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Memory search for the first target modulates the magnitude of the attentional blink

Trafton Drew · Ashley Sherman · Sage E. P. Boettcher · Jeremy M. Wolfe

Abstract The resolution of temporal attention is limited in a manner that makes it difficult to identify two targets in short succession. This limitation produces the phenomenon known as the *attentional blink* (AB), in which processing of a first target (T1) impairs identification of a second target (T2). In the AB literature, there is broad agreement that increasing the time it takes to process T1 leads to a larger AB. One might, therefore, predict that increasing the number of possible T1 identities, or target set, from 1 to 16 would lead to a larger AB. We were surprised to find that this manipulation of T1 difficulty had no influence on AB magnitude. In subsequent experiments, we found that AB magnitude interacts with T1 processing time only under certain circumstances. Specifically, when the T1 task was either well masked or had to be completed online, we found a reliable interaction between AB magnitude and the target set size. When neither of these conditions was fulfilled, there was no interaction between target set size and the AB. Previous research found that when the target set changes from trial to trial, trials with more possible targets elicited a larger AB. In the present study, the target set is held constant, reducing the demands on working memory. Nevertheless, AB magnitude still interacts with target set size, as long as the T1 task cannot be processed offline. Thus, the act of searching memory delays subsequent processing, even when the role of working memory has been minimized.

Keywords Attention · Working memory · Memory

Introduction

The limits of visual attention have been central topics in cognitive psychology over the past 30 years. However, while most undergraduate psychology students know that people can only process a finite set of items or locations in a scene at any one moment, temporal limitations on processing are not as well understood. The attentional blink (AB) has been an important paradigm in understanding the limits of visual attention in a temporal domain (Dux & Marois, 2009; Shapiro, 1994). The AB refers to the impaired processing of the second of two targets (T1 and T2) within a stream of items. Single items are presented in quick succession centrally in a rapid serial visual presentation (RSVP). Typically, processing of T2 is impaired when it appears within 200 and 500 ms of T1 (Raymond, Shapiro, & Arnell, 1992). One common measure of blink magnitude is percent correct of T2 given that T1 was correctly identified. Larger deficits are evidence of a larger "blink."

The current literature supports the notion that processing of T1 occupies some aspect of a limited-capacity central resource, thereby preventing the subsequent processing of T2. This bottleneck theory of the AB posits two stages of processing. During the first stage, items are flagged on the basis of how well they fit the target definition. Once an item is selected as a potential target, it moves to the second stage, where it receives additional processing. Importantly, this second stage is thought to be capacity limited and time consuming. Therefore, while T1 is occupying these resources, processing of T2

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is delayed, thereby making it vulnerable to masking by subsequent items in the stream (Chun & Potter, 1995).

As a result of this series of events, the difficulty in correctly identifying T1 plays a central role in determining the magnitude of the AB (Bowman & Wyble, 2007; Dux & Marois, 2009; Olivers, van der Stigchel, & Hulleman, 2007). The central interference theory (Jolicoeur & Dell'Acqua, 1998) predicts that increasing the difficulty of T1 should lead to a larger AB. Chun and Potter (1995) found that increasing T1–distractor similarity led to a larger AB, and looking across several early AB studies, Sieffert and Di Lollo (1997) found a negative correlation between AB magnitude and mean percentage correct on T1. However, despite the general consensus that increasing T1 difficulty leads to larger AB magnitude, in recent years this interpretation has become more nuanced as researchers have identified a number of situations where increasing T1 difficulty does not lead to a larger AB. This has led to an evolving understanding of what aspects of difficulty do and do not lead to a larger AB.

An important step forward in understanding the role of T1 difficulty in AB magnitude is an appreciation of the distinction between storage capacity and processing capacity (e.g., Akyürek, Hommel, & Jolicoeur, 2007; Visser, 2010). Storage capacity refers to how much information can be actively held at once. In this context, storage capacity is very similar to working memory (WM): Both are severely capacity limited. Processing capacity refers to how much information can be processed in a given unit of time. In both cases, these limitations can result in a bottleneck that leads to performance decrements. While it is difficult to come up with tasks that tap purely into one type of capacity limitation or the other, an example of a paradigm that loads more heavily on processing capacity limitations is the psychological refractory period (PRP) paradigm. In this paradigm, observers must provide speeded responses to two targets (T1 and T2) separated by a stimulus onset asynchrony (SOA). When T2 follows soon after T1, responses to T2 are typically delayed, and this delay can be modulated by the amount of time it takes to process T1 (McCann & Johnston, 1992; Pashler, 1994). On the other end of the processing-capacity–storage-capacity spectrum, holding information in WM relies on storage capacity and is not driven by processing capacity limitations.

