Grabbing Your Attention: The Impact of Finding a First Target in Multiple-Target Search

by

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Dissertation submitted in partial fulfillment
of the requirements for the degree of Doctor of Philosophy in the Department of
Psychology and Neuroscience in the Graduate School
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ABSTRACT

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Abstract

For over 50 years, the Satisfaction of Search effect, and more recently known as the Subsequent Search Miss (SSM) effect, has plagued the field of radiology. Defined as a decrease in additional target accuracy after detecting a prior target in a visual search, SSM errors are known to underlie both real-world search errors (e.g., a radiologist is more likely to miss a tumor if a different tumor was previously detected) and more simplified, lab-based search errors (e.g., an observer is more likely to miss a target 'T' if a different target 'T' was previously detected). Unfortunately, little was known about this phenomenon's cognitive underpinnings and SSM errors have proven difficult to eliminate. However, more recently, experimental research has provided evidence for three different theories of SSM errors: the Satisfaction account, the Perceptual Set account, and the Resource Depletion account. A series of studies examined performance in a multiple-target visual search and aimed to provide support for the Resource Depletion account—a first target consumes attentional and working memory resources leaving less available to process additional targets.

To assess a potential mechanism underlying SSM errors, eye movements were recorded in a multiple-target visual search and were used to explore whether a first target may result in an immediate decrease in second-target accuracy, which is known as an attentional blink. To determine whether known attentional distractions amplified the effects of finding a first target has on second-target detection, distractors within the immediate vicinity of the targets (i.e., clutter) were measured and compared to that respective target's accuracy. To better understand which characteristics of attention were impacted by detecting a first target, individual differences within four characteristics of attention were compared to second-target misses in a multiple-target visual search.

The results demonstrated that an attentional blink underlies SSM errors with a decrease in second-target accuracy from 135ms-405ms after detecting or re-fixating a first target. The effects of clutter were exacerbated after finding a first target causing a greater decrease in second-target accuracy as clutter increased around a second-target. The attentional characteristics of modulation and vigilance were correlated with second-target misses, in that worse attentional modulation and vigilance were predictive of more second-target misses. Taken together, these results are used as the foundation to support a new theory of SSM errors, the Flux Capacitor theory. The Flux Capacitor theory predicts that once a target is found, it is maintained as an attentional template in working memory, which consumes working memory resources that could otherwise be used as attentional resources to detect additional targets. This theory not only proposes why attentional resources are consumed by a first target, but encompasses the research in support of all three SSM theories in an effort to establish a grand, unified theory of SSM errors.

Dedication

I would like to dedicate this dissertation to Dr. Jake Jacobs. Without you, I never would have realized that research was my calling. Thank you for encouraging me to be creative when it comes to learning and research. Most importantly, thank you for teaching me not to believe or disbelieve.

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1. Introduction

Every day, we encounter a seemingly limitless amount of visual information presented in both space and time. Unfortunately, it is impossible to process it all, as the visual system relies on attention to aid in our perception and process objects in our surroundings (e.g., Posner, 1980). To better understand the role of attention in visual processing, two components of attention must be described. First, attention is limited in its processing abilities. When an element within the visual world is being processed, the processing of other elements may suffer (e.g., Raymond, Shapiro, & Arnell, 1992). Second, due to this limitation, the visual system must use attention to select when and where to process objects within the visual environment (e.g., Klein & Ishigami, 2012). The role of attention within visual perception is to select which objects within the visual world receive further processing, and the "how" and "why" an object is selected is a key interest for vision researchers.

One way in which attention and object selection is investigated is by studying visual search, the process of looking for targets among distractors (e.g., Treisman & Gelade, 1980). Visual search is a core skill for everyday life. In prehistoric times, visual search was critical for survival as our ancestors scouted for animals and collected berries for food. In modern day, searches can be as mundane as looking for a car in a crowded parking lot or searching for milk in the refrigerator. Beyond these mundane, everyday activities, visual search is still an especially important aspect of many life-saving professions; radiologists look for tumors in x-rays and baggage screeners search for bombs and guns in carry-on bags.

Much has been learned about attention and the processing of objects by studying visual searches that contain a single target. For example, detection of a target may be easier or more difficult depending on: 1) which visual features (e.g., color and shape) distinguishes a target from distractors within a visual search display (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980), how often a target is present across many visual search displays (e.g., Mitroff & Biggs, 2014; Wolfe, Horowitz, Van Wert & Kenner, 1997), and the amount of visual information presented within the visual search display (e.g., Rosenholtz, Li, Nakano, 2007). While single-target visual searches are a well-researched paradigm (see Eckstein, 2011; Nakayama & Martini, 2011 for a review) and much has been learned about how a target's location is selected within the search environment (e.g., Olivers, Peters, Houtkamp, & Roelsfema, 2011; Treisman, 1991; Wolfe, 1994), much less is known about multiple-target visual searches, where more than one target may be present within a search display. Unfortunately, searching for multiple targets consistently gives rise to a specific error in target detection as observers are more likely to miss a target if one was already detected (Tuddenham, 1962). This phenomenon, previously known as the Satisfaction of Search effect (Smith, 1967), and recently renamed the Subsequent Search Miss (SSM) effect (Adamo, Cain, & Mitroff, 2013), can be a real problem in the aforementioned professional searches where target detection can be a matter of life-and-death.

SSM errors are a well-known problem within the field of radiology and were first documented over 50 years ago (Tuddenham, 1962; Smith, 1967). They are a serious problem within radiological searches as they can account for up to one-third of some types of errors (Anbari & West, 1997). Because of the life-and-death nature of SSM errors, they have been extensively studied within the field of academic radiology (see Berbaum, 2012 for a review) and more recently in the field of cognitive psychology (e.g., Cain, Dunsmoor, LaBar, & Mitroff, 2011; Cain & Mitroff, 2012; Chan Courtney, & Ma, 2002; Fleck, Samei, & Mitroff, 2010).

SSM errors are found to 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). Due to the prevalence of SSM errors within radiological searches, researchers investigated whether target detection tools, such as contrast-enhanced imaging (Franken et al., 1994) and computer-aided detection (Berbaum et al., 2007), could help alleviate these errors. In comparison to plain film radiographs where an x-ray is used to investigate the area of interest, contrast-enhanced images utilize previously injected dyes in patients to help reveal, via contrast, areas more likely to contain possible abnormalities. Researchers demonstrated that not only did the SSM effect remained when searching contrast-enhanced images, it led to more errors than plain-film radiographs (Franken, et al., 1994). It was believed that more SSM errors occurred because attention was drawn to the high-contrast areas thus leaving other, non-contrast areas that contained abnormalities unexplored. Similar to contrast-enhanced imaging, the purpose of computer-aided detection (CAD) is to use technology to help identify abnormalities in x-rays. Unfortunately, researchers found no difference in SSM errors between CAD enhanced images and plain radiographs (Berbaum et al., 2007). Although these findings are problematic for search accuracy, they further emphasize the importance of understanding the mechanism(s) underlying SSM errors. With a better understanding of why they occur, there is a better chance of finding ways to eliminate them.

The search for the cause of SSM errors has been well documented within radiology (e.g., Berbaum et al., 1991; Samuel et al., 1995; Berbaum, 2012) and cognitive psychology (e.g., Adamo, Cain, & Mitroff, 2015a; Biggs, Adamo, Dowd, & Mitroff, 2015; Cain & Mitroff, 2011). Currently, there are three theories that predict why SSM errors arise in multiple-target searches: the Satisfaction account, the Perceptual Set account, and the Resource Depletion account.

Below, I will present the predictions and research pertaining to each SSM theory. Specifically, in the following two sections, I will speak about my research that supported the predictions of the Satisfaction and Perceptual set account, as the findings will be relevant for a new theory I propose in the *General Discussion* (Chapter 5) of this dissertation. After I discuss each theory individually, in the *Eye movements and SSM errors* section, I will present eye-tracking research that explored the types of errors made when searching for multiple-targets. Finally, I will summarize the support for each theory and discuss the following chapters of this dissertation.

1.1. The Satisfaction account

In the 1960s, radiological researchers exploring SSM errors, then known as Satisfaction of Search errors, believed additional target(s) were missed because observers would become "satisfied" with the meaning of the search display after finding a first target causing them to stop searching without viewing the entire image (Tuddenham, 1962; Smith, 1967). Since then, the Satisfaction account has been explored in many different ways with mixed findings (Adamo, et al., 2015a; Berbaum et al., 1991; Cain, Adamo, & Mitroff, 2013; Samuel, et al., 1995).

Initially, research exploring the Satisfaction account evaluated the time in search on single- and multiple-target search displays (Berbaum et al., 1991). It was predicted that if observers were "satisfied", they would terminate their search after finding a first target causing them to miss a second target in multiple-target searches. On average, observers searched for the same amount of time regardless of how many targets were in the search display. This provided some of the first evidence against the Satisfaction account as there was no difference in search time between single- and multiple-target searches. Building off of this research, Cain et al., (2013) used a different approach by recording eye movements and examining whether observers quit searching (i.e., made no additional eye movements to other items in search) after finding a first target. Again, there was little evidence for the Satisfaction account as observers rarely terminated search immediately after finding a first target.

The first evidence strongly in support of the Satisfaction account was found using an individual difference approach and analyzed the time between an observer finding a first target and terminating search on their own volition without finding a second target (i.e., the first-to-done time; Adamo et al., 2015a). The first-to-done times were then compared with the total amount of SSM errors each observer made with the prediction that the less time observers searched for after finding a first target, the more SSM errors observers would make. An individual difference approach proved fruitful as observers who had shorter first-to-done times committed more SSM errors (See Figure 1). This relationship was significant, even when accounting for variation in the observers' attentional vigilance. In other words, when observers searched for a longer period of time after finding a first target, fewer SSM errors would be made, even when accounting for how vigilant observers were.

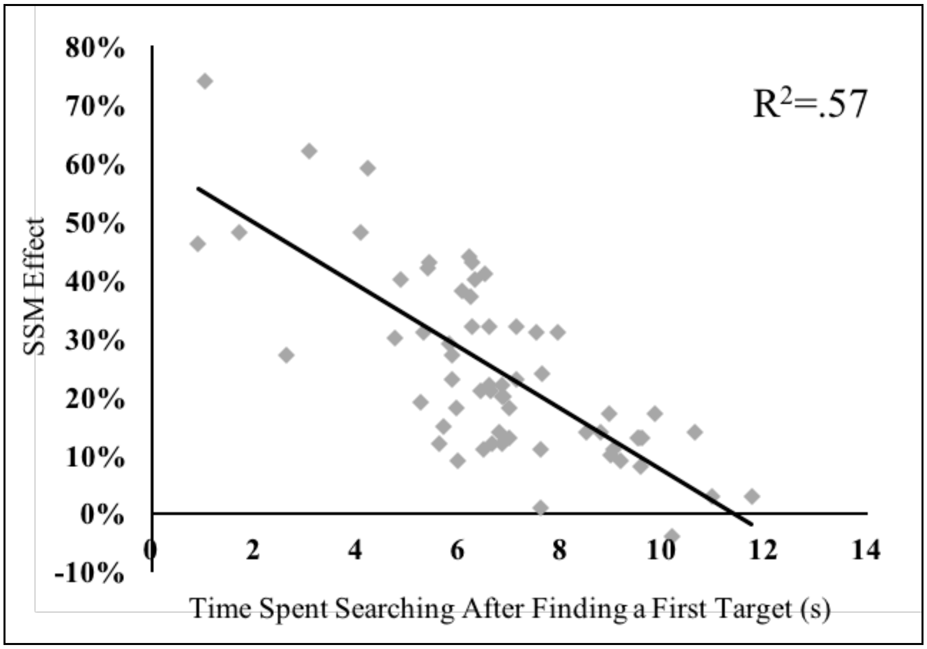

Figure 1: Satisfaction Graph. A graph depicting the correlation between the average SSM effect and the time spent searching, in seconds, after finding a first target on trials in which no second target was detected. This correlation suggests that less time spent searching after finding a first target is predictive of a larger SSM effect for a second target. The R^2 represents the goodness of fit of the model.

1.2. The Perceptual Set account

According to the Perceptual Set account, once a target is found (e.g., a bone fracture), observers are subsequently more likely to find perceptually similar targets (e.g., another fracture) and less likely to find perceptually dissimilar targets (e.g., a tumor; Berbaum et al., 1991). In other words, once an observer finds a target, they are more likely to find targets with similar characteristics and consequently more likely to miss targets with dissimilar characteristics.

Searching for multiple types of targets has a long history in cognitive psychology outside the study of SSM errors (e.g., Godwin, Menneer, Cave, Helman, Way, & Donnelly, 2010; Menneer, Cave, & Donnelly, 2009; Menneer, Donnelly, Godwin, & Cave, 2010; Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011). While most of these studies were restricted to single-target visual searches, searching for multiple types of targets has a clear, negative impact on search performance in terms of both reaction time and accuracy. For relatively simple searches, reaction times were slower and accuracy is worse when searching for multiple-target types(e.g., two colors) in comparison to searching for a single-target type (e.g., one color; Menneer et al., 2007). The pattern of worse performance when searching for multiple-target types was even found in more complex searches (i.e., x-rays with either bomb targets, gun targets, or both targets) providing evidence that searching for multiple-target types has real-world implications beyond simple search displays (Godwin, et al., 2010). While the research in multiple-target type, single-target visual searches does not speak directly to SSM errors, it is clear that having to searching for multiple-target types negatively impacts search performance.

In multiple-target searches, radiological studies have garnered some evidence for the Perceptual Set account (e.g., Berbaum et al., 1991; Berbaum et al., 2000). For example, in multiple-trauma x-rays, where one type of fracture is more obvious than another, the detection of the less obvious fracture was prone to SSM errors (Berbaum et al., 2000). According to the Perceptual Set account, it could be interpreted that a perceptual set was created for the more obvious types of fractures thereby priming observers to scan for that target type. Likewise, cognitive psychology studies have found some evidence consistent with the Perceptual Set account. Observers were more likely to miss a low-salience target after finding a high-salience target (Fleck et al., 2010). However, in the same study, a SSM effect was also found when observers searched for multiple targets of the same salience, suggesting that the Perceptual Set account cannot be the sole explanation of SSM errors. Similarly, Cain et al. (2013) explored the Perceptual Set account in terms of whether both targets had the same rotation (e.g., both targets were rotated 90 degrees to the right) or different rotations (e.g., one target was rotated 90 degrees to the right and the other target was rotated 270 degrees to the right) and found no difference in SSM errors.

To date, my colleagues and I provided the strongest evidence for the Perceptual Set account by using a wide array of targets with many different characteristics that could be explored (i.e., akin to how baggage screening personnel search for many different types of dangerous items in carry-on bags; Biggs et al., 2015). Unlike previous studies that had a limited number of possible target types and explored whether targets were similar or dissimilar based off of one characteristic (e.g., whether the targets were the same rotation or not; Cain et al., 2013), Biggs et al., (2015) explored similarities in three different ways: 1) When two targets were identical in search, 2) when two targets were perceptually related (i.e., the same color), and 3) when two targets were conceptually related (i.e., they belonged to either the same "bomb" category or the same "gun" category; see Figure 2). The results demonstrated that the likelihood of detecting a second target increased if they were identical, the same color, and of the same category. These results suggest that when there are multiple-target types and the observer does not explicitly know which item(s) will be the target of search, a found target can create a bias for the next target.

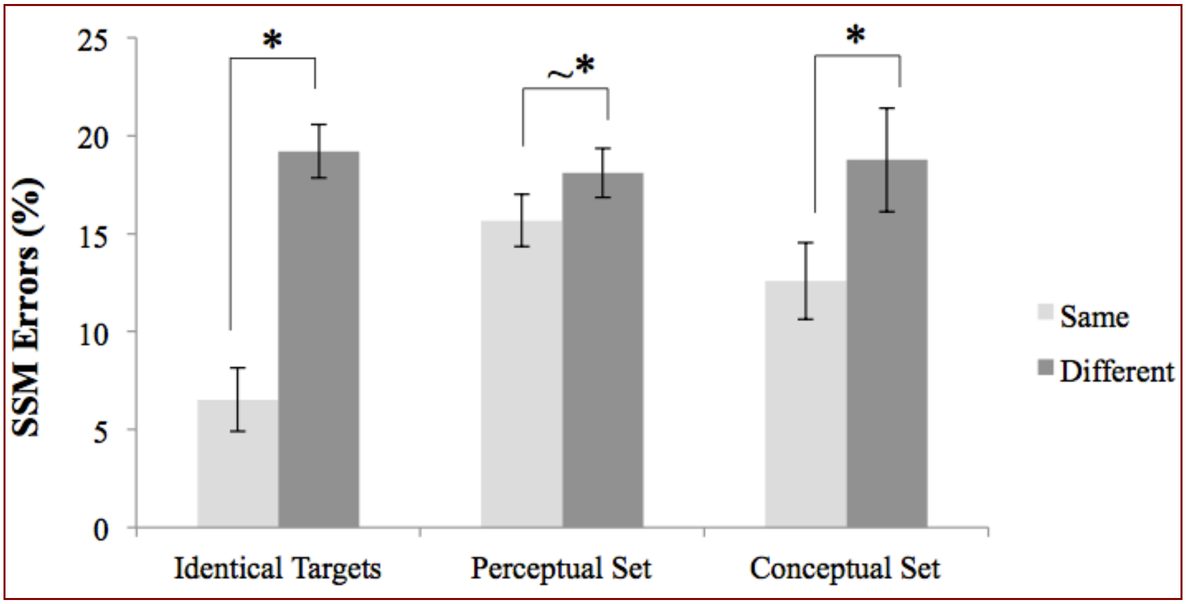

Figure 2: The percentage of SSM errors categorized by whether both targets in the search display were of the "same" type or of a "different" type across the three specific analyses. *Identical targets* represent the analysis in which the first and second targets were either the exact same item or were different items. *Perceptual set* represents the analysis in which the first and second target shared the same color or were different colors (blue and pink targets), while controlling for the conceptual relationship between targets. *Conceptual set* represent the analysis in which the first and second targets were conceptually related (e.g., were both gun related items) or were not conceptually related (e.g., one target was a gun related item and the other was a bomb related item) while controlling for their perceptual similarity. The asterisks represent *p*<.01, The combined tilde and asterisk represent *p*=.06. A subsequent analysis (not discussed here) found a significant perceptual set (*p*<.001) effect using a wider range of colors (see Biggs et al., 2015).

