far, no one theory of SSMs has been able to explain all the available data, suggesting that there may be multiple causes of SSM errors. In the present study, we will address this possibility by examining and categorizing the causes of individual SSM errors.

Taxonomies of visual search errors

Previous work from radiology has broadly categorized visual search misses (both single-target misses and SSM errors) into scanning errors, recognition errors, and decision-making errors (Berbaum et al., 1996; Kundel, Nodine, & Carmody, 1978; Nodine & Kundel, 1987; Samuel et al., 1995). Each error type is thought to occur at a different stage of search, and support has been found for the contribution of each type to search failures.

Scanning errors. Scanning errors are those in which the target was never fixated. That is, a scanning error represents a situation where the target was never in the search scan path. In radiology, scanning errors are not generally thought to be responsible for many misses, but can present a larger problem when search aids like contrast agents (i.e., injected or ingested dyes that have known X-ray or magnetic resonance properties) are used (Berbaum et al., 1996), perhaps by biasing search away from noncontrast areas (cf. Drew, Cunningham, & Wolfe, 2012). However, in a recent single-target search study in cognitive psychology using abstract displays ("T"-shaped targets among pseudo-"L"-shaped distractors) in which targets were rarely present (i.e., low-prevalence search) up to two-thirds of misses were due to searchers not fixating the target (Rich et al., 2008). Relatedly, in multiple-category search (e.g., a simulated baggage screening task in which at most one target could be present but could either be a gun *or* a bomb), keeping two categories in mind leads to an increase in fixations on distractors that do not contain task-relevant features (Stroud, Menneer, Cave, Donnelly, & Rayner, 2011), suggesting that scanning efficacy is reduced.

Recognition errors. Unlike scanning errors, the missed target is briefly fixated during a recognition error, but not fixated sufficiently long to be recognized or properly evaluated. In one relevant study (Samuel et al., 1995), pulmonary nodules in chest radiographs were missed more often in the presence of another abnormality than when no additional abnormality was present (i.e., SSMs). These missed nodules were usually fixated (90% of the time), but not for as long as would be necessary to make a correct detection (i.e., for less time than correctly identified nodules were fixated).

Decision errors. Decision errors are those where the target was fixated, and fixated for an appropriate interval (i.e., the item was at least considered as a potential target), but was still not reported. It has been argued that decision errors are the most prevalent type of miss errors in radiological search, as early eyetracking studies found 45–60% of misses were decision errors (Kundel et al., 1978; Nodine & Kundel, 1987). In particular, they may be an important cause of SSM errors in radiological search, being more prevalent than scanning errors (Berbaum et al., 2001; Manning, Ethell, & Donovan, 2004) and recognition errors (Berbaum et al., 1998). In contrast to scanning errors, decision errors in abstract searches do not appear to be affected by target prevalence (Rich et al., 2008).

The present study

We sought to update and expand the existing taxonomy of multiple-target search errors using eye-tracking methods and abstract, well-controlled displays. We also identified a number of possible sources of error that cut across multiple categories. Novice observers freely searched for T-shaped targets among pseudo-L-shaped distractors in displays with either one or two targets present. To somewhat constrain search strategies, half the targets had a higher-salience contrast with the background, making them more readily detected. The majority of trials contained more than one target, which allowed us to observe a large number of SSM errors in which the high-salience target was identified, but the low-salience target was missed. We examined the gaze fixation patterns of these errors to classify them into functionally distinct categories, with an eye towards classification criteria that will be generalizable and relatively straightforward. Here, we present a detailed taxonomy of multiple-target search errors and discuss its ability to inform both visual search theory and real-word search application.

METHODS

Participants

Thirty-four members of the Duke University community participated for $10 or partial fulfilment of a course requirement. The final sample size was determined by the number of participants who could be tested before the particular eye tracker used in this study was replaced. Data from six participants were eliminated due to poor search performance (three for timing out on >20% of trials, two for missing >15% of high-salience targets, and one for committing false alarms on >20% trials; these three values averaged <5% for included participants). The final sample of 28 participants included 11 males and 17 females and ranged in age from 18 to 25 years (*M* = 19.5 years). A subset of the data from these participants concerning "attentional blink-like" errors has been reported elsewhere (Adamo et al., in press). Research was conducted in accordance with the Declaration of Helsinki.

Apparatus

The stimuli were presented using Matlab with PsychToolbox 3 (Kleiner, Brainard, & Pelli, 2007) on a 17-inch LCD monitor. Eye positions were recorded at 50 Hz using a Tobii 1750 infrared-camera eye tracker (Tobii Technology AB, Danderyd, Sweden). Participants were seated 57 cm away from the screen with their heads supported in a chinrest to keep viewing distance constant.