Recent research in the AB literature has helped clarify whether the interaction between T1 difficulty and AB magnitude is driven by processing capacity or storage capacity. For example, Akyürek and colleagues manipulated storage capacity by asking observers to hold information in WM while performing an AB. While this manipulation led to a modest decline in overall performance, it did not lead to an interaction with AB magnitude (Akyürek & Hommel, 2005, 2006; but see Visser 2010, and the Discussion section). This is broadly inconsistent with bottleneck theories of the AB postulate that the AB is caused, at least in part, by the difficulty of loading T2 into a durable format (often thought to be WM) while T1 is still being processed. From this perspective, loading WM should increase the time it takes to encode T1 into WM, thereby leading to an interaction with AB magnitude. Along these lines, previous work has shown that an individual's WM capacity is inversely related to AB magnitude (Colzato, Spape, Pannekbakker, & Hommel, 2007). However, more recent work has suggested that it is the executive function processes involved in WM capacity, rather than simple storage capacity, that carries the weight in this relationship (Arnell, Stokes, MacLean, & Gicante, 2010).

While merely loading WM does not seem to influence AB magnitude under these circumstances, AB magnitude does interact with the size of the memory load when the T1 task is to determine whether an item is a member of a memory load that changes on each trial (Akyürek et al., 2007). Akyürek and colleagues interpreted this result as evidence in favor of the idea that processing capacity limitations on T1 directly influence AB magnitude. Certainly, the act of scanning memory to determine whether an item is a member of a target set demands processing resources (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1984). However, because the Akyürek paradigm employs a variable mapping scheme where the memory load changes on every trial, it also imposes a heavy load on the storage demands. Recent research has shown that changing the identity of the target from trial to trial results in target information being held in WM (Woodman & Arita, 2011). Recent neural evidence has demonstrated that the representation of this target item transitions from WM to some form of long-term memory (LTM) after roughly 10 trial repetitions (Carlisle, Arita, Pardo, & Woodman, 2011; Reinhart & Woodman, 2013). Therefore, Akyürek and colleges' manipulation involved both processing and storage manipulations.

While previous work has suggested that merely holding the current target set in mind does not influence AB magnitude, the memory scanning paradigm discussed previously is not an ideal paradigm to examine the influence of scanning memory on the AB alone, because it requires scanning memory while also holding information (the memory load) in WM. Thus, it is not currently clear whether the act of scanning memory influences AB magnitude in the absence of a storage load. We addressed this limitation by employing a paradigm that used consistent mapping for the memory set and varying the size of the memory set over the different blocks of trials.

In the present work, we used a novel method to manipulate T1 difficulty. We manipulated the size of the set of items that defined T1, making it easier or harder to determine whether an item in the RSVP stream was a target or not. In each block of a series of five experiments, observers were asked to memorize between 1 and 16 objects that could serve as possible T1 targets. These items can be described as residing in *activated long-term memory* (ALTM: Cowan, 1995, 2001). The memory sets used in these experiments were held for too long and were too large to be considered as purely held in WM. The items were held for many minutes. Thus, they were in LTM. They were the currently relevant items in LTM—hence, ALTM. In the Akyürek et al. (2007) study, mentioned above, the number of possible T1 items varied from 1 to 4. However, in this study, a new memory set was presented on each trial (variable mapping). This target set could be held in WM. One of the defining characteristics of WM is that it is severely capacity limited: Most observers can hold a maximum of 3–4 items in WM (Luck & Vogel, 1997). By using sets of up to 16 items, the present experiments go well beyond the limits of WM. Indeed, our group has shown that observers can perform spatial and temporal attention tasks while holding 100 or more items in memory (Drew & Wolfe, 2014; Wolfe, 2012).

