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An individual differences approach to multiple-target visual search errors: How search errors relate to different characteristics of attention

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ABSTRACT

A persistent problem in visual search is that searchers are more likely to miss a target if they have already found another in the same display. This phenomenon, the Subsequent Search Miss (SSM) effect, has remained despite being a known issue for decades. Increasingly, evidence supports a resource depletion account of SSM errors—a previously detected target consumes attentional resources leaving fewer resources available for the processing of a second target. However, "attention" is broadly defined and is composed of many different characteristics, leaving considerable uncertainty about how attention affects second-target detection. The goal of the current study was to identify which attentional characteristics (i.e., selection, limited capacity, modulation, and vigilance) related to second-target misses. The current study compared second-target misses to an attentional blink task and a vigilance task, which both have established measures that were used to operationally define each of four attentional characteristics. Second-target misses in the multiple-target search were correlated with (1) a measure of the time it took for the second target to recovery from the blink in the attentional blink task (i.e., modulation), and (2) target sensitivity (d') in the vigilance task (i.e., vigilance). Participants with longer recovery and poorer vigilance had more second-target misses in the multiple-target visual search task. The results add further support to a resource depletion account of SSM errors and highlight that worse modulation and poor vigilance reflect a deficit in attentional resources that can account for SSM errors.

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1. Introduction

1.1. Background

Visual search, the act of looking for targets amongst distractors, is an integral part of everyday life. Searches can be as trivial as a person looking for groceries in the supermarket or as serious as a radiologist searching for tumors in a radiograph. Visual search is a well-researched paradigm (see Eckstein, 2011 and Nakayama & Martini, 2011 for recent reviews), and much is known about situations that lead to better or worse performance. Unfortunately, one type of visual search has consistently given rise to poor perfor mance—multiple-target visual search. Multiple-target visual search is when more than one target can potentially be present in a given search display. These searches can give rise to one specific type of error—observers are much more likely to miss an additional target if they had already detected a target earlier in the search display (Tuddenham, 1962). This phenomenon, previously known as the Satisfaction of Search effect (Smith, 1967) and recently renamed the Subsequent Search Miss (SSM; Adamo, Cain, & Mitroff, 2013) effect, can be a real problem in visual searches where target detection is critical, such as those conducted by radiologists and airport security personnel.

SSM errors can account for up to one-third of some types of radiological errors (Anbari & West, 1997) and can occur in a wide variety of radiological exams including abdominal radiography, skeletal radiography, chest radiography, and multiple-trauma patient scans (e.g., Ashman, Yu, & Wolfman, 2000; Berbaum et al., 1994, 1998; Franken et al., 1994; Samuel, Kundel, Nodine, & Toto, 1995). Given the critical nature of SSM errors in radiological searches, a variety of attempts have been made to ameliorate the effects. For example, target detection tools such as computer-aided detection and contrast enhanced imaging have been investigated as possible tools to reduce SSM errors. However, computer aided detection was found to have no effect on alleviating SSM errors (Berbaum, Caldwell, Schartz, Thompson, & Franken, 2007)

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and contrast enhanced imaging was found to possibly even exacerbate these errors (Franken et al., 1994). A better understanding of SSM errors is critical, as failing to detect targets could be a matter of life-and-death.

A core means to counter SSM errors is to understand its primary cause(s). By determining the cognitive mechanisms that give rise to these errors, it might be possible to enact steps to eliminate them. To date, there are three proposed theoretical accounts of SSM errors: the Satisfaction account, the Perceptual Set account, and the Resource Depletion account (Berbaum et al., 1991; Biggs, Adamo, Dowd, & Mitroff, 2015b; Cain & Mitroff, 2013; Samuel et al., 1995; Smith, 1967). Below, each of these theoretical accounts is briefly discussed.

1.1.1. Satisfaction account

Originally, radiological researchers exploring the SSM phenomenon proposed that errors arose when an observer became "satisfied" with the meaning of a search display after finding a target, causing them to prematurely terminate their search (Smith, 1967; Tuddenham, 1962). Since then, there has been mixed support for the Satisfaction account (Adamo, Cain, & Mitroff, 2015a; Berbaum et al., 1990, 1991; Cain, Adamo, & Mitroff, 2013; Samuel et al., 1995). The evidence against a Satisfaction account has demonstrated that, on average, observers search for the same amount of time regardless of how many targets are in the search display (Berbaum et al., 1991) and observers rarely quit searching immediately after finding a first target (Cain et al., 2013). However, there is recent evidence in support of a Satisfaction account, which demonstrated that when observers searched for longer after finding a first target, they were more likely to find a second target, compared to observers who searched for less time (Adamo et al., 2015a).