Stimuli

Stimuli were similar to those used in previous multiple-target search studies (Cain et al., 2011; Fleck et al., 2010; see Figure 1). Each display contained 25 total items on a white background. All items were pairs of perpendicular rectangles, slightly offset from one another. Targets were defined as perfectly aligned "T" shapes while distractors were non-symmetric "pseudo-L" shapes, both subtending approximately 1.3 x 1.3 degrees of visual angle at their widest points. Items were arranged within an invisible 8 × 7 grid (spanning approximately 26.0° x 19.5°), with each item randomly offset up to 5 pixels from perfect grid alignment and in one of four possible rotations. Half of the targets and 5% of the distractors were high salience (dark gray; 57%–65% black) and the remainder of the targets and distractors were low salience (light gray; 22%–45% black). Items randomly varied independently in luminance within their respective luminance range in 0.39% increments (i.e., 1/256 of the total luminance range). This salience manipulation was designed to bias searchers toward finding the high-salience targets before the low-salience

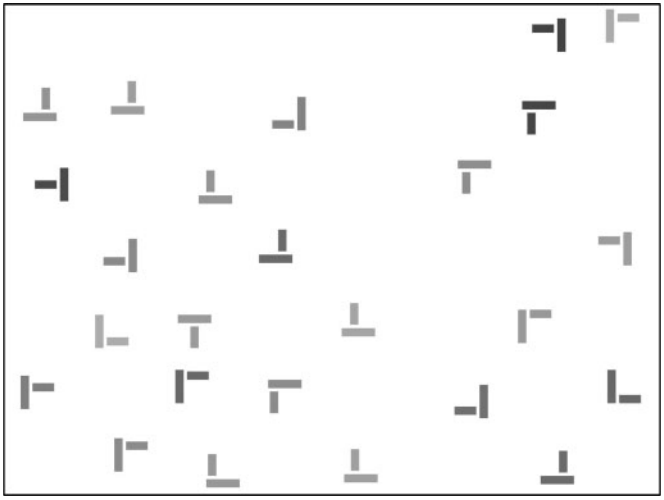

Figure 1. Example stimulus display. Targets were perfect "T" shapes and two are present here (one high salience and one low salience).

targets (Fleck et al., 2010), in order to mimic real-world search scenarios, such as when a medical X-ray image contains a relatively easy-to-spot, benign abnormality and a more subtle, more dangerous abnormality (e.g., Berbaum et al., 2007).

Procedure

Each display contained either one or two targets, with 10% high-salience single-target trials, 10% low-salience single-target trials, and 80% dual-target trials, always with both one high-salience and one low-salience target. Participants were informed that each trial would have either one or two targets, but were not explicitly informed of the ratio.

Participants used a computer mouse to click on each target they found. Each click was denoted by a small (0.3° diameter), unfilled blue ring. The blue ring served as a marker of where a click had been made, and was superimposed on the display such that it could appear on top of an item. Trials lasted 15 s (with no visible indication of time remaining) or until participants pressed the spacebar. Participants were instructed to be as accurate as possible without going over the 15 s time limit. There were 11 blocks of 25 trials each. The first block served as practice and included feedback after each trial that contained an error; practice performance was not analysed. No feedback was given on the remaining 250 experimental trials.

RESULTS

Data processing

Mouse clicks that fell within a circle with a 40-pixel (approximately 1.3°) radius centred on a target were considered correct clicks. All clicks that fell outside these areas were considered false alarms, and trials with false alarms were excluded from further analysis (2.33% of all trials). Individual gaze timepoints were excluded from analysis if one or both eyes were looking off the screen or were unable to be tracked (e.g., during eye blinks).

An object was considered fixated when the mean of the left and right eye gaze positions was within the same 40-pixel radius circle used for clicks. Fixations were defined to occur at time points with instantaneous gaze velocities below 15°/s. Sequential fixations on the same object within 100 ms with no intervening other objects fixated were considered to be the same fixation (e.g., the two time periods before and after a blink while fixating an object were counted as a single fixation).

Data presented in the Basic Results section represent averages for each participant and these values were then used for statistical analyses. Data presented in the Taxonomy of Subsequent Search Misses section represent pooled values across all participants, and the data presented are with respect to this entire population of SSM errors. Although variable, the pattern of error types was largely similar across participants, except for certain strategic errors, noted later.

Basic results

Accuracy. Accuracy for high-salience targets on single-target trials was near ceiling (M = 98.2% correct, SD = 2.8%), but was significantly reduced on dual-target trials (M = 95.3%, SD = 3.8%), $t(27) = 6.76$, $p < .001$, Cohen's $d = 1.28$ (all statistical tests for proportions were performed on arcsine-square-root-transformed data). Average accuracy for low-salience targets on single-target trials was 85.1% (SD = 12.0%). SSMs are detected by taking the difference in accuracy between single-target and dual-target trials, and here we focus specifically on performance for the low-salience targets. To provide a conservative measure of SSMs, we calculated dual-target accuracy using only those trials in which the high-salience target was correctly detected first (M = 69.5%, SD = 16.4%), and then compared this performance to accuracy on the low-salience single-target trials (85.1%). This measure of low-salience dual-target accuracy was significantly worse than low-salience single-target performance (15.6% SSMs), $t(27) = 8.21$, $p < .001$, $d = 1.10$. This quantity of SSMs is consistent with previous findings (e.g., Cain & Mitroff, 2012, control conditions;

Fleck et al., 2010, Exp. 3), suggesting that the specific target distribution employed here is sufficiently generalizable for obtaining SSMs.