Previously, Shapiro, Raymond, and Arnell (1994) manipulated the number of possible T1 items in different blocks of an experiment. T1 was a white letter in a stream of black letters. In one condition, T1 could be one of 3 letters; in another, T1 could be any of 25 letters (i.e., the entire alphabet with the exception of X, which was used as T2). There was no interaction of set size and blink magnitude. However, the task of determining whether T1 was a letter was not really a search through a memory set of 25. Rather, it was a task of object categorization with just one target category, the alphabet. By analogy, determining whether an item is an animal is not vastly harder than determining whether an item is a dog, rabbit, or fish, even though the set of all animals is vast. In the following experiments, we used distinctive objects as the targets, allowing us to have memory sets of different sizes without the complication of changing from specific targets to categorical targets.

General method

For each of the following five experiments, observers gave informed consent and were compensated at $10 per hour. All observers had at least 20/25 vision with correction, passed the Ishihara Color Blindness Test, and were fluent speakers of English. With the exception of Experiment 3, observers were seated 57 cm from a 20-in. CRT monitor with an 85-Hz refresh rate. At this viewing distance, 1 cm is equivalent to a visual angle of 1°. All experiments were written in MATLAB using the Psychophysics Toolbox (Brainard, 1997). Stimuli could either be letters (subtending 1.25°), numbers (1.25°), or real-world objects (3.25°). All were presented centrally on a gray background. Both objects and numbers were displayed on white squares that subtended 3.25°, except in Experiment 5, where all items were displayed on gray squares that matched the background. In Experiment 3, observers were 57 cm from a 19-in. LCD monitor with a 60-Hz refresh rate. The numbers in Experiment 3 subtended 1°, whereas the photorealistic objects and white squares in which the letters appeared subtended 2.5°.

All of the experiments had a similar memorization phase that preceded each block of experimental trials. Observers memorized 1–16 targets that were presented initially for 3 s each. Order of the memory blocks was randomized across observers. Objects were taken from a set of more than 3,000 unique, photorealistic objects provided by Brady and colleagues (Brady, Konkle, Alvarez, & Oliva, 2008). All target items for a given observer were selected at the beginning of the experiment, such that there was never any overlap between target sets, and items that were to be targets in other blocks of the experiments were never used as distractors. Observers were required to pass a recognition memory test to show that they had memorized the target set. In that test, single objects were displayed in the center of the screen, and observers made "old" or "new" responses, identifying items as targets (which appeared 50 % of the time) or distractors. Distractors were of the same object type (i.e., different letters or different objects). Observers were required to perform this task with at least 80 % accuracy on two consecutive tests before being allowed to proceed to the AB portion of the experiment. If they performed below 80 % correct on the test, they were required to view each of the target objects for 3 s again and take the test again. The 80 % "passing grade" is rather generous. In practice, performance on the recognition test was >95 % even with the largest memory set sizes.

SOA for all items in the stream varied across experiments. While we would have preferred to use a consistent SOA, the changes made across experiments influenced overall difficulty of the task. As a result, SOA was changed to ensure that performance at the early lag positions was reliably above chance in each experiment. Thus, at a given lag, the number of items seen prior to T2 was equated across experiments, but the time between these events was not. Graphs that depict performance as a function of lag present lag as a function of time, rather than as a function of lag number, in order to facilitate comparison between experiments.

Experiments 1, 2, and 3: Object among numbers

Introduction

In Experiments 1–3, T1 was always a single photorealistic object in a stream of numbers. Observers needed to determine whether the object was in the memory set and then to identify T2, a red number. To anticipate the results, we expected that increasing the memory set size would lead to a larger AB and were surprised that this factor had no effect on blink magnitude in Experiment 1. Experiments 2 and 3 were attempts to understand this surprising result. Experiments 1 and 2 were identical, except that the T1 task was unspeeded in

Experiment 1 and speeded in Experiment 2. The tasks in Experiment 1 and 3 were identical, aside from the fact that the T1 item was preceded and followed by a colorful pattern mask in Experiment 3.

Method

Eleven observers participated in Experiment 1, 14 in Experiment 2, and 11 in Experiment 3 (mean age: 24.6 years; 72 % female). One observer from Experiment 3 was removed from the sample due to performance on the T1 task (42 % correct) that was near chance and much worse than any of the other observers (mean performance: 97 %). In Experiments 1 and 2, observers memorized 1, 4, 8, or 16 objects prior to completing the AB portion of the experiment using the methods described in the General Method section. In Experiment 3, observers memorized 2, 4, 8, or 16 objects.

