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Multiple-Target Visual Search Errors: Overview and Implications for Airport Security

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Abstract

Visual search—the ability to locate visual targets among distractors—is a fundamental part of professional performance for many careers, including radiology, airport security screening, cytology, lifeguarding, and more. Successful execution of visual search in these settings is critically important because the consequences of a missed target can be horrific. Unfortunately, many of these professions place high demands on the people performing the searches, and either the task or the environment (or both) could lead to significant errors. One known source of error that exists across many fields is "multiple-target visual search" errors—a target is less likely to be detected if another target was already found in the same search than if the target was the only one present. These errors have proven to be stubborn and not easily eliminated. This article offers a brief overview of the existing research on multiple-target visual search errors and discusses possible policy implications of the errors for airport security screening. The policy suggestions are based on empirical research, with the hope of providing food for thought on using scientific data and theory to improve performance. Specifically, three policy suggestions are raised: shift screening to a remote location away from the checkpoint, reduce the number of prohibited items to lessen the searchers' cognitive burden, and emphasize search consistency in the training process. Note that the focus here is on airport security screening, as this is a domain most readers can relate to, but the suggestions can equally apply to many search environments.

Keywords

multiple-target visual search, satisfaction of search, subsequent search misses, airport security, cognitive psychology

Tweet

Success breeds failure? Finding one item in a search makes it harder to find other items, raising concerns for airport security.

Key Points

- Visual search is difficult, yet many professions (e.g., radiology, airport security) fundamentally depend on it being executed successfully.
- One particular challenge to search performance arises when more than one target can be simultaneously present; searchers are more likely to miss an item if they have already found a different item in the same search.
- Based on empirical research, three suggestions are offered to potentially help airport security thwart the negative impact of multiple-target visual search errors.

Introduction

Expressions like "success breeds success" imply that performing well should engender future positive outcomes. For example, correctly answering one exam question might bolster performance for the next question, winning a hand at blackjack might lead to a streak of good luck, and hitting a shot in basketball might increase the chances that your next shot will also go in. There is much debate over such "hot hand" phenomena (tellingly also referred to as the "hot hand fallacy"; Ayton & Fischer, 2004; Croson & Sundali, 2005; Gilovich, Vallone, & Tversky, 1985), and it is an interesting idea that doing well might lead to additional positive outcomes. However, there is clear and unquestionable evidence of at least one counter-example—Over 50 years of research has shown that when searchers successfully find a visual target, they become *less* likely to find another target in the same

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search (for recent reviews, see Berbaum, 2012; Berbaum, Franklin, Caldwell, & Schartz, 2010).

When radiologists find a fracture in a radiograph, they become more likely to miss additional abnormalities that might also be present. When airport security screeners find a water bottle in an X-ray image of a carry-on bag, they become more likely to miss additional (perhaps more lethal) contraband items. And when pathologists find a cancerous marker on a microscope slide, they become more likely to miss additional signs of cancer in the same search. While these examples present a fascinating psychological conundrum (success breeds failure?), the broader issue is that this phenomenon represents a severe performance limitation in some of the most important and practical visual searches.

The core problem stems from uncertainty involving the quantity and types of targets present in a visual search—an unavoidable and ubiquitous aspect of some visual searches that have security, health, and policy implications. While some searches have a predetermined and prescribed number of targets (e.g., people know to continue searching for a second shoe after finding the first), other searches have an unknown and unconstrained number of targets. For example, radiologists look at X-rays that could contain any number of abnormalities, airport security screeners look through X-rays that could contain multiple contraband items, and military personnel scan environments for any number of hostile individuals. Unfortunately, searchers cannot predetermine the number and types of targets without defeating the need for and purpose of the search, which illustrates why the problem can be so difficult to address.