On 18.3% of dual-target trials, the low-salience target was the first target to be found, with the high-salience target subsequently found on 77.3% of those trials. This suggests that the accuracy cost for high-salience targets on dual-target target trials may be also be due to SSMs. We did not scrutinize these miss errors further, as interpretability is limited since most participants committed fewer than seven such errors (representing only 4.2% of the entire dual-target trial data set). The major focus on the current study is on the 30.5% of the dual-target trials in which the high-salience target was detected but the low-salience target was missed (see Figure 3 and Table 1 for a breakdown of these misses).

Response time. On single-target trials, high-salience targets were found, on average, after 3.39 s of searching (SD = 1.21 s) and low-salience targets were found after an average of 6.34 s (SD = 0.66 s). On dual-target trials, high-salience targets were found, on average, after 3.22 s of searching (SD = 0.98), not significantly different than in single-target trials, $t(27) = 0.77$, $p = .466$, $d = .057$. Low-salience targets were found after 5.70 s (SD = 0.52, M = 6.33 s for low-salience targets found after high-salience targets), which was significantly faster than in single-target trials, $t(27) = 3.77$, $p < .001$, $d = 0.38$. One possible explanation for this difference is that those targets which would have been found relatively later in single target search are more prone to be missed in the presence of an additional target (and thus, do not contribute to the average detection time).

On single-target trials, after finding a high-salience target, searchers continued searching for a (nonexistent) low-salience target for an additional 6.95 s, on average (SD = 2.13 s). On dual-target SSM error trials, searchers quit after an average of 9.40 s (SD = 1.90 s) of total searching. As can be seen in Figure 2, this is after the majority of low-salience targets were found in successful dual-target trials. While these values are not independent (i.e., few targets would be expected to be found after the average search termination time), it suggests that time on task was not the primary cause of SSM errors in this experiment (Berbaum et al., 1991).

Taxonomy of subsequent search misses

Subsequent search misses—operationally defined here as low-salience target misses on dual-target trials on which the high-salience target was found—occurred on nearly a third of dual-target trials. Here, we examine and categorize all such misses. Major categories of SSM errors are broken down in Table 1 and Figure 3.

Low-salience target not fixated. Those trials on which the low-salience target was never fixated have previously been classified as scanning errors or sampling errors (e.g., Nodine & Kundel, 1987). This was the largest single

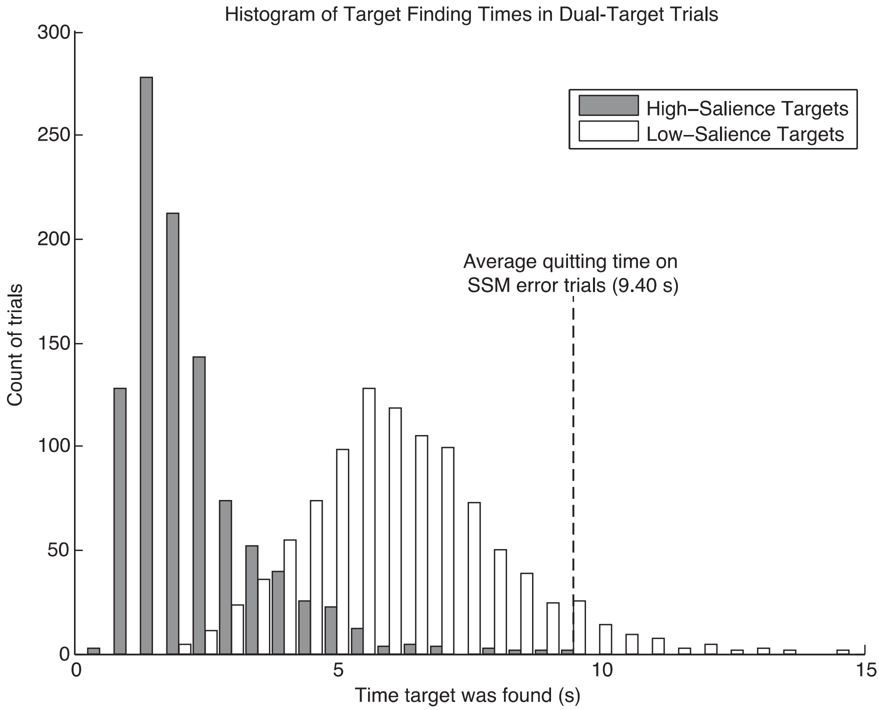

Figure 2. Histogram of target finding times for high-salience (grey bars) and low-salience (white bars) targets on dual-target trials in which both targets were successfully found. The dashed line indicates the average quitting time on subsequent search miss (SSM) trials (dual-target trials in which only the high-salience target was found).

category of error, representing 55.2% of SSMs (797 total trials). Only a very small number of trials (1.5%; 22 trials) were timeouts, suggesting that in nearly all of these cases searchers actively decided that their search was complete.