1.3. The Resource Depletion account

According to the original Resource Depletion account, SSM errors were predicted to occur because a found target captures attention leaving less available to process a second target (e.g., Berbaum et al. 1991). Expanding off this theory, Cain & Mitroff (2013) proposed an addition to the Resource Depletion account as they found evidence suggesting that the depletion of working memory resources are another potential reason for SSM errors. When removing a first target immediately after detection, there was a decrease in the amount of SSM errors made in comparison to when the first target remained after detection. Similarly, it was found that if the search ended immediately after finding the first target and the same display was later repeated without the first target, there was a decrease in the amount of SSM errors committed for a second target (Cain, Biggs, Darling, & Mitroff, 2014). Together these results suggest that working memory plays a role in SSM errors, in that working memory resources are consumed by a first target after initial detection, but these resources can be freed up if a first target is forgotten by removing it from the search display.

A working memory explanation of SSM errors is supported by cognitive psychology research that has explored working memory in single-target and multiple-target visual searches. Although some argue that visual search requires no working memory (Horowitz & Wolfe, 1998; Horowitz & Wolfe, 2001), alternative research suggests that working memory stores both the featural and spatial aspects of items within a visual search display (e.g., Beck, Peterson, & Vomica 2006; Hollinghowrth, Williams, & Henderson, 2001; Peterson, Kramer, Wang, Irwin, & McCarley, 2001;

Takeda, 2004; Woodman & Chun, 2006). For example, by investigating the eye tracking metrics of a multiple-target search, it has been found that a first target is likely consuming working memory resources (e.g., Körner & Gilchrist, 2008; Takeda, 2004). Körner & Gilchrist (2008) found that observers ere slower and less efficient in dual-target searches compared to single-target searches. This finding was credited to more distractor re-fixations in the dual-target condition suggesting a first target consumes memory resources thereby making it more difficult to remember items that had been previously searched. Similarly, Cain et al. (2013) found that re-fixations of an already found target correlated with higher SSM errors. This result suggests that the tagging of targets and distractors may call on a common memory resource that is consumed once the first target is found.

Interestingly, while there is evidence for working memory of search items in single and multiple-target searches, there is little direct evidence to support the prediction that attention allocated to the first target can lead to SSM errors, as was originally predicted by the Resource Depletion account (Berbaum et al., 1991).[1] The core focus of this dissertation is to provide evidence that attention allocated to a first target

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[1] Although the dichotomy between working memory and attention is a hotly debated issue, I will use the term attention when discussing the "resource" used to detect targets. However, it has been argued that working memory and attention should not be considered completely separate constructs as they both rely on one another and rely on the same limited resource (e.g., Kiyonaga & Egner, 2013). This is also my view on the attention/working memory debate and I will discuss this in depth in Chapter 5 when presenting a unified theory for SSM errors.

can lead to SSM errors. However, before I present the evidence to support this prediction (i.e., the following chapters), the research on eye movements and SSM errors should be discussed. This research is critical in providing further insight to the three theoretical accounts of SSM in addition to supporting the predictions of a new theory of SSM errors presented in Chapter 5.

1.4. Eye movements and SSM errors

Converging evidence from eye tracking studies have offered insight in support of the multiple theoretical accounts of SSM errors. Previous work in radiology, initially outside the study of SSM errors, utilized eye tracking to break down visual search misses into three different types of errors: sampling errors, recognition errors, and decision-making errors (e.g., Nodine & Kundel, 1987). Below I present each type of error and discuss which theoretical account they offer support for.

1.4.1. Sampling errors

Sampling errors are categorized as a situation when a target is never fixated. While they do not appear to be a significant contributor to SSM errors in certain radiological scans (accounting for 8% of the total SSM errors; Samuel et al., 1995), they can account for the majority of SSM errors in multiple-target searches in cognitive psychology paradigms (55.2% of total SSM errors; Cain et al., 2013). These types of errors may speak to the Satisfaction account, in that observers are less likely to fixate on a second target if they terminate search quickly after identifying a first target (Adamo et al., 2015a). Sampling errors may also support the Resource Depletion account, in that a depletion of cognitive resources may lead observers to dismiss the area where the target is located. It has been demonstrated that when working memory resources are consumed by a found target, there is a diminished ability to take up information in the periphery (Chan & Courtney, 1995; Takeda, 2004). These findings suggest that once a target is found in a multiple-target search, there could be a narrowing of the perceptual span (i.e., the amount of visual information that can be taken in the periphery) increasing the likelihood of committing a SSM error. While it is speculative that scanning errors support the Resource Depletion account, perceptual recognition and decision-making errors provide additional evidence for the Resource Depletion account.

1.4.2. Perceptual recognition and decision making errors

According to Nodine & Kundel (1987) perceptual recognition errors are categorized as as situation where a target is fixated, but not for long enough to make a conscious decision about whether the fixated item is a target. In contrast, decision-making errors are categorized as a fixation that is long enough to make a conscious decision about a target, but ultimately an observer still rejects the fixated item as a target.[2] In general, these errors are considered as situations where the target is fixated, but not detected, and appear to account for the majority of SSM errors in radiology (e.g., Berbaum et al., 2000; 2001; Samuel et al., 1995. For example, Samuel et al., (1995) found that about 90% missed targets were fixated and there was a 20% increase in perceptual recognition errors in multiple-target searches compared to single-target searches. SSM errors have even been shown to be exclusively perceptual and decision-making errors when the first target is of great clinical significance (e.g., a major fracture in an x-ray; Berbaum et al., 2001).

Research in cognitive psychology has also demonstrated that around 20% of SSM errors are due to perceptual recognition and decision making errors, in that after a first target was found, a second target was fixated, but not detected (Cain et al., 2013). These types of errors broadly support the Resource Depletion account stating that if a first target is consuming valuable attentional and working memory resources, less resources are available to process a second target to conscious awareness.

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[2] Unfortunately, the distinction between perceptual and decision making errors is not clear. In radiological x-rays a single, temporal threshold for classifying perceptual recognition vs. decision-making errors is difficult to deduce since different abnormalities require different dwell times (e.g., Berbaum, 2012). This suggests the possibility that some SSM errors are not actually caused by faulty decision-making, but are actually perceptual recognition errors.

1.5. Summary of introduction

By reviewing the SSM literature, a few trends emerge. First, SSM errors prevail among different types of searches: both in radiological searches (e.g., Berbaum et al., 1994; 1998; Franken et al., 1994; Samuel, et al., 1995) and cognitive psychology paradigms (e.g., Adamo et al., 2015a; Biggs et al., 2015; Cain & Mitroff, 2013; Fleck et al., 2010). Second, they are difficult to eliminate even with technological advances that aid target detection (Berbaum et al., 2007; Franken et al., 1994). Third, there are varying levels of support for the three theoretical accounts of SSM errors: the Satisfaction account, the Perceptual Set account, and the Resource Depletion account. Evidence against the Satisfaction account demonstrate that observers rarely terminate search *immediately* after finding a first target (e.g., Berbaum et al., 1991; Cain et al., 2013). However, the evidence in support of the Satisfaction account demonstrate that observers terminating search *quicker* after finding a first target are more likely to commit SSM errors in multiple-target search (Adamo et al., 2015). Converging evidence from eye tracking in support of the Satisfaction account suggest that a large number of SSM errors are due to observers never fixating a second target after finding a first target (Cain et al., 2013), which may be due to observers terminating search prematurely before they encounter a second target.

Similar to the Satisfaction account, evidence for the Perceptual Set account is mixed. On one hand, observers commit SSM errors regardless of whether targets are similar or different in salience (Fleck, Samei, & Mitroff, 2010) or rotation (e.g., Cain et al., 2013). On the other hand, when SSM errors were assessed in a visual search environment that contained many different target possibilities, a second target is more likely to be detected if identical, perceptually related (i.e., the same color), or conceptually related (i.e., the same category) to the first target (Biggs et al., 2015).

Finally, there is some evidence for the Resource depletion account, suggesting that working memory resources can be consumed by a first target leaving less available to process a second target (e.g., Cain & Mitroff, 2013). Converging evidence from eye tracking studies demonstrate that a large proportion of SSM errors occur when the second target is fixated, but not consciously detected. These errors are predicted to represent Resource Depletion errors. Despite this evidence, research to date has not directly demonstrated the role attention plays within SSM errors. This is surprising as it was initially predicted in the Resource Depletion account that a first target consumes attentional resources leaving less available to process an additional target (Berbaum et al., 1991).

1.6. Overview of this dissertation

In the following chapters, three experiments focusing on the Resource Depletion account and the role attention has on SSM errors are presented. These experiments examine attention on three different levels: 1) the target-to-target relationship, 2) distractor-to-target relationship, and 3) the observer-to-target relationship. Specifically, in Chapter 2 (Adamo, et al., 2013), the relationship between a first and second target under the lens of a well-known cognitive psychology paradigm, known as the attentional blink, is examined. An attentional blink paradigm is characterized by an immediate decrease in second-target accuracy after correctly detecting a first target (Raymond, Shapiro, & Arnell, 1992). The attentional blink is largely believed to occur when attentional resources are consumed by a first target which subsequently interferes with the processing of a second target (see Dux & Marois, 2009 for a review of attentional blink theory). This chapter demonstrates some of the first evidence of a potential mechanism underlying SSM errors that accounts for why attentional consumption by a first target can contribute to SSM errors. In Chapter 3 (Adamo et al., 2015), clutter is explored as a potential attentional distraction that can impact SSM errors. Specifically, it will be demonstrated that clutter, distractors within the immediate vicinity of a target, can affect second-target detection. This study further suggests that a first target consumes attentional resources and consequently amplifies the effects clutter has on second-target processing. In Chapter 4 (Adamo, Cain, & Mitroff, 2016), I examine the relationship between second-target misses and individual differences in four different characteristics of attention: attentional capacity, selectivity, modulation. The findings of this research provide additional evidence that attentional allocation to a target may impede second-target detection and determines that the characteristics of attentional modulation and vigilance strongly relate to second-target misses.

In Chapter 5, the Resource Depletion theory is revisited and the different ways attentional allocation to a first target results in SSM errors are summarized. Then, a new theory, the Flux Capacitor theory, is proposed to account for the findings of this dissertation and encompass all the findings in support of the Satisfaction account, the Perceptual Set account, and the Resource Depletion account. Throughout the bulk of my PhD, I have been fascinated by SSM errors and wanted to create an all-encompassing theory that could predict when and why SSM errors occur. While this theory is partially based on existing research (i.e., the bulk of the research on SSM errors) and part conjecture, my intentions for presenting this new theory is to propose a mechanism that underlies all SSM errors and make specific predictions that future research can build upon.

2. Self-Induced Attentional Blink: A Cause of Errors in Multiple-Target Search

2.1. Introduction

Visual search, the process of looking for targets among distractors, is an everyday activity (e.g., looking for one's keys) and is vital for many lifesaving jobs (e.g., radiology, baggage screening). Although participants in laboratory-based visual-search tasks typically search for a single target, many real-world searches can contain multiple targets; for example, a radiograph could contain both a tumor and a fracture, and an airport luggage X-ray could contain both a water bottle and a gun. Unfortunately, multiple-target searches are especially error prone—after a first target has been found, subsequent targets are less likely to be detected (Tuddenham, 1962). This pervasive form of error, known as *satisfaction of search* (SOS; Smith, 1967), has been studied in academic radiology for over 50 years (Berbaum, 2012), but SOS nonetheless remains problematic, proving difficult to eliminate and accounting for one third of radiological misses under certain conditions (Anbari & West, 1997). Although the primary focus of SOS studies has been with radiologists and the use of medical images, recent evidence has shown that SOS errors occur for non-expert populations using simplified displays (e.g., Fleck, Samei, & Mitroff, 2010).

SOS errors originally were believed to occur as a result of searchers' prematurely ending their search once they became "satisfied" after finding a target (Tuddenham, 1962). However, much more is at play (Berbaum, 2012), which makes the term *satisfaction* outdated and, unfortunately, misleading. Alternative theories have been proposed to address the fact that searchers do not generally display a "satisfaction" search pattern; instead, they tend to scan displays for the same amount of time regardless of whether one or multiple targets are present (e.g., Berbaum et al., 1991). According to the perceptual-set theory, after a target (e.g., a bone fracture) is found, searchers are subsequently more likely to search for targets that are perceptually similar to the first target (e.g., another fracture) and less likely to find targets that are perceptually dissimilar (e.g., a tumor; Berbaum et al., 1991). Fleck et al. (2010) provided mixed support for this theory and suggested that perceptual-set theory cannot fully explain SOS. More recent evidence has supported a resource-depletion theory, which posits that the locations and identities of found targets stored in working memory consume cognitive resources that would otherwise aid subsequent search (Cain & Mitroff, 2012).

Given that SOS errors are largely not due to satisfaction-related mechanisms, the term *satisfaction of search* is a misnomer. For this reason, we propose a new name—*subsequent search misses* (SSM). The primary goal of introducing the new name is to minimize confusion over the now outdated and theoretically confusing SOS label.

When one considers the nature of the SSM effect, it is intriguing to note that it bears a striking resemblance to the temporal-search phenomenon known as the *attentional blink* (AB; Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). In a typical AB paradigm, stimuli are presented in a rapid-serial-visual-presentation (RSVP) stream wherein items are briefly displayed one at a time and observers report how many or which predefined targets were present in the stream. An AB is a decrease in accuracy for detecting a second target (T2) presented approximately 200 to 500 ms after a correctly detected first target (T1). Theoretically, the SSM resource-depletion theory (Cain & Mitroff, 2012) is similar to a potential explanation of the AB: An AB may reflect a failure in late-stage processing (e.g., selective attention, working memory) wherein resources dedicated to processing T1 are not available to fully process T2 (e.g., Chun & Potter, 1995; Jolicœur, 1998). For example, the more difficult it is to process T1 (i.e., the more cognitive resources needed), the bigger the AB (e.g., Visser, 2007).

Although there are obvious differences in the methods used to reveal typical AB and SSM effects (e.g., quick onset and offset of items vs. all items remaining on the screen, visual masking vs. no visual masking), both are fundamentally focused on the same phenomenon—failing to detect T2 after finding T1. Is it possible that the AB and SSM phenomena are mechanistically related and that an "AB-like" effect can, at least partially, underlie SSM errors?

2.2. *Methods*

2.2.1. Participants

Thirty-four members of the Duke University community participated in return for course credit or $10. Six participants' data were removed: We excluded data from 1 participant for having a false-alarm rate higher than 20%, from 2 participants for having high error rates (missing more than 15% of the high-salience targets), and from 3 participants for having time-out rates higher than 20%. The final sample consisted of 28 participants (17 females and 11 males; mean age = 19.5 years; *SD* = 1.6).

2.2.2. Stimuli and apparatus

On each trial, one or two target T shapes were presented among distractor L shapes on a white background. Targets and distractors were formed by pairs of perpendicular rectangles and were either perfectly aligned (creating T-shaped targets) or slightly offset (creating L-shaped distractors). Half of the targets were high salience (57%–65% black) and half were low salience (22%–45% black), and 95% of the distractors were low salience (see Fig. 3a for a sample stimulus display). There were 25 items (each 1.3°x 1.3°) per display. Participants sat 57 cm from a 17-in. LCD monitor with their heads supported in a chin rest. Eye movements were tracked using a Tobii 1750, 50-Hz infrared-illuminated video eye tracker. Stimuli were displayed in MATLAB via Psychtoolbox-3 (Kleiner, Brainard, & Pelli, 2007).

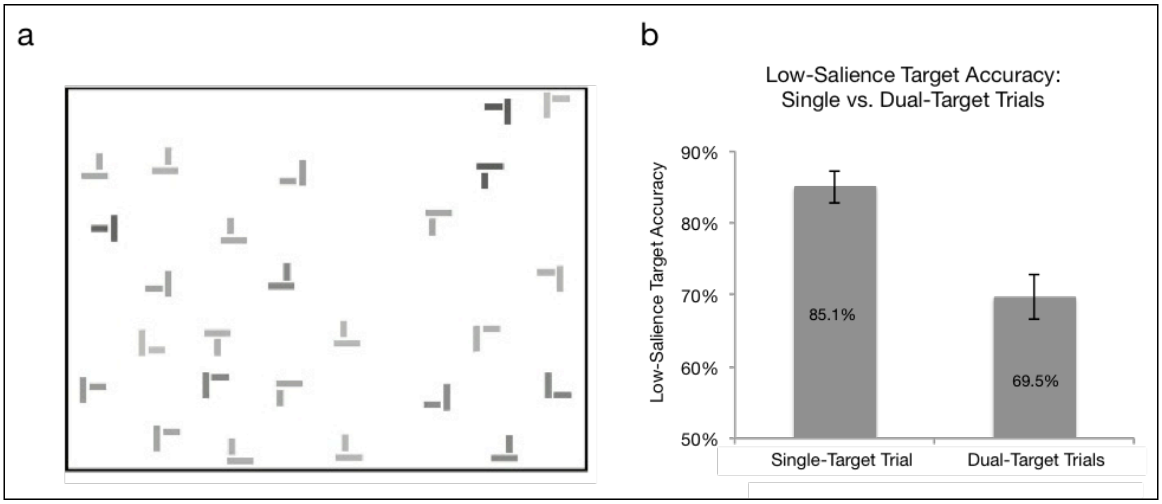

Figure 3: Example stimulus display and results from the visual-search task. The stimulus display (a) contains a high- and a low-salience T-shaped target among the L-shaped distractors. The graph (b) shows accuracy at detecting low-salience targets as a function of trial type (single-target trials vs. dual-target trials in which the high-salience target was identified before the low-salience target). Error bars represent standard errors across all participants.