1.1.2. Perceptual Set account

The Perceptual Set account posits that once a first target is detected, an observer is biased to search for targets that share similar characteristics to that of the first target (Berbaum et al., 1990, 1991; Biggs et al., 2015). Therefore, after finding a target of one type (e.g., a tumor), the observer may be less likely to find a target of a different type (e.g., a fracture). Again, there has been mixed support for the Perceptual Set account. On one hand, results have not supported this account finding that observers committed an equivalent amount of SSM errors regardless of whether two targets in the same array were similar or different in salience (e.g., if both targets were a lighter shade of gray or one target was a lighter shade of gray and one was a darker shade of gray; Fleck, Samei, & Mitroff, 2010) or rotation (e.g., if one target was rotated 90 degrees and the other was rotated 180 degrees; Cain et al., 2013). On the other hand, when SSM errors were assessed in a visual search environment that contained many different target possibilities (i.e., akin to how airport security personnel search for scores of different types of dangerous items in carry-on bags), it was demonstrated that a second target is more likely to be detected if it is identical to a detected first target (Mitroff et al., 2014). Moreover, second targets were also more likely to be detected if they were the same color or the same category as that of the first target (Biggs et al., 2015b).

1.1.3. Resource Depletion account

The Resource Depletion account posits that once a first target is found, it consumes cognitive resources, such as working memory and attention, leaving less available to process a second target (Berbaum et al., 1991; Cain & Mitroff, 2013; Samuel et al., 1995). To date, this account has received the most support. For example, if a first target is immediately removed from the display once it is detected, there is an increase in accuracy for detecting a second target (Cain & Mitroff, 2013). This finding has been interpreted to suggest that a found target is held in working memory, and thus can hinder the processing of other targets. As such, once the item is physically removed, working memory resources previously allocated to the found target can become available again, aiding in the processing of other targets. With respect to attention, a first target has been shown to induce an attentional blink (i.e., a decrease in second target accuracy when it appears 200–500 ms after a detected, first target) in a multiple-target search (Adamo et al., 2013). This study suggests that a detected, first target consumes attentional resources that are necessary for second target processing. Research on SSM errors has also demonstrated that a found, first target amplifies the effects clutter (i.e., distractors within a close vicinity to a target) has on second target processing (Adamo, Cain, & Mitroff, 2015b). Theoretically, this finding suggests that if a found, first target is already consuming attentional resources, attentional distractions have a greater impact on target accuracy compared to if no first target was found.

1.2. Current study

While there is substantial support that cognitive resources can be consumed by a detected first target, there is still ambiguity as to what is actually meant by "resources." The terms "working memory" and "attention" are often broadly defined and can describe overlapping cognitive constructs (e.g., Chun, Golomb, & Turk-Browne, 2011; Kiyonaga & Egner, 2012), and this has left the field with considerable uncertainty about what exactly is affected after the detection of a first target. The goal of the current study was to better understand how attention is affected after detecting a first target by identifying which characteristics of attention relate to second-target misses.

Chun et al. (2011) have provided a framework that offers a nice way to delineate the various aspects of attention. Specifically, they divide attention into four different characteristics: (1) Limited Capacity—attention is a finite cognitive resource that can be used to process only a subset of the visual world; (2) Selection—attention is needed to choose which visual information is selected from the visual world to receive additional processing within working memory; (3) Modulation—attention is needed to facilitate the processing of visual information within working memory so that it can be acted upon and later remembered in long-term memory; and (4) Vigilance—attention must be sustained over extended periods of time to complete demanding tasks.

The experimental logic for the current study was to investigate the relationship between attention (as defined by the four characteristics described above) and SSM errors by taking advantage of individual difference measures. People vary along a number of factors, and it can be highly informative to explore how these individual differences relate to measures of cognitive performance. For example, much has been learned about working memory and its underlying mechanisms by exploring individual differences in executive attention (see Kane & Engle, 2002 for a review). Here, SSM errors calculated from a multiple-target visual search task were assessed in light of individual differences in performance on two established attentional paradigms—an attentional blink and vigilance task. These tasks exhibit the four attentional characteristics outlined above (Chun et al., 2011), making them a potentially powerful tool for better understanding SSM errors.

An attentional blink (AB) is defined as a decrease in second target accuracy when a second target is presented 200–500 ms after a first target in a rapid serial visual presentation stream (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). Many measures can be extracted from the AB paradigm and three of them will be used to operationally define three of the four attentional characteristics (Chun et al., 2011; See Fig. 1). The first measure is

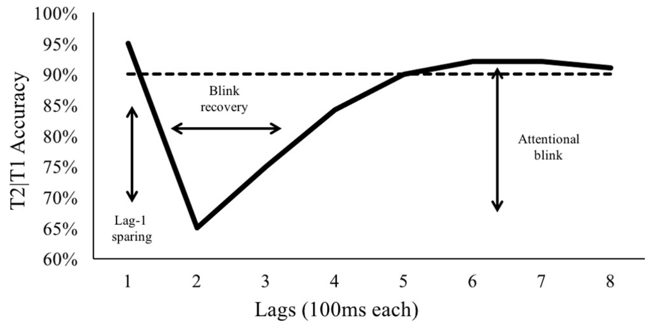

Fig. 1. Depiction of a typical attentional blink effect. In general, attentional blink graphs depict target accuracy on the y-axis and time on the x-axis, with the x-axis representing the time (lags) in which a second target (T2) appeared after a first target (T1) was displayed. Specifically, this graph depicts T2 accuracy given T1 was detected (solid, black line), and the average single-target accuracy across the experiment (dashed, black line). The three AB measures discussed in this experiment are labeled here: lag-1 sparing—higher accuracy at lag 1 compared to lag 2; blink recovery—width of the blink starting where T2 accuracy begins to decrease and where it recovers to the level of single-target accuracy; attentional blink—depth of the blink, with lower T2 accuracy approximately at lags 2 and 3 compared to the average of lags 5–8.