Search terminated immediately after high-salience target found. A total of 4.1% (59) of search trials were terminated immediately after the high-salience target was found (i.e., no other items were fixated after the fixation in which the target click was made). This type of error is best classified as a strategic error, as searchers stopped scanning without even looking for a second target, despite 80% of trials containing two targets. This may be due to searchers trying to maximize their overall search efficiency (i.e., targets found per second) rather than their overall accuracy (e.g., Cain et al., 2012; Pedersini, Navalpakkam, Van Wert, Horowitz, & Wolfe, 2013; Wolfe, 2013).

High-salience target refixated. On a further 13.3% of trials (192), the high-salience target was refixated after being found. This may have hampered the search because a found target serves as a potent distractor in multiple-target search and refixating it could consume cognitive resources that would otherwise

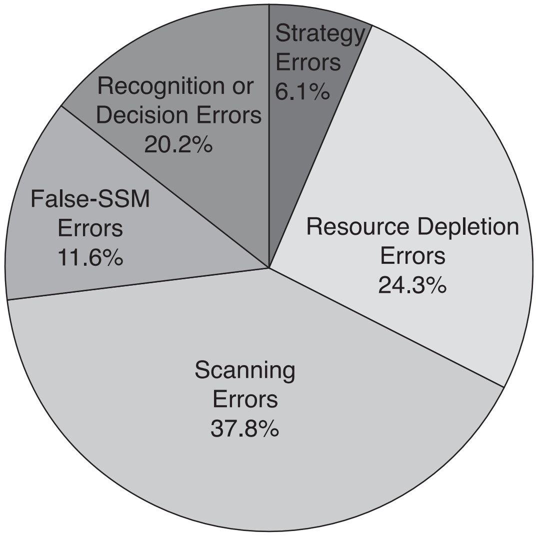

Figure 3. Breakdown of the major cateogries of subsequent search misses, pooled across participants. See Table 1 for a more detailed breakdown. Errors in which participants deliberately terminated their search early were classified as strategy errors. Errors involving refixations of found high-salience targets were classified as resource depletion errors. Errors in which the missed target was never fixated were classified as scanning errors. Errors involving fixation of the missed target were classified as recognition or decision errors. Errors where the missed target was fixated before the found target were classified as false-SSM errors.

be dedicated towards finding the low-salience target (e.g., Cain & Mitroff, 2012). These errors are discussed more fully in the Other Sources of Error section.

Other scanning errors. The remaining 37.8% (546) of error trials on which the low-salience target was never fixated were classified as scanning errors. These errors were not further subcategorized, but were also not homogenous. One source of variation among these trials was the exhaustiveness of the search. On each scanning error trial, an average of 14.4 of the 23 unique distractors were fixated (an average of 19.9 distractor items were fixated with repetitions included). The distribution of the number of unique distractor items fixated (Figure 4B) suggests that many scanning errors might be due to participants terminating their search too early (i.e., better classified as strategy errors), but the distribution is skewed leftwards, compared with that of correct dual-target trials (Figure 4A). Although it is difficult to directly compare these situations (e.g., searchers stopped fixating in correct trials upon finding a second target), this leftwards skew suggests that searchers were diligent overall and fixated a large number of items even though the low-salience target was not among them. Interestingly, the distribution of the number of unique distractor items fixated flattens substantially in the period after the first target is found (Figure 4B), further supporting the idea that a subset of these errors are potentially due to strategic effects.

TABLE 1
Detailed breakdown of all subsequent search miss (SSM) errors, pooled across participants

Fixation category	*Error description*	*Error category*	*Trial count (N = 1445)*	*% of all SSM trials*
Low-salience target not fixated			797	55.2%
	Search terminated immediately after high-salience target found	Strategy error	59	4.1%
	High-salience target refixated	Resource depletion error	192	13.3%
	Other	Scanning error	546	37.8%
Low-salience target fixated			648	44.8%
	Search terminated immediately after high-salience target found	Strategy error	29	2.0%
	High-salience target refixated	Resource depletion error	159	11.0%
	Low-salience target fixated before the high-salience target was found, but not fixated after it was found	False SSM error	168	11.6%
	Low-salience target fixated after the high-salience target was found	Recognition or decision error	292	20.2%

Errors in which participants deliberately terminated their search early were classified as *strategy errors*. Errors involving refixations of found high-salience targets were classified as *resource depletion errors*. Errors in which the missed target was never fixated were classified as *scanning* errors. Errors involving fixation of the missed target were classified as *recognition or decision errors*. Errors where the missed target was fixated before the found target were classified as *false-SSM errors*.