It has been well established that a particular target is less likely to be detected if another target was already found in the same search than if it was the only target present (Berbaum, 2012; Berbaum et al., 2010). The prevalence of these errors, however, can be difficult to assess given the many different contexts in which they occur and the uncertain nature of the various visual search parameters. It has been suggested that they account for a significant number of search errors in radiology, with estimates as high as 20% to 30% (e.g., Berbaum et al., 2010; Krupinski, 2010). In controlled laboratory experiments from cognitive psychology, this type of error consistently appears at a rate of approximately 15% in multiple-target searches (Biggs & Mitroff, 2014a, 2014b; Fleck, Samei, & Mitroff, 2010). Thus, although the magnitude of the error may vary, multiple-target visual search errors remain a real concern across many different types of searches.

While academic radiology studies conducted in laboratory-based settings and cognitive psychology studies can garner reliable estimates for the rate of multiple-target visual search errors, it is not possible to truly know the rate for other fields, such as airport security screening. However, there are several reasons to believe that similar error rates could occur at airport checkpoints. First, an airport X-ray search is fundamentally similar to a radiological X-ray search. The basic structure of visual search differs based on any number of situational factors, but at the end of the day, visual search has similar procedures regardless of whether someone is searching for a tumor or improvised explosives. Second, when officers from the United States Transportation Security Administration were tested on a controlled laboratory-based visual search task, their rate of multiple-target visual search errors was no different from nonprofessional, university-based participants (Biggs & Mitroff, 2014a, 2014b). Third, a visual search task with stimuli similar to airport checkpoint X-ray images (*Airport Scanner*; Kedlin Co.) has revealed approximately a 15% multiple-target visual search error rate across millions of trials (Biggs, Adamo, Dowd, & Mitroff, 2015)—right in line with what is observed in controlled laboratory studies. Collectively, these findings suggest that multiple-target visual search errors should be a concern for airport security personnel because the error rate holds across different participants and with different stimuli.

That radiologists, airport security personnel, and nonprofessional searchers all show similar rates of multiple-target search errors is both comforting and troubling. On one hand, it suggests that this might be a universal psychological phenomenon affecting everyone approximately equally. This is comforting, as it eliminates simple finger pointing associated with the assumption that the errors arise due to individual lapses in performance or individual differences in effort and/or skill. On the other hand, it is troubling that these errors represent a stubborn problem that has been known about for over 50 years in radiological research (Smith, 1967; Tuddenham, 1962) but has yet to be solved. If up to one third of radiological errors in some cases can be solely driven by this phenomenon (Berbaum et al., 2010; Krupinski, 2010), it is worrisome that solid solutions have yet to be implemented.

To reduce the rate of multiple-target visual search errors, it is important to understand their nature and root causes. Recent research into the underlying mechanisms of these errors has produced new insights that might provide tangible and practical prescriptions for reducing their rate (e.g., Cain, Biggs, Darling, & Mitroff, 2014; Cain & Mitroff, 2013; for a review, see Biggs & Mitroff, 2015). The goal of this article is to present these recent findings and to discuss potential implications for airport security policy.

Airport Security Screening

The primary focus of the present article is on airport security searches as there is need for using scientifically based evidence to offer tangible policy changes. Multiple-target visual search errors are likely a significant worry for airport security and a few policy changes based on experimental evidence and theory could have large, positive implications for overall performance (Biggs & Mitroff, 2015; Clark, Cain, Adamo, & Mitroff, 2012; Clark, Cain, & Mitroff, 2015).

An interesting issue arises for airport security screening that is not necessarily relevant for radiology or cognitive psychology studies—Specifically, many people assume that if an airport security screener finds a single contraband item, they will then call for a physical search of the whole bag. If this were the case, it could potentially dismiss the negative impact of having found the first target and reduce multiple-target visual search errors. Yet it is unclear whether this is necessarily the case, and even if it were, there are still concerns. First, if a screener were to incorrectly identify a near-miss distractor item as a contraband target (e.g., mistaking an electric razor for a stun gun), that item will serve as a "first target" and could reduce the likelihood of finding subsequent real targets. Second, several airport security organizations artificially project threat items into bags as they go through the checkpoint X-ray (e.g., Hofer & Schwaninger, 2005). This is done for a variety of good reasons, but one possible negative implication is that a fake threat item might be projected into a bag that actually contains a real threat item. As is discussed in more detail below, the implementation of this system is ripe for creating multiple-target visual search errors. It is a troubling prospect that a method of assessing errors may in fact be creating errors.