the blink magnitude—how much the processing of a first target to conscious awareness impacts the subsequent detection of a second target. The blink typically has the strongest impact on second target processing 200–300 ms after the display of a first target. The blink was chosen to serve as a proxy for the attentional characteristic of "limited capacity" since it is proposed that the processing of the first target leaves less attentional resources available for processing a second target, resulting in reduced second target detection (e.g., Chun & Potter, 1995). The second measure assessed was lag-1 sparing (Potter, Chun, Banks, & Muckenhoupt, 1998)—a phenomenon where second target accuracy is typically high when it appears approximately 100 ms after a first target. Lag-1 sparing offers an operational measure of the attentional characteristic of "selection" as lag-1 sparing is believed to occur due to a boost in attention allocated to a first target after it is selected for processing (e.g., Olivers & Meeter, 2008; Wyble, Bowman, & Nieuwenstein, 2009).[1] Finally, the third measure assessed was the blink recovery—the width of the blink effect in terms of how long the processing of a first target impacts the identification of a second target (Cousineau, Charbonneau, & Jolicoeur, 2006). The impact of the blink is typically seen 200–500 ms after the identification of a first target, but there is variability in how quickly observers overcome the negative, blink effect. As such, blink recovery can be used to represent the attentional characteristic of "modulation" as its duration indicates how long it took the observer to process the first target (consequently impacting detection of the second target).

To measure the final attentional characteristic of "vigilance," a standard vigilance task was employed (Temple et al., 2000). Vigilance can be assessed along a number of different fronts (e.g., state vs. trait qualities), and the focus here was on situational attentional engagement (Warm, Parasuraman, & Matthews, 2008)—the observers' state of attentional readiness at the time of testing.

To preview the results, modulation and vigilance were found to significantly correlate with second-target misses in a multiple-target visual search task, while selection and limited capacity were not. These findings remained significant even when accounting for the contributions of general search performance (see Section 2.4). These results suggest that worse attentional modulation and poor vigilance are predictive of more second-target misses.

[1] There are many different theories as to why the AB and Lag-1 sparing occur (See Dux & Marois, 2009 for a review), and the precise mechanisms and theoretical reasons why the AB occurs is beyond the scope of this study.

2. Materials and methods

2.1. Participants

Seventy-two members of the Duke community completed three tasks: an AB task, a multiple-target visual search task, and a vigilance task. The total number of participants was dictated by the number of individuals who were successfully recruited for this study during the Spring and Fall semesters of 2011 at Duke University. The experiment took 90 min to complete, and the participants were compensated with course credit or $15. The data reported here were originally collected to investigate the current research question (the relationship between different characteristics of attention and SSM errors), but previous works have included subsets of this dataset (Adamo et al., 2015a, 2015b; Biggs, Adamo, & Dowd, 2015a). The previous uses of the data were for different purposes; one study used the AB data as a control condition for how motivation affects the AB (Biggs et al., 2015a), one study focused on how clutter exacerbated SSM errors (Adamo et al., 2015b), and one study used the vigilance data as a control condition to investigate the Satisfaction account of SSM errors (Adamo et al., 2015a). Research was conducted in accordance with the Declaration of Helsinki.

2.2. Data cleaning

For each task, a participant's data could be removed either for being incomplete or not meeting the inclusion criteria for that task. For the AB task, data from five participants were removed: two participants did not complete the task, two participants had single-target accuracy rates two standard deviations below the mean, and one participant had data that poorly fit the attentional blink model used to compute the blink magnitude, lag-1 sparing, and blink recovery constructs (see Cousineau et al., 2006). For the multiple-target search task, ten participants were removed based off of pre-existing outlier criteria (Adamo et al., 2013): four participants did not complete the task, one participant had an excessive number of time outs (two standard deviations above the mean), three participants had over 20% false alarms, and two participants had two standard deviations above the mean response time for low-salience targets (when they were found first). For the vigilance task, two participants were removed: one participant did not complete the task and one participant had over 50% false alarms across all possible responses suggesting that they were not actively engaged in the task. As long as a given participant contributed data to at least two of the three tasks, they were included in further analyses; and only one participant did not meet this criterion (he/she failed to complete one task and was an outlier in another). As such, the final dataset came from 71 participants (31 females; ages 18–27; mean = 20.85).

After the outlier removal procedures described above, there were 67 participants whose data were used for the AB analyses, 62 for the multiple-target search task analyses, and 69 for the vigilance task analyses. Fifty-eight participants completed both the multiple-target search and AB tasks and 60 participants completed both the multiple-target search and vigilance tasks.