Another potential cause of scanning errors is that searchers may have been relying on their ability to take in information beyond the centre of their fixation. Although this may have been a reasonable strategy for finding the first, high-salience target, the ability to effectively take in peripheral information degrades as memory resources are taken up by found targets (McCarley et al., 2006; cf. Jefferies & Di Lollo, 2009). Moreover, the low-salience targets would be more difficult to detect outside of fixation simply because of their lower contrast against the background. There is some evidence that searchers might have adjusted their fixation strategy over the course of a trial: On trials in which the first target was successfully found, but no additional target was found (a superset of SSM error trials), participants fixated the space between several items (i.e., not fixating any individual item) more often before finding a first target (M = 2.40 fixations, SD = 0.90) than during the same duration of searching after finding a

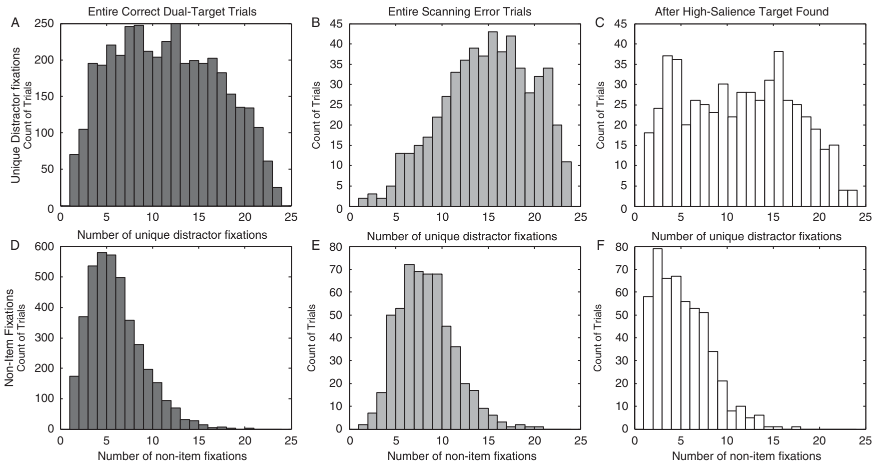

Figure 4. Histograms of correct dual-target trials (A & D) and the 546 scanning error trials in which the low-salience target was never fixated after the high-salience target was found (B, C, E, & F). The top row shows the number of unique distractor items fixated over the course of the entire trial for correct dual-target trials (A) and for scanning error trials (B) and after the high-salience target was found in scanning error trials (C). The bottom row shows the number of nonitem fixations over the course of the entire trial for correct dual-target trials (D) and scanning error trials (E) and after the high-salience target was found in scanning error trials (F). Note the variation in abscissa scaling.

first target (M = 1.72 fixations, SD = 0.49), $t(27) = 5.28$, $p < .001$, $d = 0.94$. Despite this reduction in between-item fixations, searchers may not have fully compensated for their reduced detection capacity. Histograms of nonitem fixations over the course of entire scanning error trials and during the time after the high-salience target was found first are provided in Figures 4E and 4F, respectively.

Low-salience target fixated. The missed low-salience target was fixated at least once during the trial on 44.8% of SSM error trials (648 trials). As with the scanning errors, there were a small number of timeouts (2.4%; 35), including 0.6% (eight) that had a low-salience target fixation in the last second of the trial, so might well have been hits if a response was just barely missed.

Search terminated immediately after high-salience target found. A small number of trials (2.0%; 29) were terminated immediately after finding the high-salience target without any attempt at search for a second target, suggesting a strategic error. However, as discussed later, they also represent a class of false-SSM recognition errors.

High-salience target refixated. The high-salience target was refixated after being found on 11.0% of second-target miss trials (159). These errors are discussed more fully in the Other Sources of Error section.

Low-salience target fixated before high-salience target. On 11.6% of trials (168 trials), the low-salience target was fixated, but was fixated prior to the high-salience target being found. With analyses that only examined accuracy, these misses would be classified as SSM errors. However, it is likely that these errors are unrelated to the presence of the high-salience target and represent non-SSM failures of recognition or decision making (i.e., false-SSM errors). The presence of such errors is unsurprising given that performance on low-salience single-target trials was not at ceiling.

Low-salience target fixated after the high-salience target. On the remaining 20.2% of trials (292), the low-salience target was fixated after the high-salience target was found. In previous classification schemes (e.g., Kundel et al., 1978), these trials have been classified as either recognition errors (i.e., the target was not fixated long enough to be recognized as such) or decision errors (i.e., the target was fixated sufficiently long to be recognized, but an incorrect decision was reached). However, it is difficult to truly untangle these types of errors, as the length of time needed to recognize an item is not well-defined. Previous radiological studies have used the fixation durations on found targets to establish a division between these error types (e.g., Kundel et al., 1978), but this technique is not available in the current study, as searchers had to click on found targets, introducing a systematic confound to the length of correct target inspections. However, unlike in previous radiological studies, target and distractor items in the current experiment were highly similar (see Figure 1), thus, fixation durations on distractor items provide a reasonable basis for separating recognition and decision errors. Across all trials without false alarms (i.e., not only SSM error trials), low-salience distractors were fixated for a median of 199 ms with a 75th percentile value of 260 ms. This 75th percentile value is consistent with the 252 ms/item search slope previously estimated using similar stimuli (Cain et al., 2012, supplementary experiment) and was therefore used as a cutoff between recognition and decision errors. With 179 trials (12.4% of total SSM error trials) having a low-salience target fixation with duration ≥260 ms, we estimate that 10–15% of all SSM errors were decision errors and 30–35% were recognition errors.