In the remainder of this article, we briefly discuss previous studies that have focused on multiple-target search errors and the underlying mechanisms that have been theorized as possible causes of the errors, and then consider three potential implications for airport security screening. We raise policy implications in light of specific experimental findings to highlight how research might be able to guide change.

Multiple-Target Visual Search: Early Literature Review

An immense amount of research, from academic radiology, cognitive psychology, and other fields has examined the critical workings of visual search (for reviews, see Eckstein, 2011; Krupinski, 2010; Lanagan-Leitzel, Skow, & Moore, 2015; Nakayama & Martini, 2011). However, a relatively small amount of work has focused on multiple-target visual search. The formal introduction of the phenomenon of multiple-target visual search errors came in the 1960s (Smith, 1967; Tuddenham, 1962), and it also came with the first suggestion of a possible underlying mechanism via its name—"satisfaction of search" (SOS). It was suggested that multiple-target search errors arise from the searcher becoming "satisfied" with the meaning of the search after having found the first target (Smith, 1967). Being satisfied with the meaning, the searcher would terminate their search and make their conclusions, even if they had not fully searched the image.

The SOS name has stuck for the past 50 years; however, further investigations revealed that searchers continue searching after finding a first target, yet still miss additional targets in the same search (Berbaum, Dorfman, Franken, & Caldwell, 2000; Berbaum et al., 1991). Empirical support against the "satisfaction" account of SOS has amassed in the last two decades, which means that the moniker "SOS" is itself a little misleading. As such, our research group has recently proposed a name change for this phenomenon to better reflect the multifaceted nature of the underlying causes. We have suggested the new name of "subsequent search misses" (SSM; Adamo, Cain, & Mitroff, 2013). Given that the errors appear to arise for a number of reasons—not just from the "satisfaction" account—a more theory-agnostic label seems appropriate.

Foundational research on SSM errors has come from the domain of radiology. SSM errors have been described in planar X-rays (e.g., Berbaum et al., 1994), radiographs with contrast agents (Berbaum et al., 1996), and computed tomography reconstructions (Berbaum et al., 2013). Beyond establishing that SSM errors are consistently a problem, this body of work also first proposed multiple categories of SSM errors (e.g., items that were never looked at vs. items that were looked at but miscategorized; Nodine & Kundel, 1987). These were later confirmed in the laboratory (Cain, Adamo, & Mitroff, 2013). Academic radiology has also investigated ways of reducing SSM errors, such as enforcing particular order of report or using checklists, although the results have suggested that imposing checklists could actually harm performance (Berbaum, Franken, Caldwell, & Schartz, 2006).

A recent influx of SSM research has come from cognitive psychology, and it has served to complement the radiological work. Much of this work is based on early, foundational research into vision and attention (e.g., Neisser, 1974; Schneider & Shiffrin, 1977) that examined how searchers were affected when they had to search for more than one target (e.g., look for several letters from the alphabet among distractor letters), although most of these early tasks never presented more than a single target on a given trial (e.g., Neisser, Novick, & Lazar, 1963). More recent work has provided excellent insight into the nature of what we refer to as *multiple-category search*—having to look for more than one type of target, but with never more than one possible target within a given array (e.g., searching for either a gun or a knife in a single display, but never finding both a gun and a knife in a single display). Multiple-category research has revealed detrimental effects on search performance in terms of both speed and accuracy (e.g., Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Menneer, Cave, & Donnelly, 2009), especially for targets that occur less frequently (Godwin et al., 2010). Furthermore, work with visual search for larger numbers of memorized targets (Drew & Wolfe, 2014; Wolfe, 2012) has shown that these performance detriments grow as the number of to-be-searched-for targets increases.

More recently, cognitive psychology studies have focused directly on the nature of SSM errors—examining search accuracy and timing when more than one target can appear at the same time in the same display. This work has taken a number of different approaches to understanding SSM errors, including trying to delineate the underlying causes (Cain et al., 2013) and comparing SSM errors between professional and nonprofessional searchers (Biggs & Mitroff, 2014a, 2014b).