2.3. General procedures

Participants sat 57 cm from the center of a 20-inch CRT monitor, and used a chin rest to maintain a consistent position. Stimuli presentation and response recording were done with a Dell Inspiron computer. Stimuli were presented with Matlab software (The MathWorks, Natick, MA) and Psychophysics Toolbox version 3.0.8 (Brainard, 1997). The studies were counterbalanced in their presentation with either the AB task or multiple-target visual search task administered first. The vigilance task was always presented last as to not tire out the participants before they completed the other two tasks.

2.3.1. Attentional blink task

This task was modeled after Chun and Potter (1995; see Fig. 2a), as this type of AB task with letters and number as stimuli has reliably demonstrated an attentional blink, lag-1 sparing, and recovery (e.g., Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005; Lunau & Olivers, 2010). White numbers and letters (Arial font; approximately $1° \times 1°$) were presented on a black background in a rapid serial visual presentation (RSVP) stream. Distractors were digits 2–9 and targets were all letters from the English alphabet excluding the letters B, I, O, and Q. The same letters and numbers were never repeated twice in a row. Each trial began with a white fixation dot appearing in the center of the screen (0.25° diameter) and a space bar press initiated each trial. Participants were asked to search for up to two target letters and report them at the end of each trial by typing the corresponding letters on a standard keyboard. The first target presented is referred to as "T1" and the second is referred to as "T2." A total of 16 items were displayed for 100 ms each with T1 appearing between the 3–7 position and T2 appearing 1–8 positions (lags) after T1 (positions 8–15). Eighty-percent of the trials were dual-target trials and 20% were single target trials where only T1 appeared. Participants were asked to press the space bar for each target response if the corresponding target was not seen in the RSVP stream. There were 10 practice trials and 200 experimental trials with no feedback provided. However, the experimenter made sure the participants understood the task before starting the experimental trials.

2.3.2. Multiple-target search task

This task was modeled after Adamo et al. (2013; see Fig. 2c) and was used here as it has reliably demonstrated a SSM effect (e.g., Cain, Biggs, Darling, & Mitroff, 2014; Fleck et al., 2010). Participants were asked to search for 'T' shaped targets amongst pseudo 'L' shaped distractors (the distractors were items without perfect alignment of the two bars; the cross bar offset was between 1–4 pixels from center). Items were presented in one of four possible orientations (0°, 90°, 180°, and 270°) on a white background. There were 25 items per display and they were presented on an invisible 8×7 grid (jittered 0–4 pixels in any direction from the center of the cell). Fifty percent of targets and 5% of distractors were high salience (57–65% black), and the other 50% of the targets and 95% of distractors were low-salience (22%–45% black). Ten percent of the trials were single-target, high-salience, 10% were single-target, low-salience, and 80% were dual-target with a high- and low-salience target. Participants had 15 s to search the display, click on items they believed were targets, and press the space bar when they believed that all the targets had been detected. Failing to complete the trial in this time frame was considered a time out. Participants received a warning message following any time out. There were 25 practice trials that contained accuracy feedback and 250 experimental trials with no feedback.

2.3.3. Vigilance task

This task was modeled after Temple et al. (2000; see Fig. 2e) and has previously been used to explore individual differences in observers' vigilance (e.g., Helton, Matthews, & Warm, 2009; Helton et al., 2007). Participants were asked to search for gray (45% black) target letter "O's" amongst distractor, backward and forward-facing letter "D's" in a RSVP stream on top of a noisy mask. The mask consisted of dark-gray (80% black) hollow circles (0.2° in diameter) that were spaced 0.75° horizontal, 0.4° pixels vertical, and 0.8° pixels diagonally from one another. Each item ($0.8° \times 0.8°$) appeared for 40 ms with an inter-stimulus interval of 960 ms. There were 24 targets and 96 distractors per block, with one practice block and six experimental blocks. Participants were instructed to press the space bar every time a target appeared. A space-bar press was considered a hit if pressed within one second after a target appeared and a false alarm if pressed within one second after a distractor appeared. The total task took 14 min and was broken up into seven blocks of two minutes each (with the first block serving as a practice block). While no feedback was provided, the experimenter made sure the participants understood the task before starting the experimental trials.

2.4. Planned analyses

The goal of the current study was to examine the rate of SSM errors in a multiple-target visual search task in light of various measures of attention taken from an AB task and a vigilance task. As such, there were two broad phases of the analyses. First, it was necessary to establish that the current tasks replicated the standard effects from the three employed tasks. That is, it was important to first demonstrate that the AB tasks produced a blink, lag-1 sparing, and a blink recovery effect, that the multiple-target search task produced a SSM effect, and that the vigilance task demonstrated a standard vigilance decrement effect across blocks. To foreshadow the results, all three tasks replicated the expected outcomes.

The second category of analyses focused on the core issue of they study—whether the AB and vigilance task dependent variables of interest (the blink magnitude, lag-1 sparing, blink recovery, and vigilance decrement) related to SSM errors. As outlined above, these four variables were operationally defined to reflect the four attentional characteristics outlined by Chun et al. (2011) such that the blink magnitude represents attentional capacity, lag-1 sparing represents selection, blink recovery represents modulation, and the vigilance decrement represents vigilance. To specifically assess the relationship between these four measures of attention and SSM errors, a two-step analysis process was employed. First, the attentional measures were correlated with general search performance, which was defined here as the low-salience target response time, and with the percentage of second-target misses. These analyses illustrated the relationship between the attentional characteristics and general search performance, and the attentional characteristics and second target performance. Second, a partial correlation was conducted for each attentional measure that partialled out the variance related to general search performance. These analyses illustrated how the attentional characteristics uniquely related to second-target misses.