Distinguishing between recognition and decision errors makes some intuitive sense, but given that the distributions of fixation durations for both distractors and missed low-salience targets were smooth and unimodal, both here and in is previous investigations (e.g., Samuel et al., 1995), it is unclear whether it is possible to define separate categories of recognition and decision errors in a principled manner solely on the basis of dwell time. Further, it may be more useful to view such errors on a continuum, rather than in discrete categories. Many models of perceptual decision making would generate unimodal dwell time data like that seen here; for example, models like the leaky, competing accumulator model (Usher & McClelland, 2001) and the diffusion decision model (Ratcliff & McKoon, 2007), posit that when an observer fixates an item to make a decision about whether it is a target or not, perceptual evidence is accumulated for the two possible responses. Overall, the longer the item is inspected the more reliable the decision, but this process is noisy. Especially in the current experiment, where there is a strong bias towards deciding an item is not a target, it is likely that errors in which the missed target is fixated for a short time differ from errors in which the missed target was fixated for a longer time only in the quantity of evidence accumulated before a decision threshold was reached and not in a more qualitative manner.

Other sources of error. The hierarchical nature of the taxonomy of multiple-target search errors described in Table 1 obscures some general underlying causes that may affect several different taxonomic levels. These potential underlying sources are described in more detail here.

Attentional blink. One potential cause of recognition errors is an *attentional blink* (e.g., Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). In a typical attentional blink paradigm, participants are presented with multiple targets embedded in a temporal stream of visual items. After detecting the first target, participants are less likely to notice a second target that appears 200–500 ms after the first target; it is seen but not consciously processed (see Martens & Wyble, 2010, for a review). Although a free-viewing spatial visual search task bears little surface resemblance to a typical attentional blink experiment, the large number of cases in which a target is fixated but not reported suggests that there could be mechanistic similarities. In the present experiment, participants were significantly less likely to report a low-salience target that they began to fixate 135–405 ms after fixating a high-salience target than if they encountered it later in their search or fixated it immediately after the high-salience target (a phenomenon known as Lag-1 sparing). The relationship between the attentional blink and SSM errors in this data set is reported more fully elsewhere (Adamo et al., in press).

Refixations. Eye-tracking measures provide a variety of assessments of search performance, and much can be learned from assessing the number of refixations of previously fixated items, particularly previously found targets. In single-target search, refixations of previous items are rare (e.g., 5.7% in Peterson, Kramer, Wang, Irwin, & McCarley, 2001); thus, notable levels of refixations in multiple-target search could reveal fundamental differences between the two types of search. In the present study, the high-salience target was refixated after having been correctly located on 23.7% of dual-target trials, suggesting that it might be acting as a particularly potent distractor. However, refixating the high-salience target did not lead to worse subsequent search performance overall. Across all dual-target trials on which the high-salience target was found, the low-salience target was actually found more often on trials on which the high-salience target was refixated than on trials on which it was not, $t(27) = 2.25$, $p = .033$, $d = 0.37$. This finding is somewhat counterintuitive, as it is not clear why refixating a found target should improve subsequent search performance. Perhaps searchers noticed these target refixations, alerting them to their suboptimal search strategy, leading to more conscientious performance on some trials.

Refixations on distractor items were even more frequent than refixations on the high-salience target, occurring on 75.6% of dual target trials and accounting for 23.8% of all distractor item fixations occurring after a high-salience target was found. There was a higher proportion of distractor refixations when the low-salience target was missed (29.2%) than when it was found (20.0%), $t(27) = 10.32$, $p < .001$, $d = 1.57$. These data suggest a relationship between refixations and poor second-target detection, but do not speak to the causal direction of this relationship. For example, distractor item refixations could potentially cause poorer performance by making searchers feel that they have searched more exhaustively than they actually have (e.g., searching 25 total items instead of 25 unique items; Cain & Mitroff, 2012). Alternatively, refixations could simply be a byproduct of reduced cognitive resources, increased distractibility, or other factors that, themselves, impair search.

Physical similarity. One possible influence on detection accuracy is the second target's physical similarity to the first target. Here, two targets present in the same display always had different shading, but items could appear in one of four independently selected orientations. If searchers actively avoided items with the same orientation as a found high-salience target—or were more likely to search for them, as the perceptual set hypothesis would suggest (e.g., Berbaum et al., 1991)—then the miss rate for low-salience targets would be related to whether or not the two targets had the same orientation. For SSM errors, the low-salience target's orientation matched the high-salience target's orientation on 26.5% of trials, barely different from the 25% expected by chance, $t(27) = 1.41$, $p = .171$, $d = 0.21$, suggesting that orientation similarity did not contribute to SSMs. Further, examining fixation patterns across all dual-target trials (not only those with SSM errors), the orientations of distractor items that were fixated after the high-salience target was found, but before the low salience target was found (if it was found), also matched the orientation of the high-salience target no more or less often than would be predicted by chance (24.6%), $t(27) = 1.37$, $p = .183$, $d = 0.21$. This suggests that the orientation of the first found target did not bias which items were fixated in subsequent search.

