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

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Abstract

Satisfaction of search (which we refer to as *subsequent search misses*)—a decrease in accuracy at detecting a second target after a first target has been found in a visual search—underlies real-world search errors (e.g., tumors may be missed in an X-ray if another tumor already has been found), but little is known about this phenomenon's cognitive underpinnings. In the present study, we examined subsequent search misses in terms of another, more extensively studied phenomenon: the attentional blink, a decrease in accuracy when a second target appears 200 to 500 ms after a first target is detected in a temporal stream. Participants searched for T-shaped targets among L-shaped distractors in a spatial visual search, and despite large methodological differences between self-paced spatial visual searches and attentional blink tasks, an attentional-blink-like effect accounted for subsequent-search-miss errors. This finding provides evidence that accuracy is negatively affected shortly after a first target is fixated in a self-paced, self-guided visual search.

Keywords

satisfaction of search, attentional blink, visual search, subsequent search misses, visual attention

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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 nonexpert 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

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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, 2013).

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, 2013) 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?

Method

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).

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. 1a for a sample stimulus display). There were 25 items (each 1.3° × 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).

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 time-out. 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.

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, 2013). 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,

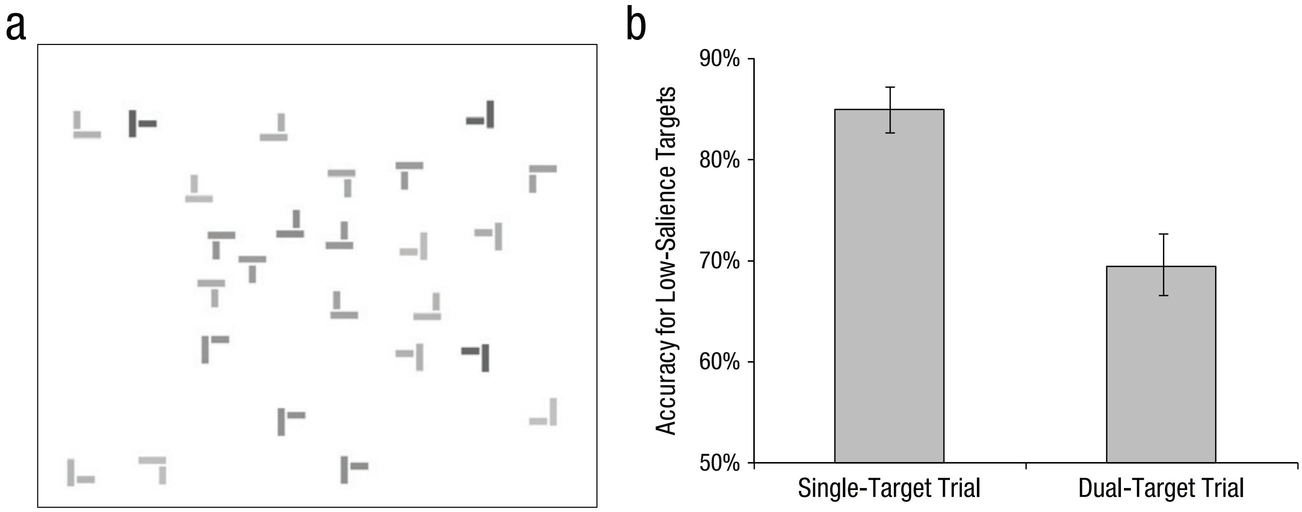

Fig. 1. Example stimulus display and results from the visual-search task. The stimulus display (a) contains a high- and a low-salience T-shaped target among the L-shaped distractors. The graph (b) shows mean accuracy at detecting low-salience targets as a function of trial type (single-target trials vs. dual-target trials in which the high-salience target was identified before the low-salience target). Error bars represent standard errors of the mean.

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. For 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. 2b). This small window of increased T2 accuracy is believed to be time based rather than item based (e.g., Nieuwenhuis et al., 2005).