2.4.1. Attentional blink

The three main variables of a typical AB task—the blink, lag-1 sparing, and blink recovery—were calculated using the conceptual and methodological framework provided by MacLean and Arnell (2012). Blink magnitude was calculated as the difference between T2 accuracy at lag 2 and the average of T2 accuracy at lags 5–8 (see Fig. 1). Only dual-target trials where T1 was correctly identified were included in all AB analyses reported here. Lag-1 sparing was defined as the difference between T2 accuracy at lag 1 and lag 2, and blink recovery was calculated as the difference between T2 accuracy at lag 5 and T1 accuracy on single-target trials.

The primary goal of employing the AB task, was to compare performance across participants between the three primary dependent variables and multiple-target search performance. To explore individual differences in the AB variables, curve-fits were employed, and they were based on the methods of Cousineau

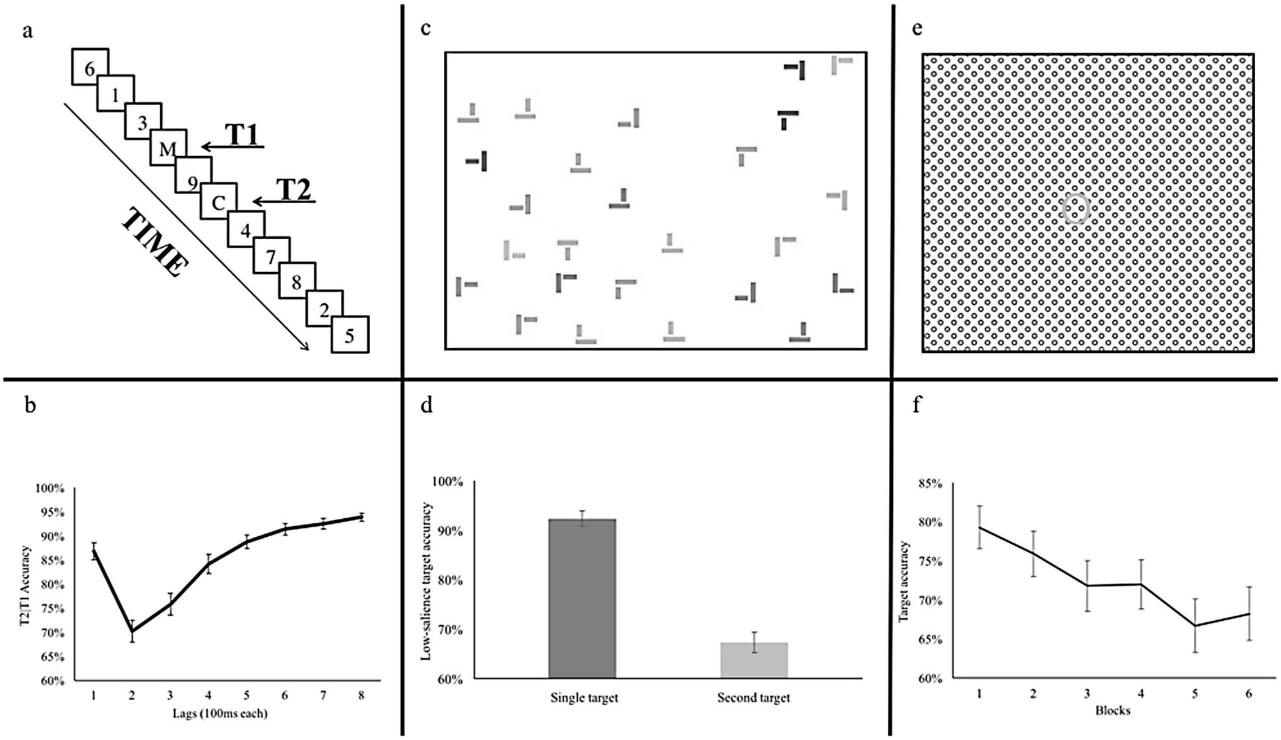

Fig. 2. Example stimuli and experimental data from the attentional blink (AB), multiple-target visual search, and vigilance tasks. (a) Sample AB task display where items are presented one at a time for 100 ms in the center of the screen. (b) AB data where participants demonstrated lag-1 sparing with higher accuracy at lag 1 compared to lag 2, a blink with lower accuracy at lag 2 compared to the average of lags 5–8, and blink recovery with similar accuracy at lag 5 compared to single-target accuracy (not pictured here). (c) Sample multiple-target search task display where participants were asked to look for target "T" shapes amongst distractor "L" shapes on a white background. (d) Multiple target search data in which low-salience, single-target trial accuracy was greater compared to "second-target accuracy," which represents accuracy for low-salience targets when a high-salience target was found first on dual-target trials. (e) Sample vigilance task display where participants were asked to detect target "O's" amongst backward or forward "D's" on top of a noisy background. (f) Vigilance data where participants demonstrated worse target detection in block 6 compared to block 1. Error bars represent the standard error of the mean.