2.2.3. Procedure

Of the trials, 10% included one high-salience target, 10% included one low-salience target, and 80% included both a high- and a low-salience target.

This ratio was used to create a high volume of dual-target trials for the eye-tracking analyses. Participants were instructed that they had 15 s to search and that there would always be one or two targets per trial. If they reached the 15 s time limit, this was considered a timeout. Participants used a mouse click to indicate the location of each target they found (a blue unfilled circle 0.3° in diameter appeared after every click) and terminated their search by pressing the space bar. There were 25 practice trials with accuracy feedback followed by 250 experimental trials with no feedback.

2.2.4. Data preparations and planned analyses

SSM errors were calculated as the difference in accuracy at detecting low-salience targets on single-target trials and on dual-target trials in which the high-salience target was located first (e.g., Cain & Mitroff, 2012). The AB-like analyses focused strictly on the dual-target trials (80% of the total trials). All data were filtered in two ways. First, trials that contained mouse clicks that were outside of a 1.3° radius from the center of the target (i.e., false alarms) were removed (2.30% of the dual-target trials). Second, analyses for dual-target trials were restricted to trials in which the high-salience target was identified first (i.e., identified before the low-salience target). Operationally defining the high-salience item as T1 and the low-salience item as T2 allowed for a consistent framework for measuring the SSM effect (e.g., Fleck et al., 2010) and complemented how the SSM effect is measured in radiological searches in which one target is easier to find than another target (Berbaum et al., 1994). The application of these two filters yielded 4,546 dual-target trials pooled across participants (77.31% of all dual-target trials).

An item was considered fixated if the mean of both eyes' gaze positions was within the circle used for determining correct clicks. Fixations were defined as time points with instantaneous gaze velocities below 15° per second. If there were sequential fixations on the same object within 100 ms with no intervening objects fixated, they were considered to be the same fixation (e.g., the two periods before and after an eye blink while fixating an object were counted as a single fixation).

In a typical AB paradigm, each item is presented at the same rate (e.g., 100 ms per item), so item-by-item processing is generally not dissociable from temporal aspects (but see Bowman & Wyble, 2007; Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005). However, participants in the current study completed a spatial visual search at their own pace, which allowed for a dissociation of fixations and time. Thus, to assess SSM errors in an AB fashion, we analyzed the subset of dual-target trials in which both T1 and T2 were fixated during the search. In the AB analyses, *T2 accuracy* represents the T2 detection rate given T2 was fixated after a T1 fixation; it does not represent the probability of fixating T2 but, rather, the probability of detecting T2 once fixating it.

For our AB-like analyses, we examined the data in two different ways—using fixation lags and temporal bins. When T1 was successfully detected, we examined five fixation lags (i.e., successive fixations) that were defined by the number of fixations between T1 and T2 (lag counts were reset if the high-salience target was refixated). To derive a temporal structure compatible with an AB analysis, we calculated the time between the offset from fixating T1 and the onset of fixating T2 for every T2 fixation after a T1 fixation. Each occurrence was categorized into one of five temporal bins, with each bin defined as the sum of the average time a distractor item was fixated (210 ms) and the average saccade time between items after T1 was fixated (60 ms). We made the first temporal bin half the length of the others to ensure that we were specifically examining the first fixation after T1 was fixated (because participants had to make only a saccade).

The temporal-bin analysis allowed for a focused analysis on the first 100 ms, the time frame necessary to examine Lag-1 sparing (Potter, Chun, Banks, & Muckenhoupt, 1998). In Lag-1 sparing, which is the most common phenomenon accompanying the AB, T2 accuracy is high for approximately 100 ms following the presentation of T1 (see Fig. 4b). This small window of increased T2 accuracy is believed to be time based rather than item based (e.g., Nieuwenhuis et al., 2005).

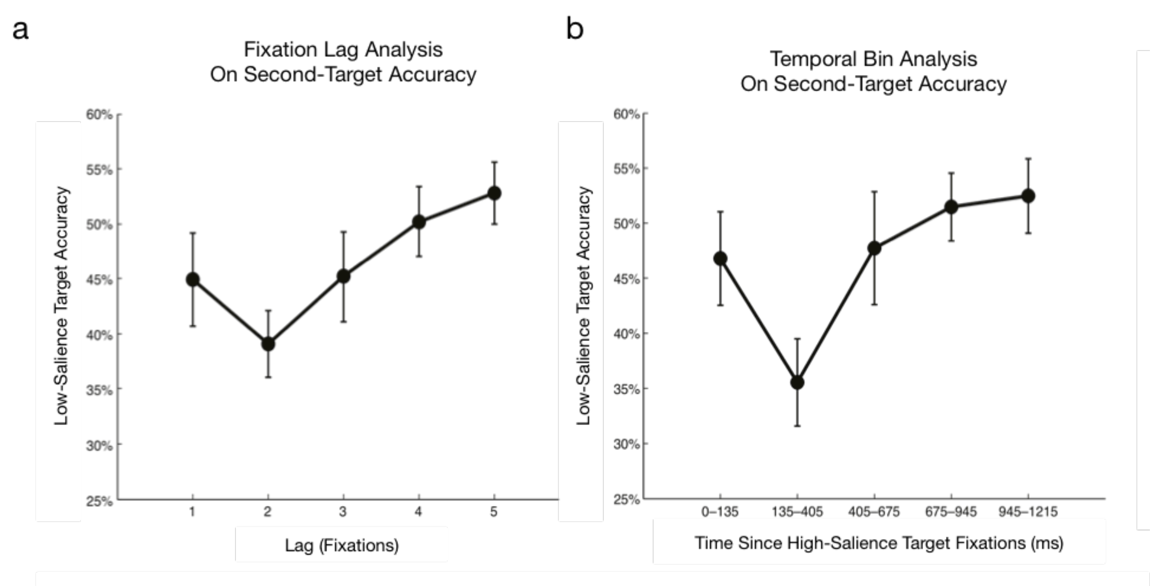

Figure 4: Results from attentional-blink-like analyses of dual-target trials. The graph in (a) shows accuracy at detecting low-salience targets as a function of the number of fixations between fixation of the high-salience target and fixation of the low-salience target (fixation-lag analysis). The graph in (b) shows accuracy at detecting low-salience targets as a function of time since the most recent fixation of the high-salience target (temporal-bin analysis). Error bars represent within-subjects confidence intervals (Morey, 2008).

2.3. Results

All statistical tests had an alpha level of .05 and were two-tailed. There was a significant SSM effect (15.6%), *t*(27) = 8.00, *p* < .001, Cohen's *d* = 1.09 (see Fig. 3b), with lower accuracy for low-salience targets in dual-target trials in which the high-salience target was found first (*M* = 69.5%, *SD* = 16.4%) compared with single-target trials (*M* = 85.1%, *SD* = 12.0%).

On dual-target trials in which participants located the high-salience target first, the fixation-lag-based analysis revealed lower accuracy at Lag 2 than at Lag 5, *t*(27) = 3.66, *p* = .001, *d* = 0.79 (see Fig. 4a), demonstrating a prototypical AB effect. There was not a significant difference between Lag 1 and Lag 2, *t*(27) = 1.33, *p* = .195, *d* = 0.33, which does not support a Lag-1 sparing effect. The temporal-bin analysis also revealed worse accuracy at Lag 2 (135–405 ms) compared with Lag 5 (945–1,215 ms), *t*(27) = 3.30, *p* = .003, *d* = 0.96, again demonstrating an AB-like effect. In addition, there was a significant Lag-1 sparing effect, with worse accuracy at Lag 2 compared with Lag 1 (0-135 ms), *t*(27) = 2.16, *p* = .040, *d* = 0.53 (see Fig. 4b), which provided further evidence that Lag-1 sparing is a time-based rather than an item-based effect.

To examine possible contributions from the spatial distance between T1 and T2, we assessed distance effects on T2 accuracy using four successive annular 125-pixel-wide bins centered on the T1 location. Distance had a marginally significant effect on T2 accuracy, $F(2.947, 66.252) = 2.947$, $p = .049$, $\eta_p^2 = .098$ (Greenhouse-Geiser corrected). It is unlikely that distance was driving the observed AB-like results, however, given that T2 accuracy was highest when closest to T1 and decreased with increasing distance, with a significant linear component, $F(1, 27) = 6.141$, $p = .020$, $\eta_p^2 = .185$, but no quadratic component, $F(1, 27) = 0.215$, $p = .5646$, $\eta_p^2 = .008$, which would be indicative of the canonical AB U-shaped curve (see Fig. 4). Furthermore, the AB effect found was not due to participants' terminating their fixations earlier at Lag 2 than at Lag 5 because the fixation durations for T2 misses at Lag 2 were not significantly different from T2 misses at Lag 5, $t(27) = 0.459$, $p = .6498$, $d = 0.107$.

2.4 Discussion

The current study reveals the existence of a self-induced AB within a spatial visual search wherein participants searched at their own pace and chose their own scan paths. Participants' performance showed an AB-like decrease in accuracy after T1 fixations, and we found this accuracy decrement in both fixation-based and time-based analyses. Despite the differences between the paradigms used to reveal AB and SSM phenomena, an analogous pattern of results was found. An AB-like effect in an SSM paradigm raises promising implications for the literature on both AB and SSM.

For the literature on AB, a self-generated AB is novel and theoretically interesting. Although there is a diverse history of introducing permutations to the typical AB paradigm—for example, variations have been made to the spatial location of items (e.g., Lunau & Olivers, 2010; Shih, 2000; Visser, Bischof, & Di Lollo, 1999), the RSVP-stream timing (e.g., Nieuwenhuis et al., 2005), and the number of items within the stream (e.g., Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1997)—this study is the first to demonstrate an AB-like effect using a spatial-visual-search paradigm in which all items remained visible and participants were able to freely search in space, at their own pace, and with no forced attentional switches.

The Lag-1 sparing effect from the temporal-bin analysis speaks to an ongoing debate regarding whether Lag-1 sparing is location specific or is an independent phenomenon from the AB (see Visser et al., 1999). Our data not only support that Lag-1 sparing can be found in spatial AB paradigms (e.g., Lunau &

Olivers, 2010; Shih, 2000) but also may fit with claims that Lag-1 sparing could be due to an enlarged field of attention after detection of T1 (Jefferies & Di Lollo, 2009). Our findings of Lag-1 sparing also distinguish our results concerning *repetition blindness* (Chun, 1997; Kanwisher, 1987). In repetition blindness, when two identical targets are presented among distractors in an RSVP stream, an AB-like reduction in second-target accuracy is typically observed, but there is no accompanying Lag-1 sparing effect. Although repetition blindness seems relevant to our study, given that our two targets were both T-shaped stimuli, the targets always differed in salience and their orientations were independently random for each display, which made them distinguishable.

The current findings also add to AB theory debates. Although our data seemingly support resource-depletion accounts, they also fit with distractor-based theories that predict that AB is due to the distractor following T1 (e.g., Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005; Olivers & Meeter, 2008); our fixation analysis demonstrated that when a distractor was fixated before T2, there was a reduction in T2 accuracy. In addition to the points raised above, existing and future AB theories will need to account for the spatiotemporal aspect of a self-paced visual search and how significant deviations from the typical RSVP stream can still produce an AB-like effect.

For the literature on visual search, the current results offer a new explanation for SSM errors—that an AB-like effect can cause misses in a multiple-target visual search. This finding confirms that searchers are not simply terminating multiple-target searches prematurely, but, rather, that SSM errors are at least partially due to the limitations of visual processing and the rate at which the visual system recovers after processing a first target.

SSM errors present real problems, given that they lead to targets' being missed in life-threatening searches (Berbaum, 2012). This is the first experiment to possibly link an AB with real-world, self-paced visual searches and suggest that an AB could underlie crucial miss errors. This knowledge can be used to implement procedural changes to increase accuracy in professional contexts (e.g., radiology and baggage screening) in which SSM errors are dangerous and have proven difficult to eliminate.

2.5. Acknowledgments

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3. Targets Need Their Own Personal Space: The Effects of Clutter on Multiple-Target Search Accuracy

3.1. Introduction

Visual search, looking for targets amongst distractors, is an activity conducted in a wide variety of contexts. Searching can be as mundane as a child looking for apple juice in the refrigerator or as serious as a radiologist looking for signs of cancer in a radiograph. While visual search has been extensively studied in laboratory settings (for recent reviews see Eckstein, 2011; Nakayama & Martini, 2011), there are many challenges encountered when moving beyond the laboratory to explore what factors influence search in "real world" settings (see Clark, Cain, Adamo, & Mitroff, 2012 for a recent review). For example, professional searchers often search for an unknown number of targets—radiologists search for multiple possible abnormalities (e.g., a radiograph can contain more than one tumor) and airport security personnel often search for multiple possible types of contraband (e.g., an X-ray image of a carry-on bag can contain both a water bottle and a gun; e.g., Menneer, Barrett, Phillips, Donnelly, & Cave, 2007).

Unfortunately, searching for multiple targets is susceptible to the *satisfaction of search* effect—a target is more likely to be missed after another target has already been detected in the same search display, compared to if it were the only target present in the display (Tuddenham, 1962). For example, a radiologist is more prone to miss a tumor if another tumor was already found in the same radiograph (Berbaum, 2012). This phenomenon, which we have recently relabeled the *subsequent search misses* effect (SSM; Adamo, Cain, & Mitroff, 2013), is troubling as it has been suggested to account for approximately one third of misses under certain radiological conditions (Anbari & West, 1997).

Research from academic radiology and cognitive psychology has focused on understanding the nature of these errors so that they can be overcome (Cain, Adamo, & Mitroff, 2013; Samuel, Kundel, Nodine, & Toto, 1995). With studies examining the underlying mechanisms of SSM errors (e.g., Adamo, Cain, & Mitroff, 2013; Berbaum et al., 1990, 1991; Cain et al., 2013) and studies examining what situational factors are most likely to give rise to the errors (e.g., Biggs & Mitroff, 2014; Cain & Mitroff, 2013; Cain, Biggs, Darling, & Mitroff, 2014; Clark, Cain, Adcock, & Mitroff, 2013), important facts about SSM have begun to accumulate. Below we briefly review three proposed theories of SSM errors, as well as review several situational factors that have been found to have relatively strong influences on multiple-target visual search performance compared to single-target visual search performance.

3.2. Theories of SSM errors

Three primary theories have been proposed for why SSM errors arise in multiple-target visual search: satisfaction, perceptual set, and resource depletion.

3.2.1. Satisfaction account

SSM errors were first proposed to arise from searchers becoming “satisfied” with the meaning of a search after finding a target—once one target was found, searchers would prematurely terminate their search without fully searching for any additional targets (Smith, 1967; Tuddenham, 1962). While this account is plausible, measurements of overall search times for single-target and multiple-target arrays have not fully supported it (e.g., Berbaum et al., 1991). Moreover, eye-tracking metrics were used in a recent study and the results suggested that a “satisfaction” account only explains a small percentage of multiple-target search errors (e.g., Cain et al., 2013). As such, the original name for the phenomenon is a bit of a misnomer, and that is why we have adopted the mechanistically agnostic label of *subsequent search misses* (Adamo et al., 2013).

3.2.2. Perceptual set account

The Perceptual Set account posits that a found target biases searchers to look for similar targets (Berbaum et al., 1990, 1991). That is, once a target has been detected, it may “prime” searchers such that they are subsequently more likely to find similar items. The downside of such priming, though, is that searchers would then be more likely to miss dissimilar targets. While this account has not received great support in the literature (e.g., Cain et al., 2013), recent evidence suggest a significant role of target similarity for multiple-target search errors (Biggs, Adamo, Dowd, & Mitroff, 2015; Mitroff et al., 2014).

3.2.3. Resource depletion account

The Resource Depletion account posits that once a target is detected in a search, attentional resources are consumed, which makes the searcher less likely to find additional targets (Berbaum et al., 1991). Attention is a limited resource, so the logic of this account is that the attention allotted to identifying a found target subsequently leaves less attention available for the process of trying to detect additional targets. Expanding this theory, it has also been suggested that the depletion of working memory resources is a potential cause for SSM errors (Cain & Mitroff, 2013); as the locations and identities of found targets are stored in working memory, the searcher's limited working memory resources are consumed, leaving less available for finding additional targets.

3.3. Situational influences on SSM errors

While much can be gained by examining the theoretical underpinnings of SSM errors, it is also valuable to explore what factors do and do not affect multiple-target search performance; by understanding what can influence SSM errors it may be possible to counteract the influences and improve performance. Several studies have recently revealed situational influences that appear to primarily affect multiple-target searches and not single-target searches (e.g., Adamo, Biggs, & Mitroff, 2013; Cain et al., 2014;

Cain, Dunsmoor, LaBar, & Mitroff, 2011). For example, SSM errors were found to increase when searchers were anxious, yet this manipulation had no effect on single-target accuracy (Cain et al., 2011). Similarly, SSM errors increased when multiple search arrays were crowding one another (akin to how multiple bags might be crammed together on a conveyor belt at an airport security checkpoint), but this did not affect single-target accuracy (Adamo et al., 2013). Conversely, SSM errors were effectively eliminated by separating multiple-target searches into several single-target searches (Cain et al., 2014).