In addition, cognitive psychology research on SSM errors has revealed numerous situational factors that can exacerbate SSM errors, including searcher anxiety (Cain, Dunsmoor, LaBar, & Mitroff, 2011), the search context (Clark, Cain, Adcock, & Mitroff, 2014), the relationship between the first found target and the subsequent second target (Biggs et al., 2015), time pressure (Fleck et al., 2010), and expectations about the number of targets that might be present (Cain, Vul, Clark, & Mitroff, 2012; Fleck et al., 2010). Moreover, studies have suggested specific procedural changes that can potentially reduce SSM errors, including splitting multiple-target searches into a series of single-target searches (Cain et al., 2014).

Brief Overview of SSM Theories

The original explanation for SSM errors—and the source of the original name—came from the notion that these errors occurred because searchers become "satisfied" upon finding a first target and discontinue searching. However, substantial evidence has demonstrated that searchers *do* continue searching, and therefore "satisfaction" alone is not a sufficient explanation (e.g., Berbaum et al., 1991; Berbaum et al., 1990; Fleck et al., 2010). Recent studies have suggested alternative/additional mechanisms as potential explanations for SSM errors, including a *perceptual set* account and a *resource depletion* account. The perceptual set account (Berbaum et al., 1991; Berbaum et al., 1990) suggests that a found target can create biases during subsequent search, where searchers look for additional targets that match the perceptual features of the first target (e.g., biased to look for blue items after finding a blue item), share a conceptual relationship with the first target (e.g., biased to look for bullets after finding a gun), or both (Biggs et al., 2015). The resource depletion account (e.g., Berbaum et al., 1991) stems from the idea that searchers, during continued search following a found target, must maintain the identity and location of the first target in working memory (Cain & Mitroff, 2013). Maintaining this information then creates a cognitive burden and reduces the cognitive resources available to the searcher upon subsequent search.

Policy Suggestions for Airport Security Screening: Reducing Multiple-Target Visual Search Errors

The remainder of this article focuses on policy implications related to SSM errors and possible suggestions to improve performance at airport security checkpoints based on the empirical research. Each suggestion has potential positives and negatives related to the implementation, and they are discussed in turn.

Suggestion 1: Remote Screening

Move the X-ray image screening process away from the airport checkpoint. One potential policy change with the potential to simultaneously address several concerns facing airport security screening searches is to move the screeners away from the security checkpoints. This idea is known as "remote screening."

Potential positives

1. Having a dedicated location either in the airport or at a centralized control room would reduce potential anxiety associated with being at the checkpoint, such as dealing with impatient travelers, or being aware of how quickly (or slowly) the line is moving. Visual searchers who are anticipating a negative event are more likely to miss second targets than when they are not feeling anxious (Cain et al., 2011).
2. Remote screening could also allow for screeners to be specialists with one target type. For example, each bag could be searched by two different screeners, one searching for metal targets such as guns and knives and another looking for organic targets such as explosives. Searches are faster and more accurate when searching for one category of item than when simultaneously searching for two categories of items (Menneer et al., 2007; Menneer et al., 2009).
3. Remote screening would allow for each bag to be viewed simultaneously by more than one screener. Although the results are somewhat mixed, there are hints that having two individuals conduct a search results in better accuracy than having only one individual complete the search (e.g., Wolfe et al., 2007).
4. When a potential threat item is found in a bag, removed, and the bag rescanned, a different screener could be assigned to the second scan. It is possible that viewing the same bag again can still lead to SSM errors with the searcher perseverating on the location of the previously found target, though it is likely that screeners are able to treat repeat scans as if they were new (Cain et al., 2014).
5. Having the X-ray images sent remotely easily allows for testing and assessment images to be added into the work flow, as has been done in mammography screening (Evans, Birdwell, & Wolfe, 2013). These can replace and/or complement the threat image projection system currently employed by several airport security organizations (e.g., Hofer & Schwaninger, 2005). Importantly, this can be done without

projecting a fake threat item into a passenger's real bag that might contain real contraband.