et al. (2006).[2] The blink magnitude is measured as the amplitude of the curve in T2 accuracy and is the difference between the asymptotic and minimum performance. Lag-1 sparing represents the relatively high T2 accuracy typically found at lag 1 in comparison to a minimum accuracy. The measure of lag-1 sparing ranges from 0 (total sparing; same accuracy as asymptotic performance) to 1 (no sparing; same accuracy as the minimum performance). Blink recovery represents the width of the attentional blink, with a lower value representing a sharper blink, with a quick descent and rise out of the blink. To ensure the data were normally distributed, the parameters for the blink, lag-1 sparing, and blink recovery were set to be at least one fourth of a lag, as this was found to provide a normal distribution for this data set. See Cousineau et al. (2006) for the equations used for each variable.

2.4.2. Multiple-target search

Three measures were calculated from the multiple-target search task. The first measure assessed whether there was an SSM effect with worse accuracy for low-salience, single-target trials compared to low-salience target accuracy on dual-target trials in which a high-salience target was first detected (Adamo et al., 2013). The individual difference measures focused on two measures from the multiple-target search task: second-target misses and general search performance. Second-target misses were calculated as the difference between perfect accuracy (i.e., 100%) and the accuracy for low-salience targets on trials when a high-salience target was detected first in a dual-target search. General search performance was calculated as the response time (RT) for low-salience targets in single-target trials or when the low-salience target was detected first in dual-target trials. RT is a common measure used to assess search performance, such as the difficulty of finding different types of targets (e.g., Treisman & Gelade, 1980). This measurement established a baseline to assess whether our attentional measures uniquely correlated with second-target misses when accounting for general search performance.

2.4.3. Vigilance

Two measures were taken from the vigilance task. The first measure assessed whether a general vigilance effect was found. This was calculated by comparing target accuracy between blocks 1 and 6, with the expectation that there would be lower accuracy in block 6 than block 1. The second measure calculated was vigilance sensitivity and was based upon the participants' hit and false alarm rates across the six experimental blocks. Vigilance sensitivity was calculated as d′ (Nevin, 1969), and it was used to represent an individual difference measure of overall vigilance.

3. Results

3.1. Main findings

The three stereotypical AB components were found for the AB task (see Fig. 1b). First, a blink was found with lower accuracy at lag 2 (M = 70.21%; SD = 18.83%) compared to the average of lags 5–8 (M = 91.62%; SD = 7.26%; $t(66) = 9.90$, $p < 0.001$). Second, lag-1 sparing was found with greater accuracy at lag 1 (M = 86.81%;

[2] While there are many ways to measure different characteristics of the blink (see MacLean & Arnell, 2012), the curve-fitting provided by Cousineau et al. (2006) allowed for easy isolation of each AB measure of interest.

Table 1
Correlation results for the attentional characteristics with general search performance and second-target misses. General search performance represents the average, combined response times for low-salience targets when found first on single-target trials and for low-salience targets when found first on dual-target trials. Second-target misses represent the average miss rate for a low-salience targets after a high-salience target was detected first on dual-target trials. The partial correlations represent the relationship between the attentional characteristics and second-target misses partialling out the variance of general search performance. Each p-value represents a within-subjects, 2-tailed correlation. The partial correlations were conducted using Bonferroni-adjusted alpha levels of 0.0125. Asterisks indicate a significant correlation.

Attentional characteristic	Measure	General search performance	Second-target misses	Partial correlation
Limited capacity	Blink magnitude	$r(57) = 0.16$ $p = 0.24$	$r(57) = -0.23$ $p = 0.08$	$r(55) = -0.29$ $p = 0.03$
Selection	Lag-1 sparing	$r(57) = 0.09$ $p = 0.53$	$r(57) = 0.16$ $p = 0.22$	$r(55) = 0.15$ $p = 0.28$
Modulation	Blink recovery	$r(57) = 0.27$ $p = 0.04^*$	$r(57) = 0.42$ $p = 0.001^*$	$r(55) = 0.38$ $p < 0.01^*$
Vigilance	Vigilance sensitivity	$r(59) = -0.25$ $p = 0.06$	$r(59) = -0.57$ $p < 0.001^*$	$r(57) = -0.54$ $p < 0.001^*$

SD = 14.59%) compared to lag 2 ($t(66) = 7.05$, p < 0.001). Finally, a typical blink recovery was observed with no significant difference between accuracy at lag 5 (M = 88.76%; SD = 11.55%) compared to overall T1 accuracy (M = 90.10%; SD = 5.98%; $t(66) = 1.19$, $p = 0.24$). Following the methods of Cousineau et al. (2006), the average and standard deviation for the blink components were calculated: blink magnitude (M = 0.41; SD = 0.25), lag-1 sparing (M = 0.31; SD = 0.29), and blink recovery (M = 0.07; SD = 0.81).