3.4. Current study

While situational influences on visual search are helpful in offering potential measures that can be taken to reduce SSM errors in real-world searches, there is still more work to be done. In the current study, we looked to address one potential influence on multiple-target visual search accuracy that has not been directly examined before—clutter. Clutter can be broadly defined as either the number of items or the organization of the items present within the vicinity of a target, with the implication that greater levels of clutter (i.e., more items and/or more complex organizations of items) produce more difficult search (Rosenholtz, Li, & Nakano, 2007). Take the example of airport security personnel tasked with finding contraband in X-ray images of carry-on luggage. Not all carry-on bags are the same; some bags are extremely cluttered with many items inside (e.g., a briefcase filled with electronics, cables, notebooks, pens, etc.) while other bags are sparse (e.g., a mostly empty duffle bag containing a few items of clothing).

Both previous research on the nature of clutter (e.g., Rosenholtz et al., 2007) and common sense would suggest that visual search will be more difficult in a cluttered search array than a sparse array, but exactly how does clutter affect multiple-target search? This is an especially important question to address, as a shift in airline policy has likely made carry-on bags more cluttered than ever before; with many airlines now charging extra fees for checked bags, passengers are likely more inclined to overfill their carry-on bags to avoid checking their bags.

Given that influences such as anxiety and the proximity of search arrays to one another have a particularly strong influence on SSM errors relative to single-target search performance (Adamo et al., 2013; Cain et al., 2011), might the clutter around a second target have a particularly strong influence on performance? To address the current question we employed a standard cognitive psychology multiple-target search experiment (e.g., Fleck, Samei, & Mitroff, 2010) while incorporating logic from the visual clutter literature.

Measuring clutter in real-world images is not necessarily straight forward, and several modeling techniques have been proposed for determining appropriate calculations of clutter, including sub-band entropy, edge density, and feature congestion (see Rosenholtz et al., 2007 for a review). These models have primarily been used to measure the clutter of an entire scene (e.g., Henderson, Chanceaux, & Smith, 2009), however, more recently a sub-band entropy model was used to calculate clutter in a restricted region around a target (Asher, Tolhurst, Troscianko, & Gilchrist, 2013). Being able to apply a restricted clutter calculation is the most relevant to our current goals here, and it was found in the previous study that a 6–7° radius around a target was the most sensitive to clutter (Asher et al., 2013). This 6-7° radius effect is interesting because it is also the general area that is sensitive to other visual phenomena such as visual crowding and lateral masking (e.g., Asher et al., 2013; Levi, 2008).

In the present study we adopted the radius-specific clutter approach from Asher et al. (2013) and used a simplified search array. This allowed us to define clutter purely as a function of the number of items near a target. Clutter has been shown to impact single-target search performance (e.g., Asher et al., 2013), but how might it affect multiple-target search performance? If a second target appeared within a cluttered location in a search array, would there be a greater SSM effect than if it appeared in a less cluttered location?

3.5. Methods

3.5.1. Participants

The current study involved 106 members of the Duke community who participated for course credit or $10 per hour. Participants were recruited either as part of an eye tracking experiment (Adamo et al., 2013; Cain et al., 2013) or a large-scale, multi-session study conducted in the Duke Visual Cognition laboratory that was focused on assessing individual differences for a variety of behavioral tasks. As such, the participants completed additional tasks that are not discussed here, and some of the current data have been published elsewhere (Adamo et al., 2013; Cain et al., 2013) and may serve as the basis for future publications. Twenty-seven of the participants were run in a version of the search task that incorporated eye-tracking measurements, but these measures were not incorporated into the current analyses. Sixteen participants' data were removed from the analyses following the filters of Adamo et al. (2013): Data from 5 participants were removed because they had greater than 15% high-salience, single-target errors, 4 for having greater than 20% false alarms, and 7 for having greater than 20% timeouts (not finishing within the 15-second time limit) leaving a total of 90 participants (age range 18–25, mean=20.2 years). Research was conducted in accordance with the Declaration of Helsinki.

3.5.2. Stimuli and apparatus

The stimuli were based off of previous SSM studies (e.g., Fleck et al., 2010). All items were pairs of perpendicular rectangles, with a small gap between them, that created 'T' or 'L' shapes and were 1.3° x 1.3°. The targets had the rectangles perfectly aligned so as to create a T-shape. The distractors had the rectangles offset from perfect alignment by 1–4 pixels so that they appeared as either a perfect 'L' or a misaligned 'L' shape. Items were presented in one of four possible orientations (0°, 90°, 180°, or 270° rotations) on a white background. A total of 25 items were displayed on an invisible 8 x 7 grid with each item offset from perfect grid alignment by 0–5 pixels. Half of the targets and 5% of distractors were "high salience"—they were relatively dark compared to the white background (57%–65% black), which made them more visually salient. The other half of the targets and 95% of distractors were "low salience" (22%–45% black), appearing as light gray against the white background. Two levels of salience were implemented to create a bias wherein participants would be more likely to find high-salience targets first (e.g., Fleck et al., 2010).

Stimuli were presented with Matlab via PsychToolbox 3 (Kleiner, Brainard, & Pelli, 2007). Sixty-three participants performed the task on a 20-inch CRT monitor and 27 participants, who were part of an eye tracking study, viewed the task on a 17-inch LCD monitor. All participants were seated 57 cm away from the monitor and used a chin rest to keep the viewing distant constant.

3.5.3. Procedure

Participants were instructed to search for 1 or 2 T-shaped targets among pseudo L-shaped distractors (see Figure 5). There were 250 trials evenly split across 10 blocks in addition to a practice block of 25 trials. Ten percent of the total trials were high-salience, single-target trials, 10% were low-salience, single-target trials, and 80% were dual-target trials with one high- and one low-salience target. This trial distribution was used to create a high number of dual-target trials in which the second target was cluttered. Participants had 15 seconds to search each display and were asked to press the space bar when they were finished. If they failed to press the space bar within the 15-second time limit, this was considered a "time out." Participants made a mouse click on each item they believed was a target and a small blue circle (0.3°) appeared after each click. This circle has been shown not to affect search performance (Cain & Mitroff, 2013).

3.5.4. Data preparation and planned analyses

We measured clutter for two different spatial areas around a target: a 100-pixel radius (3.25°) and a 200-pixel radius (6.5°) around the center of a target. Items were considered "clutter" if their center point fell within these radii. This 100-pixel range represented the smallest area wherein one item could be near another item in the current displays, thus allowing us to explore only the closest items to a target (see Figure 5). The area within the 200-pixel radius is comparable to the area in which distracting items have previously been demonstrated to influence the detection of a target (Asher et al., 2013).

Within the 100-pixel radius we explored three different levels of clutter: 0, 1, and 2 items within the radius. For the 200-pixel radius analyses we grouped sets of items into three different levels of clutter: 2 or 3 items, 4 or 5 items, and 6 or 7 items. We focused on these levels because the majority of trials had between 2 and 7 items within a 200-pixel radius area of a target, with relatively few trials having less than 2 or more than 7. Grouping into three levels of clutter also served to improve the reliability of our measurement (i.e., providing more trials to each level of clutter) and to mirror the three levels of clutter from the 100-pixel radius analyses.

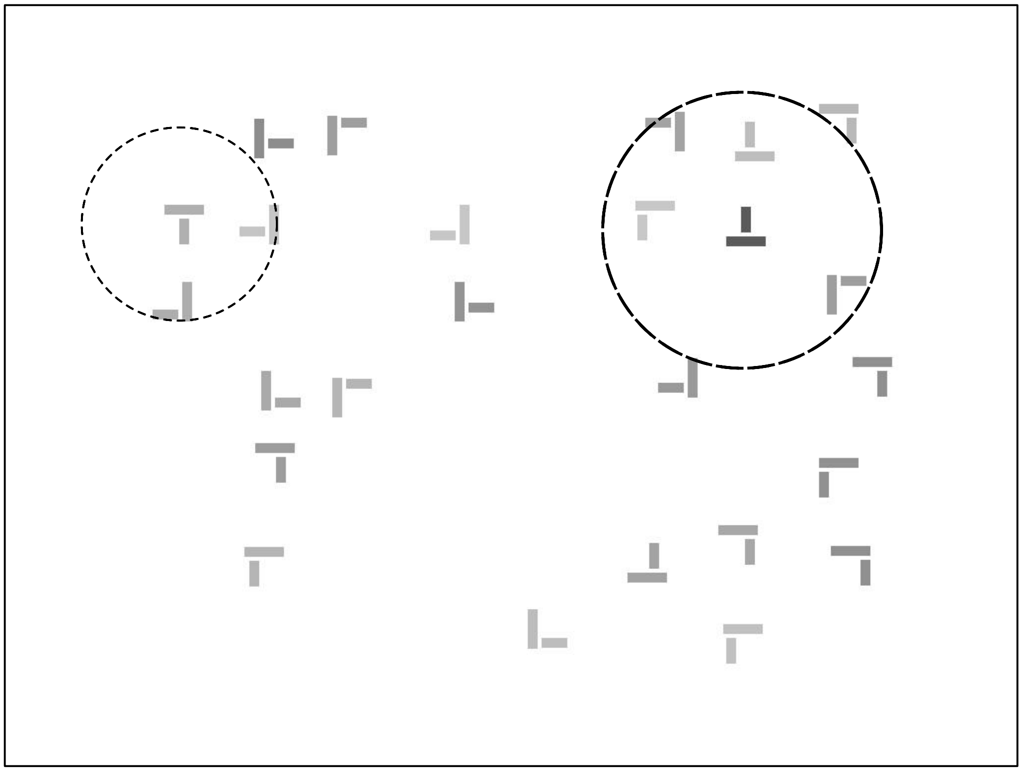

Figure 5: Sample multiple-target search display. The dashed lines (not present in the actual displays) represent the area where items were considered 'clutter.' The short dashed circle around the low-salience target 'T' represents the 100-pixel radius and the long dashed circle around the high-salience target 'T' represents the 200-pixel radius. In this image the 100-pixel radius is a 2-item example and the 200-pixel radius is a 4/5-item example.

3.6. Results

3.6.1. Data filtering

Mouse clicks within a 40-pixel radius (approximately 1.3°) from the center of a target were considered correct. Any clicks that fell outside of that radius were considered false alarms, and trials with a false alarm (2.0% of all trials) were not included in further analyses. An additional 3.8% of trials were removed due to participants timing out by reaching the 15-second time limit. Of the remaining trials, SSM errors were calculated as the difference in accuracy for detecting low-salience targets on single-target trials versus on dual-target trials after a high-salience target was detected first (e.g., Adamo et al. 2013). This led to the removal of 4.4% of dual-target trials in which the high-salience target was not found and an additional 16.2% of dual-target trials where the low-salience target was found before the high-salience target.

The distribution and layout of the distractor items were not experimentally manipulated, which resulted in a variable distribution of trials for the different levels of clutter. As a result, not every participant contributed data to each analysis: in the 100-pixel radius calculations, 87 participants contributed to the high-salience, single-target trial analyses, 88 participants contributed to the low-salience, single-target analyses and SSM calculation, and 90 contributed to the dual-target analyses; in the 200-pixel radius calculations, 89 participants contributed to the high-salience, single-target analyses, 87 participants contributed to the low-salience, single-target analyses and SSM calculation, and 90 contributed to the dual-target analyses.[1]

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[1] To make sure participant inclusion did not affect the outcome, all analyses were also re-calculated using only data from participants who contributed to every measure (N=85). The pattern of results remained the same.

3.6.2. Accuracy

Participants performed well on single-target trials with a hit rate of 99.2% on high-salience, single-target trials and 93.6% on low-salience, single-target trials (see Table 1A & B). Likewise, the hit rate for high-salience targets on dual-target trials was high (95.6%, SE = 3.55%). However, the hit rate for low-salience targets on dual-target trials after a high-salience target had already been found was 69.7% (Table 1C), resulting in a significant SSM effect of 24.0%, ($t(89)=15.18$, $p<.01$; Table 1D).

The high-salience and low-salience, single-target hit rates did not significantly vary by clutter level, for either the 100-pixel or 200-pixel radii (see Table 1A and B). In contrast, hit rate for the low-salience targets on dual-target trials in which the high-salience target had already been found significantly decreased as the level of clutter increased for both the 100-pixel and 200-pixel radii (Table 1C and Figure 6). As a result, there was a significant increase in the magnitude of the SSM effect as the clutter level increased (100-pixel radius: $F(1.92,170.8)=14.2$, $p<.01$, $\eta^2=.138$; 200-pixel radius: $F(1.88,169.1)=11.3$, $p<.01$, $\eta^2=.112$; see Table 1D)[2]. The influence of clutter did not differ between the 100-pixel and 200-pixel condition ($F(1,87)=.03$, $p=.87$).

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[2] All ANOVAs were Greenhouse Geisser corrected.

3.6.3. Response time

There were no significant influences of clutter level on the response time data (see Table 1E–H) except for one analysis—response times for the high-salience, single-target trials significant decreased as the clutter level increased for the 200-pixel radius analysis ($F(1.95,171.3)=.31$, $p=.04$, $\eta^2=.036$; Table 1E). This effect appears to be driven by a significant difference between the 4/5 and 6/7 items condition ($t(88)=2.48$, $p=.02$) as the other possible combinations (i.e., comparing 2/3 to 4/5 and 2/3 to 6/7 conditions) were non-significant (*p's*>.09).

Table 1: Accuracy and response time metrics (with standard errors). The amount of distractors is indicated underneath the two radii analyses. Each *p*-value represents a within-subjects, 1-way ANOVA with the main effect of clutter for each radius analysis.

Measure	Overall Average	100-pixel radius				200-pixel radius			
		Number of Items				Number of Items			
		0	1	2	*Sig.*	2/3	4/5	6/7	*Sig.*
A. High-salience, single-target hit rate	99.23% (0.23%)	98.64% (0.57%)	99.55% (0.26%)	99.84% (0.16%)	*p*=.08	98.78% (0.59%)	99.42% (0.29%)	99.40% (0.43%)	*p*=.45
B. Low-salience, single-target hit rate	93.63% (1.10%)	93.89% (1.49%)	93.46% (1.30%)	94.28% (1.48%)	*p*=.87	93.59% (1.15%)	92.93% (1.77%)	93.65% (1.71%)	*p*=.89
C. Low-salience, second target hit rate	69.66% (1.86%)	72.41% (1.93%)	69.43% (1.85%)	67.52% (2.05%)	***p*<.01**	71.61% (1.85%)	69.49% (1.93%)	66.92% (2.03%)	***p*<.01**
D. SSM effect (B minus C)	23.97% (1.58%)	21.78% (1.99%)	24.52% (1.85%)	27.24% (1.96%)	***p*<.01**	22.30% (1.82%)	23.74% (2.02%)	27.03% (2.06%)	***p*=.05**
E. High-salience, single-target response time	3.33s (0.13s)	3.28s (0.15s)	3.40s (0.14s)	3.38s (0.19s)	*p*=.70	3.27s (0.15s)	3.50s (0.17s)	3.11s (0.15s)	***p*=.04**
F. Low-salience, single-target response time	5.99s (0.10s)	5.98s (0.19s)	5.87s (0.15s)	6.12s (0.20s)	*p*=.57	6.00s (0.20s)	6.02s (0.15s)	5.61s (0.18s)	*p*=.18
G. Low-salience, second target response time	6.42s (0.09s)	6.41s (0.10s)	6.43s (0.09s)	6.49s (0.11s)	*p*=.48	6.43s (0.10s)	6.34s (0.10s)	6.46s (0.11s)	*p*=.20
H. Time between first & second target click	3.82s (0.06s)	3.83s (0.08s)	3.82s (0.07s)	3.81s (0.08s)	*p*=.85	3.82s (0.07s)	3.75s (0.07s)	3.85s (0.08s)	*p*=.27
I. Time between first target click & done time	6.61s (0.21s)	6.62s (0.22s)	6.66s (0.22s)	6.59s (0.21s)	*p*=.77	6.63s (0.22s)	6.51 (0.21s)	3.62s (0.23s)	*p*=.52

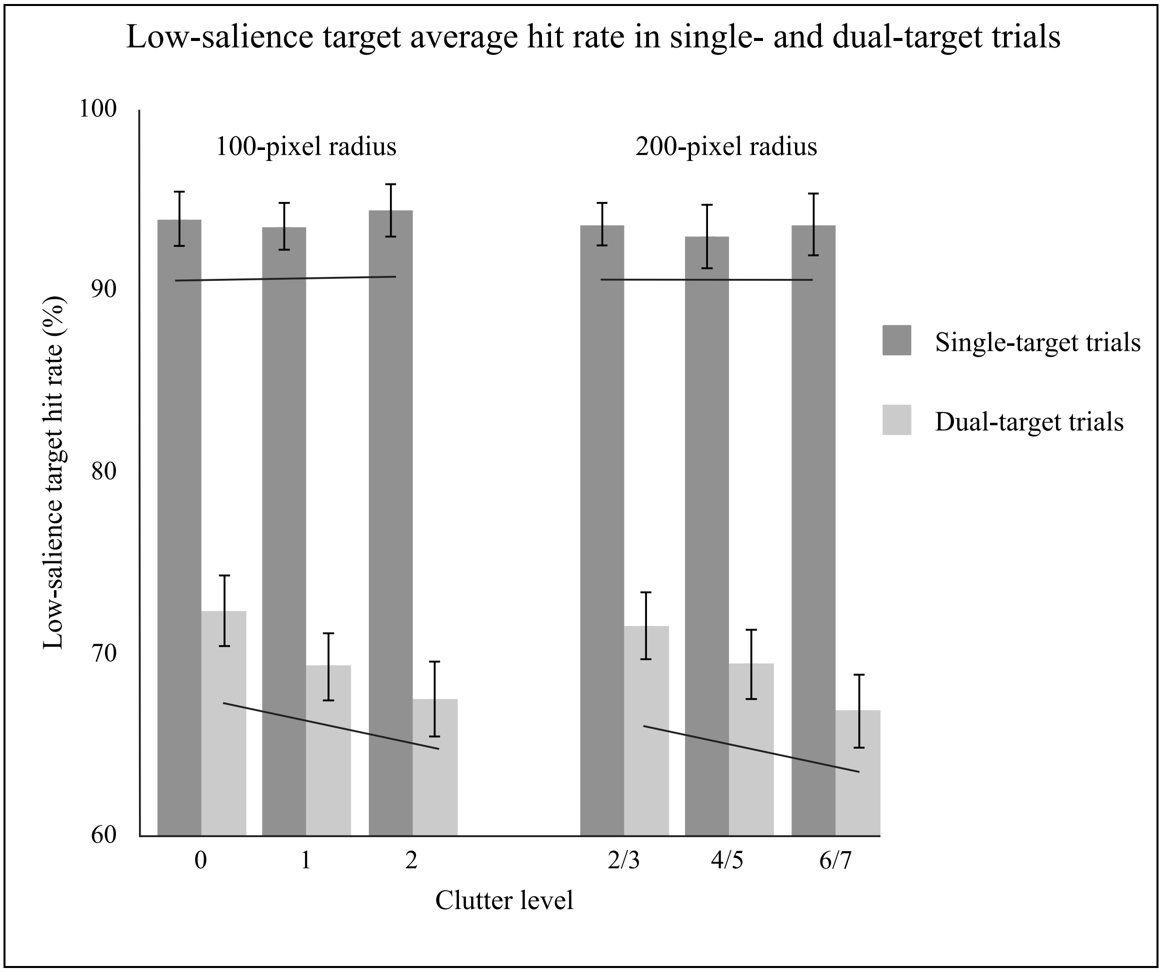

Figure 6: Hit rates for low-salience targets in the single-target (dark gray) and dual-target (light gray) conditions as a function of clutter level for both the 100-pixel (3.25°) and 200-pixel (6.5°) analyses. The hit rate for dual-target trials is for trials in which a high-salience target was previously detected. Error bars represent the standard error of the mean and the lines represent the trend line for clutter level across single- and dual-target trials.