Proximity. Another possible source of error is the physical proximity of the two targets. For example, a second target might be more likely to be found if it is close to a found target, as it would be closer to the point of fixation. Alternatively, targets situated near other targets might be particularly susceptible to factors such as the attentional blink (Adamo et al., in press) which is strongest closest to the location of the first target and weaker further away from it (Kristjánsson & Nakayama, 2002). To investigate these possibilities, we examined low-salience target accuracy on all dual-target trials in which the high-salience target was found. Trials were divided according to intertarget distance into four 125-pixel bins—with each bin representing a ring of cells in the invisible rectangular item grid centred on the first target's cell. There was a marginal effect of intertarget distance, $F(2.947, 66.252) = 2.947$, $p = .049$, $\eta_p^2 = .098$, Greenhouse-Geiser corrected), with low-salience accuracy declining as the two targets were further separated. However, increased intertarget distance did not appear to selectively produce one type of error over another. For example, the average distance between targets when the low-salience target was fixated ($M = 365.2$ pixels, $SD = 30.2$), was not different than the average distance when the low-salient target was not fixated ($M = 368.9$ pixels, $SD = 42.1$), $t(27) = 0.81$, $p = .426$, $d = 0.10$. Thus, while the arrangement of the display may affect search patterns generally, it does not appear to particularly affect SSMs, at least in abstract, relatively unstructured spatial displays such as these.

DISCUSSION

Subsequent search misses have long been acknowledged as a stubborn source of errors in multiple-target searches, but a common explanation of such errors has proven elusive. In the present study we tracked observers' eye movements as they searched displays containing one or two target items. On nearly a third of dual-target trials, searchers successfully found the high-salience target but missed the low-salience target. All of these misses would ordinarily be classified simply as SSM errors. However, eye movement data can reveal that not all such miss errors are alike. Here, these error data were able to be divided into several forms of errors: scanning errors, recognition errors, decision errors, resource depletion errors, strategy errors, and false-SSM errors. By providing such a taxonomy of errors, we hope to inform and guide future research into the various causes of multiple-target search errors.

Multiple-target visual search may appear to be a simple extension of the well-studied task of single-target search, but the possible presence of more than one target can have dramatic effects. In particular, multiple-target search is subject to all the same problems inherent in single-target search tasks (e.g., deciding when to quit searching and how to track what areas have already been searched), but with the added complexity that these cognitive processes can be affected by having found a target in memory (Cain & Mitroff, 2012). Thus, multiple-target visual search is useful tool for more deeply understanding the component processes of visual search, but it comes with the cost of added complexity and it can demand more sophisticated analysis than is afforded by examining accuracy alone. By using eye tracking we were able to tease apart several distinct causes of errors, but it is clear that there may be additional sources of error that future work will be needed to fully understand.

Implications for theories of subsequent search misses

The eye-tracking results of the present study suggest that there are multiple types of errors that all contribute to the SSMs. In turn, these results provide selective support for several different theories; no single theory can explain all the current data, but some types of errors appear consistent with each theory.

Satisfaction. The original conception of SSMs was that radiologists spent insufficient time scanning X-ray images for additional targets because they felt that they already understood the diagnosis allowed by the images (Smith, 1967; Tuddenham, 1962). However, subsequent investigations in radiology have not fully supported this idea (e.g., Berbaum & Franken, 2011). Here we found further evidence that the majority of SSM errors were not due to insufficient time-on-task: Searchers spent longer, on average, searching in vain for an absent low-salience target after finding a high-salience target on a single-target trial than was necessary, on average, to find a present low-salience target on a dual-target trial. However, when examining individual trials, searchers quit immediately after finding the high-salience target on 6.1% of trials. These immediate termination errors could reflect searchers actually feeling confident that they had conducted a sufficiently exhaustive search before finding the high-salience target to have found a low-salience target. They could also be due to searchers making a strategic choice to end the trial and move on to the next in order to maximize their overall rate of finding targets rather than to maximize their overall accuracy (Cain et al., 2012). It should be noted that, unlike the other categories of errors described earlier, just two participants contributed over half of this type of strategic error, suggesting that there may be important individual differences in this particular strategy selection.

Perceptual set. The perceptual set hypothesis argues that once a searcher has found a target, they are more likely to find additional targets that match the found target and, importantly, are less likely to find additional targets that do not match (e.g., Berbaum et al., 2010). In radiological searches, potential targets can have very different appearances (e.g., tumours vs. fractures), but in the current study all targets were defined by having the same T shape, making a full test of the perceptual set hypothesis difficult. However, targets could appear in one of four orientations. If the perceptual set induced by finding a target includes orientation, then the perceptual set hypothesis would predict that items with the same orientation as the found target should be more likely to be fixated than items with a mismatching orientation. We found no evidence of such a perceptual set effect here as there was no influence of target orientation congruence on second-target accuracy. This finding rules out a strong form of the perceptual set hypothesis—that all individual features of a found target bias subsequent search towards matching features—but we cannot rule out the possibility that the perceptual set works at the level of the whole object (though previous work with similarly coloured Ts does not provide support for this idea; Cain et al., 2012; Fleck et al.,

2010) or only on the most task-relevant dimensions (which would not include orientation in this experiment). Parametric studies of the perceptual similarity of targets will be necessary to fully characterize or rule out the effects of perceptual set.