For the multiple-target search task, there was a typical SSM effect was found with worse low-salience target accuracy after a high-salience target was detected first (i.e., second-target accuracy; M = 67.34%; SD = 21.30%; $t(61) = 4.51$, $p < 0.001$) compared to single, low-salience target accuracy (M = 92.35%; SD = 12.27%; see Fig. 2d). The averages and standard deviations for the multiple-target search characteristics used for the correlations were second-target misses (M = 32.66%; SD = 21.30%) and general search performance (M = 4.41 s; SD = 0.68 s).

For the vigilance task, a typical vigilance effect was found with higher target accuracy in block 1 (M = 78.97%; SD = 22.84%) compared to block 6 (M = 67.73%; SD = 28.46%; t(68) = 4.52 $p < 0.001$; see Fig. 2f). The individual difference measure of d' had a mean of 2.50 with a standard deviation of 1.28.

3.2. Individual difference analyses with attentional characteristics

The crux of the current study was using an individual differences approach to examine which attentional characteristics, if any, relate to the ability to detect second targets in a multiple-target visual search. Critically, the question at hand was about second-target detection and not about general search performance overall. As such, the following analyses looked to reveal any relationships between the attentional characteristics and second-target misses while controlling for general search performance. This was accomplished by using partial correlation analyses to look at relationships with second-target search misses, above and beyond the contributions of general search performance.

Tests of the four partial correlations with second-target misses (accounting for the contribution of general search performance) were conducted using Bonferroni-adjusted alpha levels of 0.0125 per test (0.05/4). The results indicated that modulation ($r(55) = 0.38$, $p < 0.01$) and vigilance ($r(57) = -0.54$, $p < 0.001$) were significant (see Table 1). These partial correlations revealed that worse attentional modulation and vigilance predicted more second-target misses in the multiple-target visual search and limited capacity and selection were not predictive of second-target misses.

4. Discussion

The Resource Depletion account of SSM errors posits that cognitive resources (i.e., attention and working memory) are consumed by a found first target leaving less available to process additional targets (Berbaum et al., 1991; Cain & Mitroff, 2013). So far, research in support of the Resource Depletion account has broadly demonstrated that attention is a main contributor to SSM errors: for example, finding a first target induces an attentional blink for a second target (Adamo et al., 2013) and exacerbates the attentional effects of clutter on second target accuracy (Adamo et al., 2015b). Here, the aim was to better understand which specific characteristics of attention might account for second-target misses in multiple-target search. This experiment investigated four different characteristics of attention (Chun et al., 2011) operationally defined as measures extracted from an attentional blink (AB) task and a vigilance task. The results indicated selection (as defined by lag-1 sparing in the AB task) and limited capacity (as defined by blink magnitude in the AB task) were not predictive of second-target misses. However, worse attentional modulation (as defined as blink recovery in an AB task) and worse vigilance (as defined as sensitivity in a vigilance task) were predictive of more second-target misses. These findings are discussed below in terms of their possible interpretations and their implications for real-world searches.

4.1. Non-significant correlations for lag-1 sparing (selection) and blink magnitude (limited capacity)

The current results suggested that lag-1 sparing and blink depth (i.e., limited capacity and attentional selection, respectively) were not predictive of second-target misses. At first, this might seem surprising given that previous research demonstrated that lag-1 sparing and an attentional blink were found to underlie SSM errors (Adamo et al., 2013). However, given that lag-1 sparing and the attentional blink only accounted for a relatively small amount of the total variance in second-target misses, it makes sense that current results were not significant. Specifically, the results of Adamo et al. (2013) showed that lag-1 sparing and the attentional blink only accounted for SSM errors when a second target was fixated 0–405 ms after a first target was fixated (the timeframe in which lag-1 sparing and the attentional blink typically occur), which is likely why no relationship was found in the current dataset.

4.2. Attentional blink recovery (modulation)

While there are many differences between a typical AB task and a multiple-target visual search task (e.g., search items that are displayed in the same place one at a time vs. spatially distributed search items that are all displayed at the same time), the relationship between blink recovery and second-target misses suggests that SSM errors are likely due, in part, to the ongoing processing of a first target. Since the width of the blink represents how long the processing of a first target within working memory impacts the detection of a second target (e.g., Bowman & Wyble, 2007;

Chun & Potter, 1995), this reinforces the prediction of the resource depletion theory (Berbaum et al., 1991; Cain & Mitroff, 2013)—a found first target is a highly potent distractor that can consume cognitive resources necessary to find additional targets throughout the duration of search (Cain & Mitroff, 2013; Cain et al., 2014).

4.3. Vigilance (vigilance sensitivity)

The results also indicated that when observers were in a less vigilant state, they were more prone to missing a second target. A reason for why poorer vigilance relates to more second-target misses in the current study can be found from research in support of the Mental Fatigue account of vigilance (also known as the "Resource account"; e.g., Helton & Russell, 2011; Parasuraman, Warm, & Dember, 1987; Warm et al., 2008). The Mental Fatigue account proposes that there is a limited amount of cognitive resources available and that they need to be replenished when used. However, when there is continuous demand for these cognitive resources, such as in vigilance tasks (e.g., continuous signal-to-noise discrimination tasks), these cognitive resources are utilized at a faster rate than they can be replenished. Hence, there is a diminished pool of cognitive resources, which results in a decline in performance found in vigilance tasks.