3.7 General discussion

In many critical, real-world visual search settings, professionals are tasked with searching for an unknown number of targets in cluttered environments. The cost of failure can be high—there are potentially fatal implications of a missed tumor in a radiological examination or a prohibited item making it through an airport security screening. SSM errors, the failure to detect a target after a previous target was already found, are a known problem for professional searchers (e.g., Berbaum, 2012) and the current study found that the errors can be exacerbated by visual clutter. SSM errors were present for all levels of clutter tested, and the error rate significantly increased as the amount of clutter increased around a second target.

There are multiple hypotheses for the underlying mechanisms that produce SSM errors and we below we briefly discuss each of them with respect to the current results. The "satisfaction" account (Smith, 1967; Tuddenham, 1962) does not appear to account for SSM errors in conjunction with clutter, as time spent searching after finding a first target did not change across different levels of clutter (see Table 1). It is also unlikely that the Perceptual Set account (Berbaum et al., 1990, 1991) could explain the current results as the targets only differ in luminance and orientation. Previous research, using a subset of these data (Cain et al., 2013), found that orientation (i.e., whether the first and second target were the same orientation) did not significantly account for a difference in second target detection. However, we cannot fully rule out the Perceptual Set account, in general, as recent work has found evidence for both perceptual and conceptual sets guiding second-target detection in multiple-target visual search (Biggs et al., 2015). Specifically, this study assessed performance via a mobile technology app that allowed for testing visual search across a large numbers of possible targets. This target variability reduced the chances that a small number of targets would be "chronically" primed across an experiment, and perceptual and conceptual set evidence arose (Biggs et al., 2015).

The current data appear to most closely align with a Resource Depletion account of SSM errors (e.g., Berbaum et al., 1991; Cain & Mitroff, 2013). Previous research has demonstrated that finding a target in a visual search array can tax cognitive resources, such as attention (Adamo et al., 2013) and working memory (Cain & Mitroff, 2013), which leaves the searcher more vulnerable to missing additional targets. In a similar theoretical vein, previous research has also demonstrated that crowding, the inability to detect items in cluttered displays, can tax attentional resources (e.g., Dakin, Bex, Cass, & Watt, 2009; Scolari, Kohen, Barton, & Awe, 2007; Whitney & Levi, 2011), thereby requiring attention to reduce the distance over which distractors affect detection accuracy (Yeshurun & Rashal, 2010). The current experiment also appears to support the notion that as clutter increases, so does the need for attention. In relation to the Resource

Depletion account, if the first target is draining attentional resources, clutter can impose an additional load on attention, leaving even *less* attentional resources to detect a second target.

Previous research has demonstrated an impact of visual clutter on search performance in single-target searches (e.g., Rosenholtz et al., 2007) and, more recently, within a 6–7° radius around a target (Asher et al., 2013). However, the current results did not demonstrate a significant effect of clutter on the low- or high-salience, single-target hit rates or response time measures. More work is needed to fully elucidate this difference, but our hypothesis is that we did not find an effect of clutter on single-target trials because the current searches were relatively simple and there was always at least one target present per search. This is easily seen when looking at the overall accuracy for single-target trials—the high-salience, single-target accuracy was at ceiling (99.2%) and the low-salience, single-target accuracy was also very high (93.6%), which leaves little room to assess effects of clutter. We purposely manipulated the nature of the high-salience and low-salience targets to make the high-salience items easy to detect (to allow for an investigation of the low-salience targets on dual-target trials), but this was not optimal for assessing the impact of clutter on the single-target trials. Moreover, there were relatively few single-target trials, which limited the experimental power for this question.

Going beyond the theoretical accounts of SSM errors, it is noteworthy that the results reported here are similar to the phenomena of crowding and lateral masking. In general when viewing a target in the periphery surrounded by distractors, crowding can be defined as impairment in the ability to recognize a target and lateral masking can be defined as impairment in the ability to distinguish target features. As mentioned in Asher et al., (2013), clutter within a 6–7° radius around a target likely lead to masking of the target, either due to crowding or lateral masking, which may ultimately result in a lower target hit rate. While eye movements could be made in our experiment (unlike typical crowding and lateral masking experiments), it could be that eye movements were less likely to actually land on or near the second target due to masking. In our experiment, the masking of a second target may be harder to overcome if the attentional resources needed to help counteract masking were being consumed by the first target (i.e., as predicted by the resourced depletion hypothesis; Cain & Mitroff, 2013).

To summarize, the current study found that clutter had a selective influence on second-target accuracy in visual search—there was an increase in SSM errors as clutter increased around a second target. This result has direct implications for critical, real-world searches such as those conducted in radiology and baggage screening; professional searchers often encounter cluttered search displays and SSM errors are a persistent and troubling concern in both radiology (Berbaum, 2012) and airport baggage screening (Biggs, Cain, Clark, Darling, & Mitroff, 2013). Clutter may exasperate the SSM effect, and SSM errors can be better accounted for through a better understanding of the role of clutter.

3.8. Funding

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4. An Individual Differences Approach to Multiple-Target Visual Search Errors: How Search Errors Relate to Different Characteristics of Attention

4.1. Background

Visual search, the act of looking for targets amongst distractors, is a part of nearly all daily activities. 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 performance—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 et al., 2007) 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, 2015, Cain & Mitroff, 2013; Samuel, et al., 1995; Smith 1967). Below, each of these theoretical accounts is briefly discussed.

4.1.1. 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).

4.1.2. 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 has been 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., 2015).

4.1.3. 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 200-500ms after a detected, first target) in a multiple-target search (Adamo, et al., 2013). This finding suggests that a first target consumes attentional resources, leaving less available to process a second target. 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.

4.1.4. 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, 2013), 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 examine 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 examine how these individual differences relate to 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 200-500ms 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 Figure 1). The first measure is 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 200–300ms after the display of a first target. The blink can 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—a phenomenon where the processing of a second target is greatly enhanced if it appears approximately 100ms after a first target (Bowman & Wyble, 2007;

Nieuwenhuis et al., 2005). 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)[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 200–500ms 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, & Mathews, 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

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[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 are beyond the scope of this study.

selection and limited capacity were not. These findings remained significant even when accounting for the contributions of general search performance (see Planned Analysis section). These results demonstrate that worse attentional modulation and poor vigilance are predictive of more second-target misses.

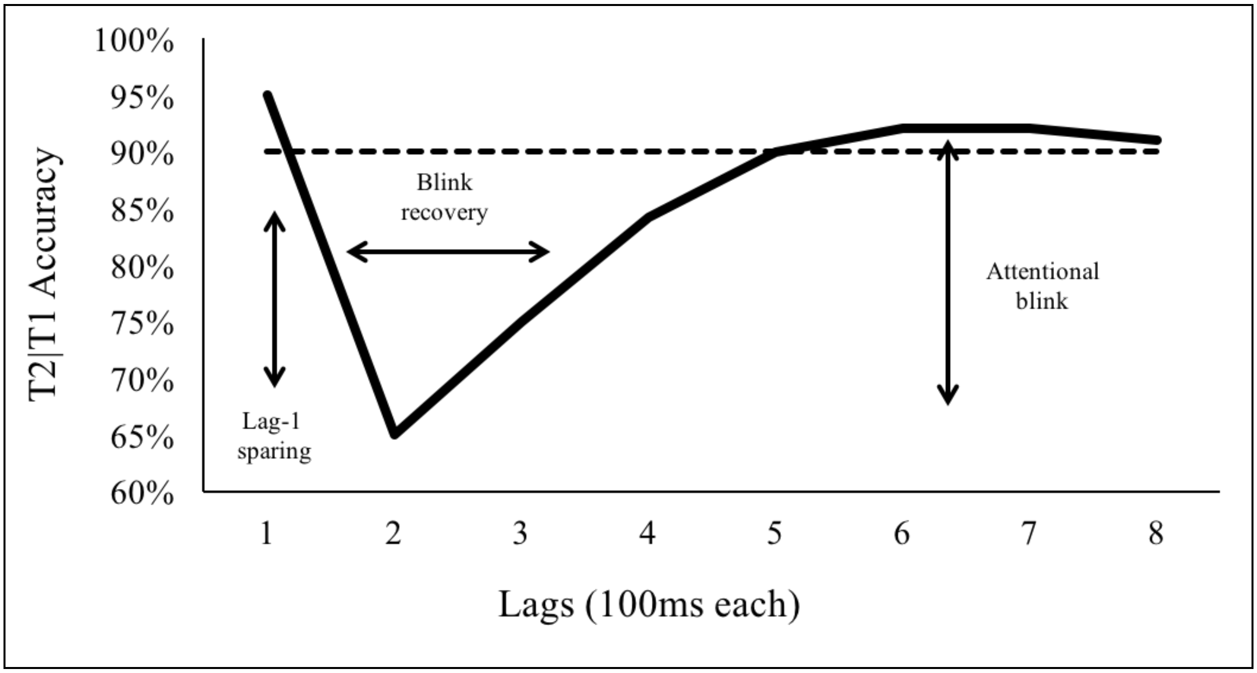

Figure 7: Depiction of a typical attentional blink effect. In general, attentional blink graphs depict target accuracy on the y-axis and time on the x-axis, with the x-axis representing the time in which a second target (T2) appeared after a first target (T1) was displayed. Specifically, this graph depicts 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.

4.2. Methods

4.2.1. 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 experiment took 90 minutes to complete, and the participants were compensated with course credit or $15. Data from a subset of these participants have been reported elsewhere (Adamo et al., 2015a,b; Biggs, Adamo, & Mitroff, 2014) for different purposes; one study used the AB data as a control condition for how motivation affects the AB (Biggs et al., 2014), 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).

4.2.2. 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: 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. 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 competed both the multiple-target search and vigilance tasks.

4.2.3. General procedures

Participants sat 57cm 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.

4.2.4. Attentional blink task

This task was modeled after Chun & Potter (1995; see Figure 8a). White numbers and letters (Arial font; approximately 1° x 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 100ms 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.

4.2.5. Multiple-Target search task

This task was modeled after Adamo et al. (2013; see Figure 8c). 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 x 7 grid (jittered 0–4 pixels in any direction from the center of the cell). Half of the targets and 5% of distractors were high salience (57–65% black), and the other half of the targets and 95% of distractors were low-salience (22%–45% black). Ten percent of the trials had a single, high-salience target, 10% had a single, low-salience target, and 80% trials had both a high- and low-salience target. Participants had 15 seconds to search the display, click on items they believed were targets, and press the space bar when they felt they had found all the targets in the display. 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.

4.2.6. Vigilance task

This task was modeled after Temple et al. (2000; see Figure 8e). Participants were asked to search for grey (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-grey (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 (See Figure 8e). Each item (0.8° x 0.8°) appeared for 40ms with an inter-stimulus interval of 960ms. 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 minutes 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.

4.3. 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 atttentional 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.

4.3.1. 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 & Arnell (2012). Blink magnitiude was calculated as the difference between T2 accuracy at lag 2 and the average of T2 accuracy at lags 5-8 (see Figure 7). 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 Consineau et al., (2006). 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 insure 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.

4.3.2. 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. 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 by taking the difference between perfect accuracy (i.e., 100%) and the accuracy for low-salience targets after 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.

4.3.3. 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.

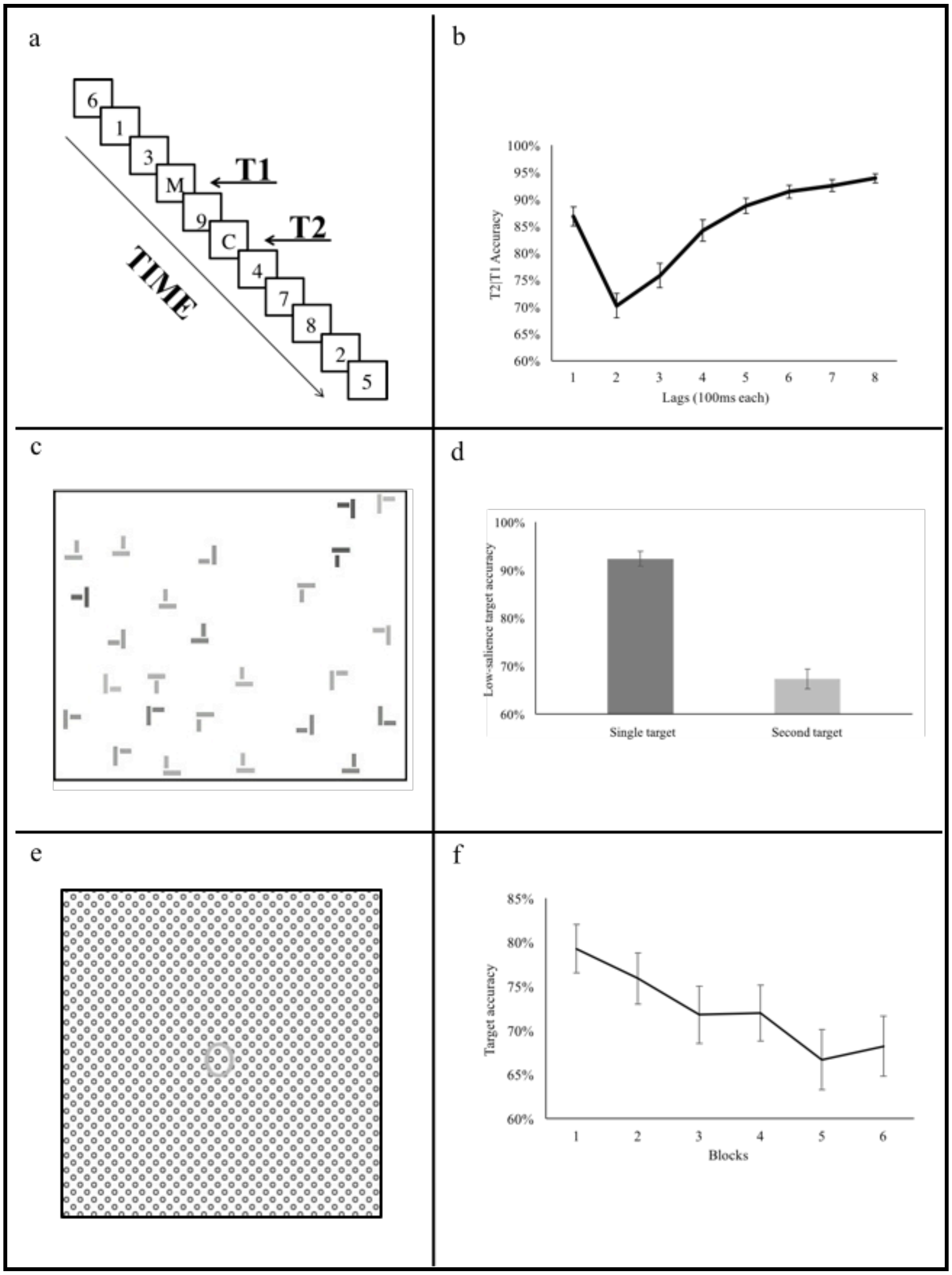

Figure 8: Example stimuli and experimental data from the attentional blink (AB), multiple-target visual search, and vigilance tasks. (a) Sample AB task display where items are presented one at a time for 100ms in the center of the screen. (b) AB data where participants demonstrated lag-1 sparing with 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.

4.4. Results

4.4.1. Main findings

The three stereotypical AB components were found for the AB task (see Figure 8b). 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*<.001). Second, lag-1 sparing was found with greater accuracy at lag 1 (M=86.81%; SD= 14.59%) compared to lag 2 (*t*(66)=7.05, p<.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*=.24). Following the methods of Consineau 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, 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%; $t(61)=4.51$, $p<.001$) compared to single, low-salience target accuracy (M=92.35%; SD=12.27%; see Figure 8d). 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= 4.41s; SD=0.68s).