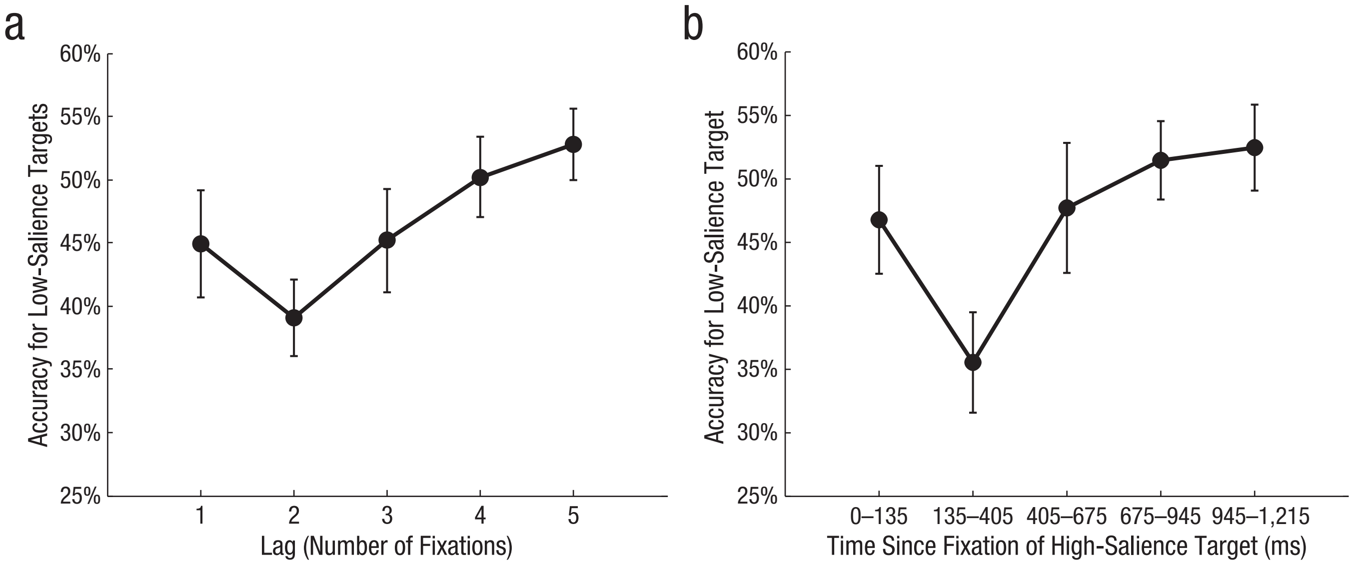

Fig. 2. Results from attentional-blink-like analyses of dual-target trials. The graph in (a) shows mean accuracy at detecting low-salience targets as a function of the number of fixations between fixation of the high-salience target and fixation of the low-salience target (fixation-lag analysis). The graph in (b) shows mean 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).

Results

All statistical tests had an alpha level of .05 and were two-tailed. There was a significant SSM effect (difference in accuracy = 15.6%), $t(27) = 8.00$, $p < .001$, Cohen's $d = 1.09$ (see Fig. 1b), 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. 2a), 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. 2b), 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. 2). 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, $t(27) = 0.459$, $p = .6498$, $d = 0.107$.

Discussion

The current study revealed 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 indicate 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's 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.

Author Contributions

S. H. Adamo collected and analyzed the data and drafted the manuscript. M. S. Cain led the programming efforts and assisted with the data analysis and manuscript preparation. S. R. Mitroff oversaw the project at each step.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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References

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

Berbaum, K. S. (2012). Satisfaction of search experiments in advanced imaging. *Proceedings of SPIE*, *8291*(1), Article 82910V. Retrieved from http://spiedigitallibrary.org/proceedings/resource/2/psisdg/8291/1/82910V_1

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

Berbaum, K. S., Franken, E. A., Jr., 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.

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

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

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*, 1398–1408.

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.

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.

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.

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

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*, 60–71.

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.

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

Kleiner, M., Brainard, D. H., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception, 36*, ECVP Abstract Supplement. Retrieved from http://www.perceptionweb.com/abstract.cgi?id=v070821

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

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

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

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.

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.

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.

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.