A study in support of the Mental Fatigue account demonstrated that the pool of attentional resources needed for vigilance tasks can also be diminished by holding items in working memory (Helton & Russell, 2011). By having observers complete a spatial working memory task (i.e., remembering where items are located on the screen) intermixed with a vigilance task (the same vigilance task used in the current study; Temple et al., 2000), observers showed a greater decline in vigilance and spatial memory over time, in comparison to a control condition where these tasks were not intermixed. This finding suggests that the processing of an item in working memory and attentional vigilance draw on the same pool of cognitive resources and are detrimental to one another when performed in conjunction. When an item is processed within working memory, this leaves fewer attentional resources available for a vigilance task and when attentional resources are replenished at slower rate, because of a vigilance task, there are fewer resources available to process and item in working memory.

Extrapolating the Mental Fatigue account and Helton & Russel's (2011) results to the vigilance finding of the current study, it suggests that fewer attentional resources were available to process a second target. The combination of processing a first target in working memory (i.e., modulation) and a slower replenishing of resources over time (i.e., vigilance) resulted in fewer attentional resources available to detect and process a second target. This proposed explanation speaks towards the overlap between the attentional characteristics and how the taxing effects on one characteristic of attention can impact another.

4.4. Future work

The current study was primarily focused on correlational relationships between multiple-target search errors and attentional components. Several insights were found, but much more is left to discover. For example, correlations do not speak to causation and the mechanistic directions of the relationships. It would be theoretically interesting to conduct an intervention study where vigilance was systematically manipulated (i.e., depleted) and measure potential effects on multiple-target visual search performance. Likewise, and as highlighted in the above example, there is potential ambiguity about whether the current results are necessarily tapping into "individual differences" measures. For example, vigilance can be a trait or state attribute, and the current study primarily treats it as a stable individual difference trait. However, it is also possible that there could be a contribution of state attributes as well. An interesting extension of the study would be to test the same individuals multiple times to assess the stability of the various attentional measures.

4.5. Real-world implications

Going beyond the theoretical accounts linking modulation and vigilance to second-target misses, the results from the current study may also help to explain why certain visual search techniques may improve target detection in real-world searches. For example, a common practice in airport security screening is to remove a prohibited item (if detected) in a carry-on bag and re-search the bag (Biggs & Mitroff, 2014). This technique has been shown to decrease the amount of SSM errors made in multiple-target searches similar to the one conducted in the current study (Cain & Mitroff, 2013; Cain et al., 2014). The correlation between modulation and second-target misses found in the current study may help to explain why this technique is effective in reducing SSM errors. Removing a found target would effectively result in no modulation of a first target and free up attentional resources that can then be utilized for detecting an additional target.

5. Conclusion

To summarize, the current study investigated a proposed cause of SSM errors: attentional resources are consumed by a first target leaving less available to process additional targets. The goal of this study was to better understand how attention is affected after detecting a first target by identifying which characteristics of attention related to second-target misses. The results demonstrated that attentional modulation (as operationally defined by blink recovery in an AB task) and vigilance (as operationally defined by target sensitivity in a vigilance task) related to second-target misses.

The finding that worse attentional modulation correlated with second-target misses suggests that SSM errors occur, in part, because once a first target is found, the first target is continually processed after initial detection (i.e., attentional modulation) leaving fewer attentional resources available to detect a second target. Previous studies alluded to this finding by removing a first target and observing an improvement in second target detection (Cain & Mitroff, 2013; Cain et al., 2014). The present study provided corroborating evidence to this prediction and did so not by experimental manipulation (e.g., by removing a found target), but by exploring individual differences of the observer. Also, by defining modulation as blink recovery in an AB task, these results demonstrated the importance of exploring this often unreported measure in the AB literature. With regards to this study, blink recovery was quite informative in terms of how observers process a found target and its implications for other visually demanding tasks.

The finding that poor vigilance was predictive of second-target misses implies that when the attentional system is busy processing a first target the deleterious effects of vigilance are compounded in terms of processing additional targets within the visual environment. Previous research exploring the underlying mechanisms of vigilance has suggested that attentional resources needed for vigilance tasks can also be diminished by the processing of other items (Helton & Russell, 2011). The current results bolstered this finding by demonstrating how the processing of a first target in combination with poor vigilance can be predictive of more second-target misses in a multiple-target visual search.

Overall, exploring individual differences proved to be a fruitful method in helping to identify the underlying mechanisms of SSM errors. Theoretically, the results of the current study suggest that attention plays a key role in second-target misses and provides additional support for the Resource Depletion account of SSM errors. Beyond the theoretical implications, the knowledge gained from this study can help us better understand why current and future protocols used for improving target detection may or may not be effective. SSM errors are known to occur in critical, real-world searches and by studying the underlying mechanisms to why observers miss a second target, we better understand how to eradicate the problem of SSM errors.

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