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 $p<.001$; see Figure 8f). The individual difference measure of d' had a mean of 2.50 with a standard deviation of 1.28.

4.4.2. 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 Bonferoroni-adjusted alpha levels of .0125 per test (.05/4). The results indicated that modulation ($r(55)=0.38$, $p<.01$) and vigilance ($r(57)=-0.54$, $p<.001$) were significant (see Table 2). 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.

Table 2: Correlation results for the attentional characteristics (and their respective measure from the attentional blink or vigilance task) 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 .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*=.24	*r*(57)= –0.23 *p*=.08	*r*(55)= –0.29 *p*=.03
Selection	Lag-1 Sparing	*r*(57)= 0.09 *p*=.53	*r*(57)= 0.16 *p*=.22	*r*(55)= 0.15 *p*=.28
Modulation	Blink Recovery	*r*(57)= 0.27 *p*=.04*	*r*(57)= 0.42 *p*=.001*	*r*(55)= 0.38 *p*<.01*
Vigilance	Vigilance Sensitivity	*r*(59)= –0.25 *p*=.06	*r*(59)= –0.57 *p*<.001*	*r*(57)= –0.54 *p*<.001*

4.5 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.

4.5.1. 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 face value, this might seem surprising given that previous research demonstrated that these AB components were related to second-target misses after first target detection in a multiple-target visual search task (Adamo et al., 2013). However, given that the previous relationships accounted for a relatively small amount of the total variance in second-target misses (Adamo et al., 2013), it makes sense that current results were not significant. Specifically, the previous work focused on a specific time frame of performance immediately after a first target was detected, allowing for a relatively small effect to be revealed. Regardless, it is theoretically interesting that limited capacity and attentional selection were not found to be significant predictors of second-target detection accuracy. This suggests that the attentional selection to a first target and an observers' capacity of attentional resources are not contributing much to second-target misses.

4.5.2. 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 that a first target is a highly potent distractor that can consume cognitive resources necessary to find additional targets throughout the duration of search (Cain, Biggs, Darling, & Mitroff, 2014; Cain & Mitroff, 2013). This finding suggests that when a portion of the limited attentional resources are used to process a first target, fewer attentional resources are available to process a second target, which is in-line with the predictions of the Resource Depletion account (Berbaum et al., 1991; Cain & Mitroff, 2013).

4.5.3. 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 & Russell'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.

4.5.4. 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 et al., 2014; Cain & Mitroff, 2013). 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.

Another example of a technique used to improve target detection is when radiologists consult a patient's clinical history prior to examining the patient's radiograph (e.g., Berbaum et al., 1993). By reviewing a patient's history, this can help a radiologist estimate the likelihood of whether an abnormality is present within that patient's radiograph. Berbaum et al. (1993) found that when no clinical history was provided for an abnormality, the abnormality could be missed as a result of the SSM effect. However, when abnormalities were linked with a patient's clinical history, the abnormality was found resulting in no SSM effect. This improvement in abnormality detection could be a result of increased vigilance. If a radiologist believes that an abnormality could be present within a certain area of a radiograph, this may result in increased vigilance towards that area when searching, resulting in improved abnormality detection.

4.6 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 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 et al., 2014; Cain & Mitroff, 2013). 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 account 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.

5. General Discussion

5.1. Summary of previous chapters

The goal of this dissertation was to identify if attention contributes to SSM errors and determine a mechanistic explanation for why this happens. In order to accomplish these goals, I explored multiple-target search on three different levels: 1) the target-to-target relationship, 2) the distractor-to-target relationship, and 3) the observer-to-target relationship.

The target-to-target relationship, studied in Chapter 2, is such that the consumption of attention by one target can lead to missing a second target through a self-induced attentional blink. A self-induced attentional blink is one in which the detection or fixation of a first target leads to a decrease in second target detection. Thus, this chapter offers a potential mechanism underlying SSM errors: the first target causes an attentional blink for the second target.

The distractor-to-target relationship, explored in Chapter 3, demonstrated that clutter, distractors within the immediate vicinity of a target, affects second-target detection within a multiple-target visual search. This study reinforces that attention is consumed by a first target and illustrates a consequence of this process: detecting a first target can amplify the attentional deficits caused by clutter on second target processing.

The observer-to-target relationship, investigated in Chapter 4, provides further insight into the attentional predictors of second-target misses. There are four proposed characteristics of attention: selectivity, capacity, modulation, and vigilance (Chun et al., 2011). This study explored individual differences in these characteristics and suggested that attentional modulation and vigilance are most predictive of missing a second target. Specifically, this study suggests that the worse attentional modulation and poorer vigilance in target detection is predictive of second-target misses. 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 less attentional resources available to detect a second target. These results speak towards the overlap between the attentional characteristics and how the taxing effects on one characteristic of attention can impact another.

With these results as a foundation, I will use the remainder of this discussion to present a new theory of SSM errors. The basic premise of the theory is that after a first target is detected, the first target is maintained in an attentional template of working memory, which consumes attentional resources that could otherwise be used to detect additional targets. This theory offers a mechanistic account for *why* attentional resources are consumed by a first target, can demonstrate why a first target can impact a second target past the attentional blink window (Chapter 2; Adamo et al., 2013), and expands off the research presented in this dissertation.

5.2. Overview of discussion

The remainder of the dissertation will be organized as follows. In the *Review of attentional template* section, I motivate the theory by presenting relevant background for research concerning the attentional template. Next, in the *Assumptions of the model* section, I will discuss the concept of "cognitive resources," disambiguating with respect to the ideas of "working memory resources" and "attentional resources." In the *Flux capacitor theory* section, I will present a new theory of SSM errors and will present the four tenets of the Flux Capacitor theory. In the *Tenets of the model* section, I will address each tenet, discuss the relevant research (both attentional template and multiple-target search research) that motivated each tenet, and discuss (if applicable) what future research needs to be conducted to help support the predictions made. Finally, I will conclude by reviewing the chapters of this dissertation and discuss the real-world implications of this research.

As a disclaimer, while this theory is motivated by the research on SSM errors and the attentional template, many of the predictions are conjecture. My ultimate hope is that this theory will provide a stepping stone towards a unified theory of SSM errors that myself and other researchers can build upon.

5.3. Review of attentional template research

Most models of visual search predict there is a special area in working memory that maintains an active representation of the search goal called an attentional template (also called the "target template" or "search template"; e.g., Bundesen, Habekost, & Kyllingsbaek, 2005; Gunseli, Olivers, & Meeter, 2014; Hout & Goldinger, 2015). The attentional template is predicted to bias attention towards items in the visual world that are similar to the template and away from items that are dissimilar (e.g., Duncan & Humphreys, 1989; Olivers et al., 2011). It is proposed that only one item can be utilized as the attentional template and other items within working memory, known as accessory memory items, will not bias attention in search (Olivers et al., 2011). Research investigating the attentional template typically presents an item/cue that is to be held within working memory for a subsequent memory task. Observers are then presented a visual search display, before the memory task, with either a target or distractor that match or mismatch the item in the attentional template. Results from these experiments typically find that search is facilitated when a target matches or shares the same feature(s) as the template. However, when a distractor matches or shares the same feature(s), visual search is hindered (Greene, Kennedy, & Soto, 2015; Soto, Heinke, Humphreys, & Blanco, 2005).

Although the attentional template is important in guiding attention in visual search, its involvement can fade as the attentional template is learned. Recent event related potential (ERP) experiments have suggested that working memory is less involved in maintaining the attentional template when the attentional template is repeated (Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli et al., 2014). Contralateral delay activity, an ERP index of how many items are maintained within working memory (e.g., McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004), is reduced when the attentional template, which was predictive of the target in search, was repeated for single-target, pop-out visual searches (Carlisle et al., 2011) and single-target, serial visual searches (Gunseli, et al., 2014). These results were interpreted that when an attentional template is learned, it transfers from visual working memory to long-term memory, thereby losing its attentional template status within visual working memory.

While the attentional template research discussed above is brief in comparison to what is currently known about the attentional template, the purpose of this short review was to introduce the function of the attentional template and establish the fluid nature of the template. Importantly, I wanted to establish that: 1) an attentional template is a special area within working memory that can consume working memory resources and guide attention in search and 2) items held within an attentional template can transition to long-term memory. These characteristics of an item held within an attentional template are important for the theory described below as I propose that these characteristics can account for SSM errors in multiple-target visual search.

5.4 The Flux Capacitor theory

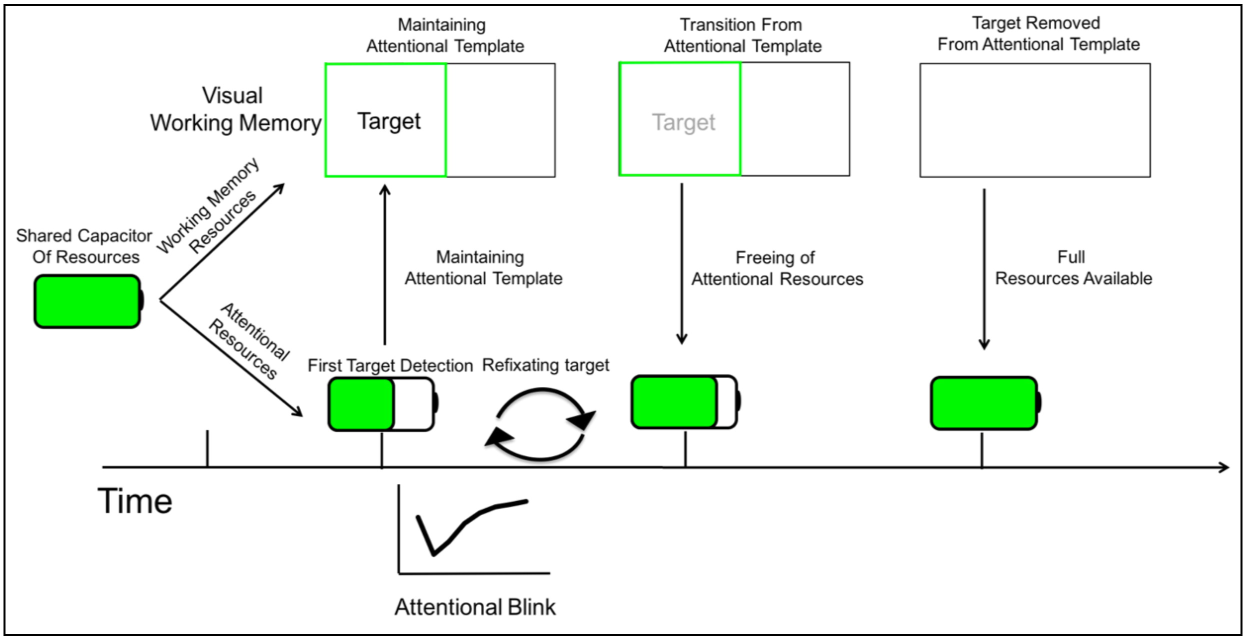

Figure 9: Depiction of the Flux Capacitor models freeing of attentional resources. Before search begins, the capacitor of cognitive resources is full as there is no item maintained within visual working memory and no search is being conducted. After initial target detection, working memory resources are first utilized to process a first target into working memory and then maintain that target within the attentional template. As search progresses (without re-fixating a first target), the first target gradually transitions from the attentional template freeing up working memory resources that can then be used as attentional resources in detecting targets. However, re-fixating a first target can cause a temporary fluctuation in the attentional resources available as the first target is again processed and maintained within working memory.

My Flux Capacitor theory seeks to integrate attentional template and SSM effect research in order to provide an explanation for why a first target consumes attentional resources necessary for second target detection. The foundation of this theory is that after a first target is found, it is maintained as the attentional template resulting in a consumption of attentional resources (See Figure 9). Based on this foundation, there are three tenets of this theory that explain how attentional resources may fluctuate through the duration of search which will aid or hinder second target detection: 1) When a first target is initially established as the attentional template, it will consume more working memory resources after initial detection. This high consumption of resources can cause an attentional blink for a second target if it is encountered during the attentional blink window (Chapter 2; Adamo et al., 2013). 2) After the attentional blink window, the first target remains in the attentional template. However, during search, the first target can transition out of the attentional template, which would result in a freeing of attentional resources. The transfer of a first target may happen because the first target is either learned and transitions to long-term memory, or the first target is forgotten. 3) Attentional resources in search may fluctuate depending on challenges presented within the search environment, the attentional state of the observer, or re-fixating a first target. In particular, re-fixating a first target can have both a negative and positive impact on second target detection. The negative impact may come in the form of another attentional blink for a second target if the second target is fixated within the attentional blink window. The positive impact may be that re-fixating a first target expedites learning and the first target transitions to long-term memory.

Below, I will discuss one main assumption of the Flux Capacitor theory that is necessary for each tenet of the theory. Then I will discuss the specific predictions of each tenet of the Flux Capacitor theory and provide future research directions when applicable.

5.5 Assumption of the model

The main assumption of the Flux Capacitor theory is that there is a shared, limited cognitive resource utilized both in maintaining an item(s) in working memory and detecting a target(s) within search (e.g., Awh, Jonides, Lorenz, 1998; Kiyonaga & Egner, 2013). In this theory, the term "flux" refers to how this shared resources can fluctuate between *maintaining* a found target within working memory (i.e. working memory resources) and *detecting* targets (i.e., attentional resources). Attentional resources can also fluctuate depending on the attentional state of the observers (i.e., their level of vigilance) and distracting elements encountered within the visual search (e.g., clutter).

The term "capacitor" refers to the limited cognitive resources underlying working memory and attention. Although the dichotomy between working memory and attention is a hotly debated issue, it is argued that they can compete for the same limited resources (Kiyonaga & Egner, 2013). The Flux Capacitor theory relies on this idea as it explains why maintaining a first target in working memory consumes attentional resources necessary to find additional targets.

5.6. Tenets of the model

5.6.1. Establishing the first target in the attentional template

The main tenet of the Flux Capacitor theory is that once a first target is detected, it is maintained within the attentional template. This tenet was motivated, in part, by the Perceptual Set account—a second target is more likely to be detected if it is similar to a first target and less likely to be detected if it is dissimilar (Berbaum et al., 1991). My colleagues and I previously demonstrated that observers are more likely to detect a second target if it is identical, the same color, or the same category as the first target (Biggs et al., 2015). This finding runs parallel to research on the attentional template, which demonstrates that an item held within the attentional template can bias attention towards items that are similar and away from items that are dissimilar (e.g., Olivers et al., 2011; Duncan & Humphreys, 1989). If attention is biased towards similar items as a result of the attentional template (i.e., the first target), this could explain why a similar, second target is more often detected within multiple-target visual search. The prediction that a first target is maintained by the attentional template was also motivated by the research presented in Chapter 4 which demonstrates a correlation between the attentional modulation of a first target and second-target misses. This research suggests the longer a first target is processed within working memory, the more likely an observer is to miss a second target. If a first target is maintained within an attentional template, this would suggest *why* the first target remains within working memory and is continually processed after initial detection.

Future research could check the validity of the prediction that a first-target is maintained as an attentional template by observing eye-movements in a multiple-target visual search where targets and distractors can vary in shape and color. Support for the attentional template prediction would suggest that after observers detect a first target, they would be more likely to fixate targets or distractors that share the same color or shape as the first target and more often detect additional targets that are a similar color or shape.

5.6.2. An attentional blink

The second tenet of the Flux Capacitor theory is that when a first target is initially established within the attentional template, a high amount of working memory resources are consumed and can result in an attentional blink (AB) for a second target. As discussed in Chapter 2 of this dissertation, one known mechanism that underlies SSM errors is a self-induced AB. While there are many differences between a typical AB task and a multiple-target visual search, one *key* difference is that while in an AB task, the blink occurs *before* a first target is consciously detected and in a multiple-target visual search task, the blink occurs *after* a first target is consciously detected. In an AB paradigm, all theories predict that a second target is missed while a first target is being processed within working memory before conscious awareness (see Dux & Marois, 2009 for a review of attentional blink theories). Within a multiple-target search, the blink for a second target can happen after a first target is already consciously identified. The prediction made in the Flux Capacitor theory can help to explain the discrepancy between findings; the working memory resources used to maintain the attentional template are greatest after initial detection which is why the blink occurs after conscious detection of the first target. Working memory consumption may be greatest after initial detection because the shared resources are initially reserved to preserve the attentional template status. However, once search continues after finding the first target, the amount of working memory resources will fluctuate and can be allocated towards attentional resources for target detection (See Figure 9).

5.6.3. Leaving the attentional template

The third tenet of the Flux Capacitor theory is that over time a first target will transition from the attentional template which will free up additional attentional resources. The motivation for this prediction stems from the research in support of the Satisfaction account—observers who search longer after finding a first target are more likely to detect a second-target (Adamo et al., 2015a). In order to explain this finding, the Flux Capacitor theory predicts that when a first target transfers from working memory, working memory resources are freed up and reallocated as attentional resources. The transition of a first target from the attentional template could happen due to two different reasons: 1) the first target transitions to long-term memory or 2) the first target is forgotten and dropped from working memory. Both are plausible ways an item can leave working memory and the research described below is what motivated these predictions.