6. The incentive structure for screeners could be shifted away from a time-based structure to a piece-work structure (e.g., a break after every hundred bags rather than a break after 20 min). This work structure is akin to many radiological work settings, and it has been found that it is more resistant to SSM errors (Clark et al., 2014).
7. Aside from screening accuracy advantages, a handful of centralized screening locations for all airports could have benefits for staffing and scheduling, as the same screeners could handle the morning rush in New York City and then the rush in Los Angeles.

Potential negatives

1. Implementing a remote screening operation would necessitate a good deal of infrastructure upgrades, especially if screening is to happen in centralized locations.
2. This process would raise information privacy and security concerns if images were transmitted from the checkpoints to the remote screening location(s).
3. Centralizing screening would raise the possibility that an attack or natural disaster at the remote facility could affect air travel nationwide.
4. Changes in infrastructure would be needed to allow the screener to communicate to the security personnel stationed at the checkpoint. Even if the remote screening station occurred at a remote location in the same airport as the checkpoint, various communication issues could arise when searchers locate contraband. Specifically, a new system would be challenged with effectively communicating which bag actually contained contraband.

Summary. There is much to like about the idea of remote screening. There are hurdles to implementing it efficiently and safely, but the potential payoffs for performance make it worth considering. Note also that such a system would raise the possibility for "crowdsourcing" airport X-ray screening. Images could be simultaneously viewed by dozens or hundreds of individuals so that each bag is viewed by a large number of people in a small amount of time. This could be done via a website or mobile application.

Suggestion 2: Reduced List of Prohibited Items

Reduce the number of to-be-searched-for items to only those deemed high threats. New potential security concerns often are related to a specific possible threat (e.g., explosives in shoes, liquid explosives, box cutters). With each new possible threat, the list of prohibited items grows. Not only can this cause confusion and annoyance for passengers, but an increased list of prohibited items is also potentially a detriment to the security screening procedure—Having to simultaneously search for a large number of items comes with a cost such that overall accuracy suffers (Wolfe, 2012).

Potential positives

1. In general, searchers are faster to find targets when they have fewer possible targets to hold in long-term memory (Wolfe, 2012). If searchers have fewer targets to find, they may search faster and more accurately. An added benefit of the faster search would be increasing the speed at which passengers move through the checkpoints.
2. One step further than removing a few items, entire categories could be removed from the list of prohibited items. Such a large reduction could have an even greater impact, as searching for items from multiple categories is harder than searching for items from one category (Menneer et al., 2009).
3. Reducing the number of prohibited items has the potential to produce fewer SSM errors, as there would be fewer bags with multiple targets—leaving a relatively higher proportion of more accurate single-target searches.
4. The greatest impact could potentially come from removing commonplace objects from the prohibited list. These are typically the most common items and are usually easy to detect (e.g., a passenger forgets to remove a water bottle). More common and more salient items are usually detected first, meaning that other items that are potentially more dangerous are disproportionally the "second" target in a search, which are more vulnerable to SSM errors.

Potential negatives

1. Determining which items actually pose a credible risk is not an easy task, requiring the various airport security organizations around the world to determine what is and is not a risk. Moreover, it is sometimes difficult to know which items are truly benign, and which items are dangerous items camouflaged to appear benign. For example, even if water bottles were removed from the prohibited item list, the X-ray screen cannot tell whether the liquid inside the bottle is actually water or something potentially hazardous.
2. The nature of potential threats is constantly changing and new concerns arise from time to time. As such, it is important to have a dynamic and responsive system that can add (and remove) items from the prohibited list as appropriate. As noted above, though, this is not necessarily an easy task.

Summary. Airport security organizations provide a fairly extensive list of prohibited items. For example, as can be seen on the various organizations websites, the United States prohibits more than 70 categories of items, Australia more than 45, Hong Kong and Canada more than 40, and the European Union more than 35 (as of 2015). Given these large lists, it is enticing to consider ways to reevaluate each item to determine the credibility of its risk. For example, if the greatest risk facing airport security is an explosive, then it might be possible to minimize the effort that screeners dedicate to looking for other (potentially less threatening) items. However, despite the relatively low structural and training costs to implement this suggestion, there could be political mine fields to traverse in deciding what items to deprioritize, which makes it potentially difficult to pursue.