Resource depletion. We have hypothesized elsewhere that SSMs could be caused by memory resource depletion (Cain & Mitroff, 2012). Specifically, if searchers maintain memory representations of found targets' identities and/or locations, this might consume working memory resources that would otherwise have aided search for subsequent targets. In particular, due to competition for working memory resources, a portion of the recognition errors reported here are likely the result of a self-induced attentional blink when searchers fixated the low-salience target 200–500 ms after finding the high-salience target (see Adamo et al., in press). Maintaining a memory representation of a found target could be especially problematic in the current experiment, as working memory capacity for stimuli like those used here is only 1.3 items (Cain et al., 2012, supplementary experiment). While the present experiment did not directly probe the contents of searchers' memories, it does allow for some insight into available memory capacity. In particular, the large number of refixations on previously searched distractor items suggests that memory for searched locations, which is normally quite large (e.g., Takeda, 2004), may be disrupted. Similarly, the notable numbers of refixations on found targets suggests that the features of these targets may be present in item memory, as visual search has been shown to be biased towards items that match the contents of working memory (e.g., Dowd & Mitroff, in press; Soto, Heinke, Humphreys, & Blanco, 2005).

Caveats

The general findings of the current study will likely be applicable broadly to multiple-target visual searches; however, some important limitations should be noted. First, the target distribution was unusual for a laboratory visual search experiment. Targets were present on every trial and the majority of trials had two targets. Previous work had suggested that the SSM effect is sensitive to the ratio of single-, dual-, and no-target trial types (Fleck et al., 2010); thus, we were surprised by the magnitude of the SSM effect given the 4:1 ratio of dual-target to single-target trials, which we anticipated might bias searchers towards searching exhaustively for both targets. However, even with two targets present on 80% of the trials, a strong and significant SSM effect was obtained, with better accuracy for the low-salience target on single-target trials than on dual-target trials. Why did participants not realize that they should find two targets most of the time? One possibility is the absence of feedback. Recent computational modelling work with a related multiple-target search task suggests that participants exhibit a strong prior expectation of 50% target prevalence (Cain et al., 2012), and, in the absence of feedback, such an expectation may have led participants to systematically underestimate the proportion of dual-target trials, leading to SSMs. Regardless, given that we obtained a pattern of accuracy results that was similar to that obtained with other target distributions (e.g., Cain & Mitroff, 2012; Fleck et al., 2010), concerns about the unusual target distribution are greatly diminished. Interestingly, nearly half the SSM errors committed in the present study were due to the missed item never being fixated, but such errors are much rarer in radiological studies (e.g., Samuel et al., 1995). Thus, even though radiology caseloads are primarily target-absent trials—which might encourage scanning errors—radiologists may actually be more complete in their scanning of images, suggesting that their training and motivation are likely effective at reducing this source of error. However, professional searchers who are under stricter time pressure, such as baggage screeners, may still be prone to such errors.

Second, the properties of our abstract search task were necessarily different from those of real-world visual searches (Clark, Cain, Adamo, & Mitroff, 2012). For example, the prevalence of targets in actual baggage screening and radiological searches is quite low, which leads to greater numbers of miss errors in single-target searches (e.g., Wolfe, Horowitz, & Kenner, 2005; but see Fleck & Mitroff, 2007), an effect that gets exponentially worse at extremely low prevalence (Mitroff & Biggs, 2013). Such factors likely affect the ratios of particular errors committed—for example, decision errors may increase as the target/nontarget decision becomes more difficult or as decision criterion shifts toward more conservative responding at low prevalence (e.g., Wolfe & Van Wert, 2010)—and may introduce other types of errors (e.g., inattentional blindness; Drew, Võ, & Wolfe, 2013). However, there is good reason to believe that professional searchers such as airport security screeners (Biggs, Cain, Clark, Darling, & Mitroff, 2013) and cytologists (Evans, Tambouret, Evered, Wilbur, & Wolfe, 2011) are susceptible to the same types of errors as novice searchers. Thus, although the exact proportions of errors may depend on both the searcher and the search environment, the broad conclusion that multiple types of errors contribute to SSMs should provide useful guidance towards real-world interventions.

CONCLUSIONS

The consequences of subsequent search misses have been a persistent problem for both novice and professional searchers and the causes of SSMs have presented a puzzle to researchers both in radiology and cognitive psychology. Here, a systematic examination of the miss errors in a well-controlled visual search task revealed that the difficulty in providing a single cause of SSM errors appears to be that there are in fact several causes of such errors.

Each source of SSM errors supported here likely has its own cognitive underpinning and, as such, SSM errors can best be described as arising from a combination of attentional, mnemonic, strategic, and motivational influences.

Practically, the key to reducing SSM errors, therefore, may be addressing each cause in turn: Training may be needed to ensure that the entire display is scanned, motivation may be needed to reduce strategic errors, and interventions such as splitting multiple-target searches into multiple single-target searches may be needed to relieve cognitive load. Only through a multifaceted approach can accuracy be ensured for critical multiple-target searches.

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