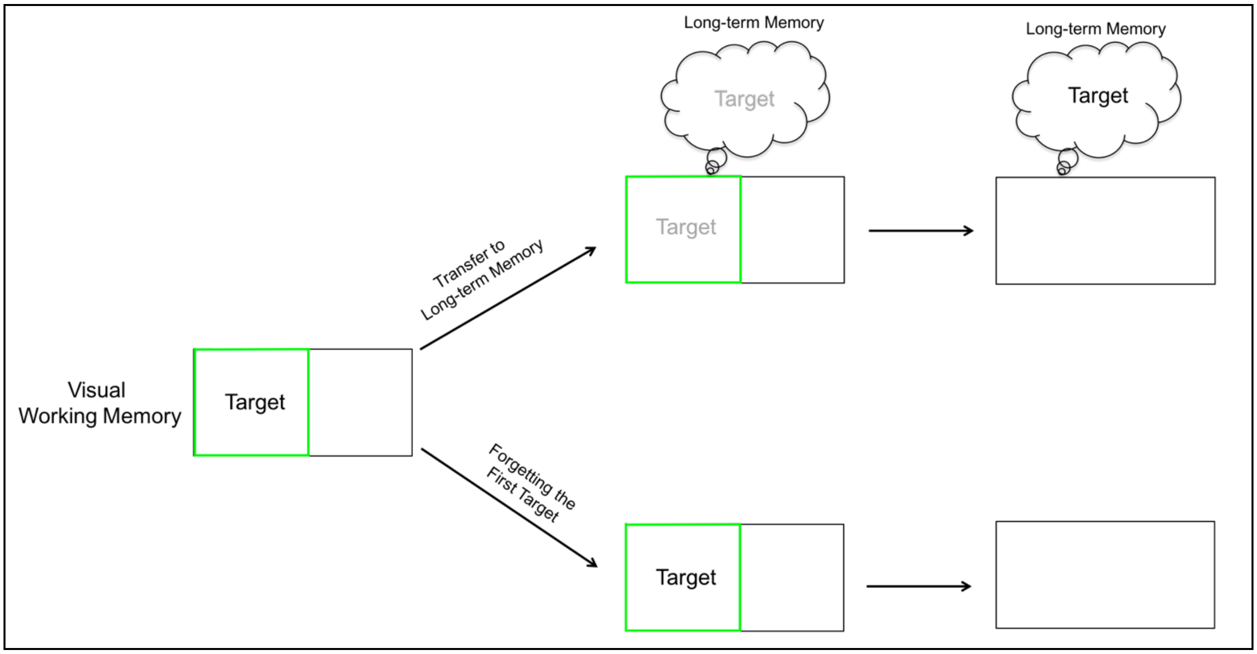

Figure 10: Depiction of how a first target can transition from the attentional template. The first way is that as a first target is learned, it can transfer to long-term memory (top of the figure). The second way is that a first target can be forgotten (bottom of the figure). Both ways free up working memory resources so it can be utilized as attentional resources for target detection.

As discussed within the *Review of the attentional template research* section, an item held within the attentional template can transfer from visual working memory to long-term memory as the attentional template is repeated from trial-to-trial (Carlisle et al., 2011; Gunseli et al., 2014; See Figure 10). In multiple-target visual search, the first target may also transfer from the attentional template to long-term memory. For example, in the search task discussed in Chapters 2, 3, and 4 there were only two-target types: a high-salience target 'T' and a low-salience target 'T'. Observers were explicitly aware that there were two target types and these targets were repeated from trial-to-trial. Over time, it is likely that observers learned these two targets and a first target would transfer to long-term memory after initial detection. Similarly, learning of a first target could occur within a single trial as the observer is constantly exposed to the target in the search display, either when the target is in the periphery or when re-fixating a target in search. Over time, the observer could learn what and where the first target is located which could lead to the transfer of the first target to long-term memory.

Future research could check the validity of the prediction that a first-target transitions to long-term memory by exploring the contralateral delay activity (CDA) following the detection or fixation of a first target. The CDA is an event related potential index of how many items are within working memory (e.g., McCollough et al., 2007; Vogel & Machizawa, 2004) and has been used as reliable ERP marker to determine if an item is being held within the attentional template (Carlisle et al., 2011; Gunseli, et al., 2014). If a first target transitions to long-term memory, there should be a reduction in the CDA across trials as the first target is learned within the experiment. Similarly, if a first target is re-fixated after initial detection, there could be a reduction in the CDA between initial detection and re-fixations suggesting that the first target is learned within a trial and is transitioning to long-term memory.

A different way a first target can leave the attentional template is by forgetting a first target. Items within visual working memory have been shown to suddenly drop from memory after a few seconds (Zhang & Luck, 2009). While this has not been explicitly demonstrated to occur naturally for a first target, forced forgetting of a first target (that was presumed to be held within working memory) has been shown to improve search performance (Cain et al., 2014; Cain & Mitroff, 2013). By removing a first target from the search display after initial target detection (Cain & Mitroff, 2013) and terminating the search after initial target detection, and repeating the search a few trials later without the first target in the display (Cain et al., 2014), SSM errors decreased for a second target.[1]

Future work could explore whether a first target is forgotten by having observers report the identity of the target and where it was located after initial detection. If observers are forgetting a target, they would likely show poorer performance in identifying and reporting a target's location. This probing question could be asked at different time intervals after detecting a first target, or after a search was finished, to obtain a time estimate of if/when a first target is forgotten.

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[1] Although forgetting a first target is a plausible way to free up working memory resources, it seems unlikely that is happening naturally (i.e., without any experimental manipulations) within multiple-target searches. As mentioned in Chapter 1, research in single-target visual search has unequivocally demonstrated there is memory for previously searched items in visual search displays (e.g., e.g., Beck, et al., 2006; Dickson & Zelinsky, 2005; Hollingworth, et al., 2001; Peterson, et al., 2001; Takeda, 2004). Research in multiple-target search offers evidence that there is even better memory for a found target in search as it re-fixated more often (23.7%; Cain, et al., 2013) in comparison to non-target items within a single-target search display (5.7%; Peterson et al., McCarley, 2001). These findings suggests that it is unlikely that a first target is simply forgotten after detection. None-the-less, forgetting a first target is offered as a possible way a first target can leave the attentional template as forgetting would theoretically explain how working memory resources could be freed up within a multiple-target visual search.

5.6.4. Fluctuations of attentional resources

The last tenet of the Flux Capacitor theory is that the availability of attentional resources fluctuate depending on challenges presented within the search environment, the attentional state of the observer, or re-fixating a first target. In this dissertation, I presented two known factors that can cause attention to fluctuate. The first factor is clutter, which is a well known attentional distraction that negatively impacts target detection in single-target visual searches (e.g., see Rosenholtz et al., 2007). My research in Chapter 3 (Adamo et al., 2015b) demonstrates that the negative effects of clutter is exacerbated by finding a first target and leads to a greater decrease in second-target accuracy, as clutter increases around a second target. In the Flux Capacitor theory, clutter is a challenge that can be encountered within multiple-target visual searches that can cause the attentional resources to fluctuate depending on the amount of clutter around a second target.

The second factor previously presented that can cause the amount of attentional resources to fluctuate is the vigilance of the observer. In Chapter 4, I demonstrated that the less vigilant an observer is at the time of search, the more likely they are to miss a second target. According to the Mental Fatigue account, attentional resources need to be constantly replenished during use, and vigilant decrements occur when attention is utilized at a faster rate than it can be replenished (Parasuraman et al., 1987). In the Flux

Capacitor theory, attentional resources will in turn fluctuate depending on the vigilant state of the observer: if an observer is less vigilant, less attentional resources will be available and if an observer is more vigilant, more attentional resources will be available.

The final proposed factor that can cause the amount of attentional resources to fluctuate is re-fixations of a first target. According to the Flux Capacitor theory, re-fixations of a first target can both decrease and increase the amount of attentional resources available to process a second target. Initially, re-fixating a first target can cause a decrease in the amount of attentional resources available. This prediction stems from the finding that re-fixating a target can cause a self-induced attentional blink for the first target (Chapter 2; Adamo et al., 2013) when an attentional blink for a second target occurs. This finding could be due to the reprocessing of a first target within working memory and could subsequently leave less attentional resources. However, after the attentional blink window, re-fixations of a first target could expedite the transfer of a first target from the attentional template to long-term memory. This prediction stems from the research demonstrating that as the same attentional template is repeated over trials, the attentional template eventually transfers to long-term memory (Carlisle et al., 2011; Gunseli et al., 2014). The transfer to long-term memory would free up working memory resources that can be reallocated to finding a second target. Research in eye tracking and SSM errors support this prediction. Cain et al., (2013) demonstrated that there was a decrease in the amount of SSM errors made the more often an observer re-fixated a found target in a multiple-target search. This finding could be because the re-fixations of a first target are having a similar effect as repeating an attentional template across search trials. By fixating a found target more often, this could expedite the process of a first target transferring to long term memory and frees up attentional resources to detect additional targets. As discussed earlier, future research could explore whether the CDA following the fixation of a first target decreases as the first target is re-fixated. A reduction in the CDA would suggest that a first target is learned and transitioning to long-term memory.

5.7. Conclusion

SSM errors have been in thorny problem in the side of radiologist for over 50 years. A key way to remedy these errors is by better understanding the underlying mechanism(s) of SSM errors, so the problem can be identified and changes can be made to how observers search. Over the 50 plus years of SSM error research, three theoretical accounts have been proposed. The original theoretical account proposed was the Satisfaction account—observers become "satisfied" with the meaning of the search display after finding a first target causing them to prematurely terminate their search and miss the second target. The second theory proposed was the Perceptual Set account—once a target is found, observers are subsequently more likely to find perceptually similar and less likely to find targets that are perceptually dissimilar. The third theory proposed was the Resource Depletion account—a found, first target consumes attentional and working memory resources leaving less cognitive resources available to detect additional targets. While my colleagues and I have provided evidence in support of the Satisfaction account (Adamo et al., 2015a) and the Perceptual Set account (Biggs et al., 2015), the underlying support for the role of attention in the Resource Depletion account has largely remained elusive. In this dissertation, I explored the causal mechanism of the Resource Depletion account and provided the first evidence that a found target can consume attentional resources necessary to detect a second target. I demonstrated this on three different levels: 1) the target-to-target relationship (Chapter 2; Adamo et al., 2013), 2) the distractor-to-target relationship (Chapter 3; Adamo et al., 2015), and 3) the observer-to-target relationship (Chapter 4; Adamo et al., 2016).

In Chapter 2, I demonstrated a very specific temporal connection when processing a first and second target: A second target is more likely to be missed if fixated 135ms-405ms after detecting a first target. This time frame of reduced second-target accuracy is known as an attentional blink (Raymond et al., 1992) and has an extensive literature demonstrating that attentional resources consumed by the first target can inhibit the processing of a second target (see Dux & Marois, 2009 for a review). In relation to the Resource Depletion account, this finding provided the first evidence to a potential mechanism that underlies SSM errors in that a first target can cause an attentional blink for a second target in a self-paced, multiple-target visual search.

In Chapter 3, I showed that the spatial proximity between targets and distractors can affect target detection. After a first target is found, second target detection decreases as distractors within a close proximity (i.e., clutter) increases around a second target. In relation to the Resource Depletion account, if the first target is draining attentional resources, this finding suggests that additional attentional distractions, such as clutter, can impose an additional load on attention, leaving even less attentional resources available to detect a second target.

In Chapter 4, I used individual differences to reveal which characteristics of attention affect second target detection. Observers who had poorer attentional modulation (i.e., it took them longer to process a target) and lower vigilance were predictive of worse second target detection. In relation to the Resource Depletion account, these findings suggest that attentional modulation is predictive of second target detection and that a first target is continually processed after initial detection. Similarly, the finding that vigilance is predictive of second target detection suggests that the effects of attentional resource consumption by a first target has on second-target detection can be compounded as attentional vigilance declines.

In this chapter, I proposed a new theory of SSM errors, the Flux Capacitor theory. At its core, it embraced the research presented in this dissertation, accounted for the findings in support of the Satisfaction and Perceptual set account, and offered a specific mechanism as to why all SSM errors occur. The Flux Capacitor theory predicts that after a first target is detected, it is maintained as an attentional template in working memory. By maintaining the target in the attentional template, working memory resources are consumed that could otherwise be allocated to attentional resources used for detecting additional targets. Over the course of search, the first target may transition from the attentional template by either transferring to long-term memory or by being forgotten and leaving working memory. When a first target leaves the attentional template, working memory resources are freed up and can be reallocated as attentional resources. Finally, the attentional resources available to detect a second target may fluctuate after finding a first target depending on challenges presented within the search environment, the attentional state of the observer, or re-fixating a first target. While the predictions of this theory are part conjecture, they are rooted in the research on SSM errors and the attentional template.

Unlike other attentional paradigms, such as the attentional blink, SSM errors were not discovered in a lab; they were discovered because abnormalities were being missed in radiological scans. SSM errors are a critical problem in real-world searches such as those conducted by radiologists and airport security personnel. A better understanding of the cause of SSM errors and ways that they can be exacerbated is important because it can literally save lives. Hopefully this dissertation has demonstrated that SSM errors are not simply due to an observer becoming "satisfied" and prematurely terminating their search, as was originally predicted over 50 years ago. SSM errors occur because our minds attend to items in the visual world in specific ways and the visual processing of items has its advantages and disadvantages. By better understanding how and why failures in visual processing happen, the closer we will be in finding ways to counteract these critical cognitive pitfalls of attention.

Works Cited

Adamo, S. H., Biggs, A. T., & Mitroff, S. R. (2013, May). Bags need their own personal space. Presented at the Vision Sciences Society Meeting, Naples, FL.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2013). Self-induced attentional blink: A cause of errors in multiple-target search. *Psychological Science*, *24*(12), 2569–2574.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2015a) Satisfaction at last: Evidence for the "satisfaction" hypothesis for multiple-target search errors. *Visual Cognition, 23*(7), 821–825.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2015b). Targets need their own personal space: The effects of clutter on multiple-target search accuracy. *Perception, 44*(10), 1203–1214.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2016). An individual differences approach to multiple-target visual search errors: How search errors relate to different characteristics of attention. Manuscript submitted for publication.

Anbari, M. M., & West, C. O. (1997). Cervical spine trauma radiography: Sources of false-negative diagnoses. *Emergency Radiology*, *4*, 218–224.

Asher, M. F., Tolhurst, D. J., Troscianko, T., & Gilchrist, I. D. (2013). Regional effects of clutter on human target detection performance. *Journal of Vision*, *13*(5):25, 1–15.

Ashman, C. J., Yu, J. S., & Wolfman, D. (2000). Satisfaction of search in osteoradiology. *American Journal of Roentgenology*, *175*(2), 541–544.

Awh, E., Jonides, J., & Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 780–790.

Beck, M., Peterson, M. S., & Vomela, M., (2006). Memory for where, but not for what is used during visual search. *Journal of Experimental Psychology: Human Perception & Performance*, *32*, 235–250.

Beck, V. M., Hollingworth, A., & Luck, S. J. (2012). Simultaneous control of attention by multiple working memory representations. *Psychological Science*, *23*(8), 887–898.

Berbaum, K. S., Brandser, E. A., Franken, E. A., Dorfman, D. D., Caldwell, R. T., & Krupinski, E. A. (2001). Gaze dwell times on acute trauma injuries missed because of satisfaction of search. *Academic Radiology, 8*(4), 304–314.

Berbaum, K. S., Caldwell, R. T., Schartz, K. M., Thompson, B. H., & Franken Jr., E. A. (2007). Does computer-aided diagnosis for lung tumors change satisfaction of search in chest radiography? *Academic Radiology, 14*(9), 1069–1076.

Berbaum, K. S., El-Khoury, G. Y., Franken Jr., E. A., Kuehn, D. M., Meis, D. M., Dorfman, D. D., … Kathol. (1994). Missed fractures resulting from satisfaction of search effect. *Emergency Radiology*, *1*(5), 242–249.

Berbaum, K. S., Franken Jr., E. A., Anderson, K. L., Dorfman, D. D., Erkonen, W. E., Farrar, G. P., … Phillips, M. E. (1993). The influence of clinical history on visual search with single and multiple abnormalities. *Investigative Radiology, 28*(3), 191–201.

Berbaum, K. S., Franken Jr., E. A., Dorfman, D. D., Miller, E. M., Caldwell, R. T., Kuehn, D. M., & Berbaum, M. L. (1998). Role of faulty visual search in the satisfaction of search effect in chest radiography. *Academic Radiology*, *5*(1), 9–19.

Berbaum, K. S., Franken Jr., E. A., Dorfman, D. D., Rooholamini, S. A., Coffman, C. E., Cornell, S. H., . . . Kao, S. C. (1991). Time course of satisfaction of search. *Investigative Radiology*, *26*, 640–648.

Berbaum, K. S., Franken Jr., E. A., Dorfman, D. D., Rooholamini, S. A., Kathol, M. H., Barloon, T. J., … Montgomery, W. J. (1990). Satisfaction of search in diagnostic radiology. *Investigative Radiology, 25*(2), 133–140.

Berbaum, K. S., Franken Jr., E. A., Dorfman, D. D., Caldwell, R. T., & Krupinski, E. A. (2000). Role of faulty decision making in the satisfaction of search effect in chest radiography. *Academic Radiology, 7*(12), 1098–1106.

Berbaum, K. S. (2012). Satisfaction of search experiments in advanced imaging. *Proceedings of SPIE, 8291*(1), 82910V–82910V–8.

Biggs, A. T., Adamo, S. H., Dowd, E. W., & Mitroff, S. R. (2015). Examining perceptual and conceptual set biases in multiple-target visual search. *Attention, Perception, & Psychophysics, 77*, 844–855.

Biggs, A. T., Adamo, S. H., & Mitroff, S. R. (2014). Rare, but obviously there: Effects of target frequency and salience on visual search accuracy. *Acta Psychologica, 152*, 158–165.

Biggs, A. T., & Mitroff, S. R. (2014). Improving the efficacy of security screening tasks: A review of visual search challenges and ways to mitigate their adverse effects. *Applied Cognitive Psychology, 29*(1), 142–148.

Bowman, H., & Wyble, B. (2007). The simultaneous type, serial token model of temporal attention and working memory. *Psychological Review*, *114*, 38–70.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*, 433–436.