Suggestion 3: Emphasize Search Consistency in Training and Search Execution

Enhance accuracy with new training and standard operating procedures. Another policy change that would not require modifying the current infrastructure would be to increase the focus on *consistency* of search patterns. Visual search of a novel scene can often be executed in a spatially random fashion, as searchers direct their gaze from the most salient location to the second most salient, and so on (Itti & Koch, 2001; Itti, Koch, & Niebur, 1998), starting with large eye movements across the image and progressing to smaller and smaller changes in gaze (Over, Hooge, Vlaskamp, & Erkelens, 2007). While this might be suitable for day-to-day searches, professional visual searchers in security (Biggs, Cain, Clark, Darling, & Mitroff, 2013) and radiology (Leong, Nicolaou, Emery, Darzi, & Yang, 2007) are more accurate when they execute their search in (mostly) the same way from one bag to the next. The suggestion would be to make search consistency a focal point of employee training and to make it a cornerstone of the checkpoint standard operating procedures.

Potential positives

1. Systematic search is less vulnerable to miss errors (e.g., Biggs et al., 2013; Riggs, Cornes, Godwin, Guest, & Donnelly, 2015) in part because visual search places a memory burden upon the searcher (Dickinson & Zelinsky, 2007)—that is, people have to remember the spatial locations where they have and have not searched. A systematic search imposes less of a memory burden than a more chaotic search because the search pattern is familiar and reliable. This fits with the resource depletion account of SSM errors (cf. Cain & Mitroff, 2013).
2. This policy change has the advantage of not requiring new technology, and it can be implemented incrementally.
3. Consistent search does not necessarily mean that every employee must search the same as their coworkers, just that each individual is internally consistent from bag to bag. This potentially allows for the screeners to find their own solution while also increasing their effectiveness.
4. Once consistent search patterns are well learned and become second nature, they should be efficient. This could have an added benefit of increasing search speed at the checkpoint without a detrimental effect on accuracy.

Potential negatives

1. This approach would require both new training as well as additional research into which search patterns are most effective—if, indeed, there is a performance difference between the myriad of potential search patterns to use.
2. More research is needed to prove that search consistency will indeed improve performance. Preliminary data are positive (Biggs et al., 2013), but more work is needed.
3. Learning a new skill takes time and effort before it becomes second nature and fully mastered (e.g., you do not learn to ride a bike in 1 day), so each employee, training manager, and supervisor would need to have the patience (and support from the organization) to engage in a long training process.

Summary. Recent research (e.g., Biggs et al., 2013) has suggested that executing a visual search in the same way over and over has positive benefits as it frees up valuable cognitive resources—If you do not have to remember where you have and have not searched, you can dedicate more of your cognitive abilities to the primary job of trying to identify each item in a bag as safe or as a threat. The theoretical idea is sound, but more research is needed to confirm the expected benefits for airport security searches.

Conclusion

Several careers heavily rely upon visual search, and it is critical that all efforts are taken to minimize errors. Radiology, airport security, lifeguarding, termite inspections, and other careers require personnel to look for specific targets, and the consequences of missing a target can be grave. One specific factor that negatively affects search performance is the presence of multiple targets in a single search, wherein searchers are more likely to miss a target if they have already found another target in the same display than if it is the only target present (Berbaum, 2012; Berbaum et al., 2010). We refer to these errors as SSM errors, and they can account for up to one third of errors in some forms of radiological search (Berbaum et al., 2010; Krupinski, 2010). The goal here was to discuss possible policy implications of SSM errors for airport security screening. We have focused on airport security screening as it is an area that most readers can relate to and as most airport security organizations around the world are typically interested in ways to potentially improve operations. That said, the above suggestions could potentially be applied to most every form of professional search. Our objective for each of the above suggestions was to base it upon the available empirical research, and each suggestion is accompanied by possible positive and negative outcomes related to its implementation. More work is needed to fully understand the nature of SSM errors, but great progress has been made, and the above suggestions can hopefully help airport security organizations consider possible policy changes.

Authors' Note

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the official policy or position of the Department of Homeland Security (DHS) or of the U.S. Government.

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