Broadbent, D., & Broadbent, M. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics*, *42*, 105–113.

Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2011). A neural theory of visual attention and short-term memory (NTVA). *Neuropsychologia*, *49*(6), 1446–1457.

Cain, M. S., Adamo, S. H., & Mitroff, S. R. (2013). A taxonomy of errors in multiple-target visual search. *Visual Cognition*, *21*(7), 899–921.

Cain, M. S., Biggs, A. T., Darling, E. F., & Mitroff, S. R. (2014). A little bit of history repeating: Splitting up multiple-target visual searches decreases second-target miss errors. *Journal of Experimental Psychology: Applied*. *20*(2), 112–125.

Cain, M. S., Dunsmoor, J. E., LaBar, K. S., & Mitroff, S. R. (2011). Anticipatory Anxiety Hinders Detection of a Second Target in Dual-Target Search. *Psychological Science, 22(7)*, 866–871.

Cain, M. S. & Mitroff, S. R. (2013). Memory for found targets interferes with subsequent performance in multiple-target visual search. *Journal of Experimental Psychology: Human Perception and Performance*. *39*(5), 1398–1408.

Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *The Journal of Neuroscience*, *31*(25), 9315–9322.

Chan, H. S., & Courtney, A. J. (1995). Visual performance on detection tasks with two targets. *International Journal of Human Factors in Manufacturing, 5*(4), 417–428.

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology, 62*, 73–101.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 109–127.

Chun, M. M. (1997). Types and tokens in visual processing: A double dissociation between the attentional blink and repetition blindness. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 738–755.

Clark, K., Cain, M. S., Adamo, S. H., & Mitroff, S. R. (2012). Examining influences on applied visual search performance. In M.D. Dodd & J. H. Flowers (Eds.), *The Influence of Attention, Learning, and Motivation on Visual Search* (Vol. 59, pp. 147–181). New York, NY: Springer.

Clark, K., Cain, M. S., Adcock, R. A., & Mitroff, S. R. (2013). Context matters: The structure of task goals affects accuracy in multiple-target visual search. *Applied Ergonomics*, *45*(3), 528–533.

Cousineau, D., Charbonneau, D., & Jolicoeur, P. (2006). Parameterizing the attentional blink effect. *Canadian Journal of Experimental Psychology, 60*(3), 175–189.

Dakin, S. C., Bex, P. J., Cass, J. R., & Watt, R. J. (2009). Dissociable effects of attention and crowding on orientation averaging. *Journal of Vision*, *9*(11):28, 1–16.

Di Lollo, V., Kawahara, J., Shahab Ghorashi, S. M., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research*, *69*, 191–200.

Dowd, E. W., & Mitroff, S. R. (2013). Attentional guidance by working memory overrides salience cues in visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(6), 1786–1796.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458.

Duncan, J., Ward, R., & Shapiro, K. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, *369*, 313–315.

Dux, P. E., & Marois, R. (2009). The attentional blink: A review of data and theory. *Attention, Perception & Psychophysics*, *71*(8), 1683–1700.

Eckstein, M. P. (2011). Visual search: A retrospective. *Journal of Vision*, *11*(5), 1–36.

Fleck, M. S., Samei, E., & Mitroff, S. R. (2010). Generalized "satisfaction of search": Adverse influences on dual-target search accuracy. *Journal of Experimental Psychology: Applied, 16(*1), 60–71.

Franken, E. A., Jr, Berbaum, K. S., Lu, C. H., Kannam, S., Dorfman, D. D., Warnock, N. G., … Pelsang, R. E. (1994). Satisfaction of search in the detection of plain-film abnormalities in abdominal contrast studies. *Investigative Radiology, 29*(4), 403–409.

Godwin, H. J., Menneer, T., Cave, K. R., Helman, S., Way, R. L., & Donnelly, N. (2010). The impact of relative prevalence on dual-target search for threat items from airport X-ray screening. *Acta Psychologica, 134*(1), 79–84.

Greene, C. M., Kennedy, K., & Soto, D. (2015). Dynamic states in working memory modulate guidance of visual attention: Evidence from an n-back paradigm. *Visual Cognition*, *23*(5), 546–560.

Gunseli, E., Olivers, C. N. L., & Meeter, M. (2014). Effects of search difficulty on the selection, maintenance, and learning of attentional templates. *Journal of Cognitive Neuroscience*, *26*(9), 2042–2054.

Helton, W. S., & Russell, P. N. (2011). Working memory load and the vigilance decrement. *Experimental Brain Research*, *212*, 429–437.

Henderson, J. M., Chanceaux, M., & Smith, T. J. (2009). The influence of clutter on real-world scene search: Evidence from search efficiency and eye movements. *Journal of Vision*, *9*(1):32, 1–8.

Hollingworth, A., Williams, C. C., & Henderson, J. M. (2001). To see and remember: Visually specific information is retained in memory from previously attended objects in natural scenes. *Psychonomic Bulletin & Review, 8*(4), 761–768.

Hollingworth, A., & Hwang, S. (2013). The relationship between visual working memory and attention: Retention of precise colour information in the absence of effects on perceptual selection. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *368*(1628), 20130061.

Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature, 394*(6693), 575–577.

Horowitz, T. S., & Wolfe, J. M. (2001). Search for multiple targets: Remember the targets, forget the search. *Perception & Psychophysics, 63*(2), 272–285.

Hout, M. C., & Goldinger, S. D. (2015). Target templates: The precision of mental representations affects attentional guidance and decision-making in visual search. *Attention, Perception & Psychophysics*, *77*(1), 128–149.

Jefferies, L. N., & Di Lollo, V. (2009). Linear changes in the spatial extent of the focus of attention across time. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1020–1031.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded task decisions. *Memory & Cognition*, *26*, 1014–1032.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review, 9*(4), 637–671.

Kanwisher, N. G. (1987). Repetition blindness: Type recognition without token individuation. *Cognition*, *27*, 117–143.

Kiyonaga, A., & Egner, T. (2013). Working memory as internal attention: Toward an integrative account of internal and external selection processes. *Psychonomic Bulletin & Review, 20*(2), 228–242.

Klein R. M., & Ishigami Y. (2012). Searching in space and time. In The Influence of Attention, Learning, and Motivation on Visual Search (pp. 5–22). New York: Springer.

Kleiner, M., Brainard, D. H., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception*, *36*, ECVP Abstract Supplement.

Körner, C., & Gilchrist, I. D. (2006). Memory processes in multiple-target visual search. *Psychological Research*, *72*(1), 99–105.

Levi, D. M. (2008). Crowding–an essential bottleneck for object recognition: A mini-review. *Vision Research*, *48*(5), 635–654.

Lunau, R., & Olivers, C. N. L. (2010). The attentional blink and lag 1 sparing are nonspatial. *Attention, Perception, & Psychophysics*, *72*, 317–325.

MacLean, M., & Arnell, K. (2012). A conceptual and methodological framework for measuring and modulating the attentional blink. *Attention, Perception, & Psychophysics, 74*(6), 1080–1097.

McCollough, A.W., Machizawa, M. G., & Vogel, E. K. (2007). Electorphysiological measures of maintaining representations in visual working memory. *Cortex*, *43*, 77–94.

Menneer, T., Cave, K. R., & Donnelly, N. (2009). The cost of search for multiple targets: Effects of practice and target similarity. *Journal of Experimental Psychology: Applied, 15*(2), 125–139.

Menneer, T., Donnelly, N., Godwin, H. J., & Cave, K. R. (2010). High or low target prevalence increases the dual-target cost in visual search. *Journal of Experimental Psychology: Applied, 16*(2), 133–144.

Menneer, T., Barrett, D. J. K., Phillips, L., Donnelly, N., & Cave, K. R. (2007). Costs in searching for two targets: Dividing search across target types could improve airport security screening. *Applied Cognitive Psychology, 21*(7), 915–932.

Mitroff, S. R., & Biggs, A. T. (2014). The ultra-rare item effect: Exceedingly rare items are highly susceptible to search errors. *Psychological Science*, *25*(1) 284–289.

Mitroff, S. R., Biggs, A. T., Adamo, S. H., Dowd, E. W., Winkle, J., & Clark, K. (2014). What can 1 billion trials tell us about visual search? *Journal of Experimental Psychology: Human Perception & Performance 41*(1), 1–5.

Morey, R. D., (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, *4*, 61–64.

Nakayama, K., & Martini, P. (2011). Situating visual search. *Vision Research*, *51*(13), 1526–1537.

Nevin, J. A. (1969). Interval reinforcement of choice behavior in discrete trials. *Journal of Experimental Analysis of Behavior*, *12*, 875–885.

Nodine, C. F., & Kundel, H. L. (1987). Using eye movements to study visual search and to improve tumor detection. *Radiographics, 7*(6), 1241–1250.

Nieuwenhuis, S., Gilzenrat, M. S., Holmes, B. D., & Cohen, J. D. (2005). The role of the locus coeruleus in mediating the attentional blink: A neurocomputational theory. *Journal of Experimental Psychology: General*, *134*, 291–307.

Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review*, *115*, 836–863.

Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*(7), 327–334.

Parasuraman, R., Warm, J.S., & Dember, W.N. (1987). Vigilance: Taxonomy and utility. In L. S. Mark, J. S. Warm , & R. L. Huston (Eds.), *Ergonomics and Human Factors: Recent Research,* (pp. 11–32). New York: Springer-Verlag.

Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science, 12*(4), 287–292.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 979–992.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860.

Rosenholtz, R., Li, Y., & Nakano, L. (2007). Measuring visual clutter. *Journal of Vision*, *7*(2)*,* 1–22.

Samuel, S., Kundel, H. L., Nodine, C. F., & Toto, L. C. (1995). Mechanism of satisfaction of search: Eye position recordings in the reading of chest radiographs. *Radiology, 194*(3), 895–902.

Scolari, M., Kohen, A., Barton, B., & Awh, E. (2007). Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays? *Journal of Vision*, *7*(2):7, 1–23.

Shih, S. I. (2000). Recall of two visual targets embedded in RSVP streams of distractors depends on their temporal and spatial relationship. *Perception & Psychophysics*, *62*, 1348–1355.

Smith, M. J. (1967). *Error and variation in diagnostic radiology.* Springfield, IL: Charles C Thomas.

Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(2), 248–261.

Stroud, M. J., Menneer, T., Cave, K. R., Donnelly, N., & Rayner, K. (2011). Search for multiple targets of different colours: Misguided eye movements reveal a reduction of colour selectivity. *Applied Cognitive Psychology, 25*(6), 971–982.

Takeda, Y. (2004). Search for multiple targets: Evidence for memory-based control of attention. *Psychonomic Bulletin & Review, 11*(1), 71–76.

Temple, J. G., Warm, J. S., Dember, W. N., Jones, K. S., LaGrange, C. M., & Matthews, G. (2000). The effects of signal salience and caffeine on performance, workload, and stress in an abbreviated vigilance task. *Human Factors, 42*(2), 183–194.

Treisman, A. (1991). Search, similarity, and integration between and within dimensions. *Journal of Experimental Psychology. Human Perception and Performance*, *17*, 652–676.

Treisman, A. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*(1), 97–136.

Tuddenham, W. J. (1962). Visual search, image organization, and reader error in roentgen diagnosis. *Radiology*, *78*, 694–704.

Visser, T. A. W. (2007). Masking T1 difficulty: Processing time and the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 285–297.

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin*, *125*, 458–469.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748–751.

Ward, R., Duncan, J., & Shapiro, K. (1997). Effects of similarity, difficulty, and nontarget presentation on the time course of visual attention. *Perception & Psychophysics*, *59*, 593–600.

Warm, J. S., Parasuraman, R., & Matthews, G. (2008). Vigilance requires hard mental work and is stressful. *Human Factors, 50*(3), 433–441.

Whitney, D., & Levi, D. M. (2011). Visual Crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences, 15*(4), 160–168.

Wolfe, J. M. (1994). Guided search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238.

Wolfe, J. M., Horowitz, T. S., Van Wert, M. J., & Kenner, N. M. (1997). Low target prevalence is a stubborn source of errors in visual search tasks. *Journal of Experimental Psychology: General*, *136*(4), 623–638.

Woodman, G. F., & Arita, J. T. (2011). Direct electrophysiological measurement of attentional templates in visual working memory. *Psychological Science*, *22*(2), 212–215.

Woodman, G. F., & Chun, M. M. (2006). The role of working memory and long-term memory in visual search. *Visual Cognition, 14*(4-8), 808–830.

Woodman, G. F., Luck, S. J., & Schall, J. D. (2007). The role of working memory representations in the control of attention. *Cerebral Cortex*, *17*(suppl 1), i118–i124.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision*, *10*(10):16, 1–12.

Zhang, W., & Luck, S. J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science*, *20*(4), 423–428.

Biography

Stephen Hunter Adamo was born in Tucson, Arizona on August 13th, 1987. He enrolled at the University of Arizona in 2005 and graduated with honors, earning a Bachelors of Science degree with a major in Psychology and a minor in Evolutionary Biology. While there, he conducted research in laboratories of Dr. Mary Peterson and Dr. Anna Dornhaus. He then attended Duke University in Durham, North Carolina for graduate school in 2010 with Dr. Stephen Mitroff as an advisor. In 2014, he studied abroad at Virje University in Amsterdam, Netherlands and studied under the guidance of Dr. Christian Olivers. In 2015, he followed Dr. Stephen Mitroff to Washington D.C. and became a visiting researcher at George Washington University for his final year of graduate school.

Journal Articles & Book Chapters

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2016). An individual differences approach to multiple-target visual search errors: How search errors relate to different characteristics of attention. Manuscript submitted for publication.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2015) Satisfaction at last: Evidence for the "satisfaction" hypothesis for multiple-target search errors. *Visual Cognition, 23*(7), 821–825.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2015). Targets need their own personal space: The effects of clutter on multiple-target search accuracy. *Perception, 44*(10), 1203–1214.

Biggs, A. T., **Adamo, S. H.**, & Mitroff, S. R. (2015). Mo' money. Mo' problems: Monetary motivation can exacerbate the attentional blink. *Perception*, *44*(4), 410–422.

Biggs, A. T., **Adamo, S. H.**, Dowd, E. W., & Mitroff, S. R. (2015). Examining perceptual and conceptual set biases in multiple-target visual search. *Attention, Perception, & Psychophysics*, *77*(3), 844–855.

Biggs, A.T., **Adamo, S. H.**, & Mitroff, S. R. (2014). Rare, but obviously there: Effects of target frequency and salience on visual search accuracy. *Acta Psychologica, 152*, 158–165.

Mitroff, S. R., Biggs, A. T., **Adamo, S. H.**, Dowd, E. W., Winkle, J., & Clark, K. (2014). What can 1 billion trials tell us about visual search? *Journal of Experimental Psychology: Human Perception & Performance 41*(1), 1–5.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2013). Self-induced attentional blink: A cause of errors in multiple-target visual search. *Psychological Science, 24*(12), 2569-2574.

Cain, M. S., **Adamo, S. H.**, & Mitroff, S. R. (2013). A taxonomy of errors in multiple-target visual search. *Visual Cognition, 21*(7), 899–921.

Clark, K., Cain, M. S., **Adamo, S. H.**, & Mitroff, S. R. (2012). Examining influences on applied visual search performance. In M. D. Dodd & J. H. Flowers (Eds.), *The Influence of Attention, Learning, and Motivation on Visual Search* (Vol. 59, pp. 147–181). New York: Springer.

Professional Conference Presentations

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2015, May). An individual differences approach to multiple-target search errors: Errors correlate with attentional deficits. Presented at the Vision Sciences Society Meeting, St. Pete Beach, FL.

Adamo, S. H., Biggs, A. T., & Mitroff, S. R., (2013, November). Mo' money. Mo' problems: Monetary motivation can exacerbate the attentional blink. Presented at the Object Perception and Memory Meeting, Toronto, Canada.

Bel-Bahar, T., Gentzler, E., **Adamo, S. H.**, Wang, L., Krasich, K., Hughes, L., Mitroff, S. R., & Appelbaum, L. G. (2013, November). *Visuomotor performance is predicted by ERP amplitudes in a rapid serial visual presentation (RSVP) protocol*. Poster presented at the annual meeting of the Psychonomic Society, Toronto, ON, Canada.

Adamo, S. H., Biggs, A. T., & Mitroff, S. R., (2013, May). Bags need their own personal space. Presented at the Vision Sciences Society Meeting, Naples, FL.

Adamo, S. H., Cain, M. S., & Mitroff, S. R. (2012, November). Self-induced attentional blink: A cause of errors in multiple-target visual search. Talk given at the Object Perception and Memory Meeting, Minneapolis, MN.

Mitroff, S. R., Biggs, A. T., Cain, M. S., Darling, E. F., Clark, K., **Adamo, S. H.**, & Dowd, E. W. (2012, November). *In search of experience effects: How TSA officers differ from undergraduates on visual search tasks*. Paper presented at the annual meeting of the Psychonomic Society, Minneapolis, MN.

Cain, M. S., **Adamo, S. H.**, & Mitroff, S. R. (2012, May). *What eye-tracking can tell us about multiple-target visual search*. Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Mitroff, S. R., Biggs, A. T., Cain, M. S., Darling, E. F., Clark, K., **Adamo, S. H.**, & Dowd, E. W. (2012, May). *Visual search at the airport: Testing TSA officers*. Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Adamo, S. H., Cain, M., & Mitroff, S. (2011, October). Targets need their own personal space. Talk given at the Annual Ford Fellowship Conference, Orange County, CA.

Academic Awards and Honors

Predoctoral Ford Foundation Fellowship, 2011 – 2016
National Science Foundation (NSF) Graduate Research Fellowship, 2011 – 2016
Graduate Research Opportunities Worldwide (GROW) Fellowship, 2014 – 2015