After successful completion of the memorization phase at the start of the block, observers completed 20 practice AB trials, followed by 140 experimental AB trials for Experiments 1 and 2. There were 300 experimental AB trials for Experiment 3. Each trial consisted of a stream of black numbers displayed one at a time at the center of the screen. SOAs were the following: Experiment 1, 94 ms; Experiment 2, 106 ms; Experiment 3, 140 ms. Different times were used to keep T1 performance roughly constant across tasks. Each trial contained one object and one red number. There were 18 items in the RSVP stream for Experiments 1 and 2. There were 19 items in Experiment 3. In all three experiments, the task was to determine whether the object was a member of the target set (T1) and to identify the red number (T2).

In Experiment 1, we asked observers to emphasize accuracy for both T1 and T2 tasks. At the end the RSVP sequence, Observers used a buttonpress to report whether the object was or was not from the memory set. Then they typed the number that they thought had been presented in red. Experiment 2 used the same stimuli but asked observers to respond as quickly as possible once they knew whether the single object in the RSVP stream was a target or a distractor. In Experiment 2, if a “target-present” response to T1 occurred more than 2 s after the presentation of the target, observers saw a message asking them to try to respond faster. Experiment 3 was the same as Experiment 1, except that the frames immediately before and after the target object were occupied by colorful pattern masks made up of many overlapping pieces of objects.

In pilot testing, it was clear that the T1 task was made much more difficult by the addition of the pattern masks included in Experiment 3. In an effort to roughly equate T1 difficulty across Experiment 2 and 3, we increased the SOA from 106 ms in Experiment 2 to 141 ms in Experiment 3. As a result, T1 accuracy was similar across the two experiments: 95 % in Experiment 2 and 97 % in Experiment 3.

The position of the T1 item in the stream varied from positions 5 to 7. In Experiments 1 and 2, the T2 appeared at lag position 1, 3, 5, 7, or 9 items after the T1 item. In Experiment 3, lag position was two, five, or eight items after the T1 item.

Results

Analysis strategy

Over the course of the five experiments reported here, we used a consistent analysis strategy aimed at determining whether our manipulation of the number of T1 items being held in memory influences AB magnitude. In previous work, we have shown that the amount of time needed to process a single target item in an RSVP stream in strongly influenced by the size of the memory set. Accordingly, we expected that either T1 response times (RTs) would increase or T1 accuracy would decrease as memory set size increased. As with any dual-task paradigm, one concern is that observers could delay processing of first task (T1) in preparation of the second (T2). In order to rule out this possibility, in each experiment, we tested to determine whether there was a significant effect of lag on T1 and whether this factor interacted with memory set size. An interaction would suggest that the likelihood of adopting this sort of strategy was influenced by the memory set size, but we did not observe this pattern of results in any of these experiments.

To determine whether the magnitude of the AB was influenced by the memory set size, we computed repeated measures ANOVAs in each experiment, with lag and memory set size as factors. As is common in the AB literature, the dependent variable for this analysis was T2 performance on trials where T1 was correct. In our results, a significant interaction between these terms indicated that a larger memory set size led to larger AB magnitude. Here and throughout the article, where appropriate, we report generalized eta-squared (η_g^2) as a measure of effect size (Bakeman, 2005).

Experiment 1

As in our lab’s previous work using this methodology to teach memory sets prior to each block of the experiment (Wolfe, 2012), performance on the memory test was very good. Observers are capable of encoding 16 items into ALTM with very few errors. Overall, our observers failed to achieve >80 % correct on just 3 out of 101 (3 %) memory tests.

The mean accuracy for the T1 task in Experiments 1–3 are shown in Fig. 1. In Experiment 1, there was no effect of lag, $F(4, 40) = 0.14$, $p = .96$, $\eta_g^2 < .01$, or memory set size, $F(3, 30) = 2.00$, $p = .14$, $\eta_g^2 = .03$, on T1 accuracy, and the two factors did not interact significantly, $F(12, 120) = 1.19$, $p = .30$, $\eta_g^2 = .05$.

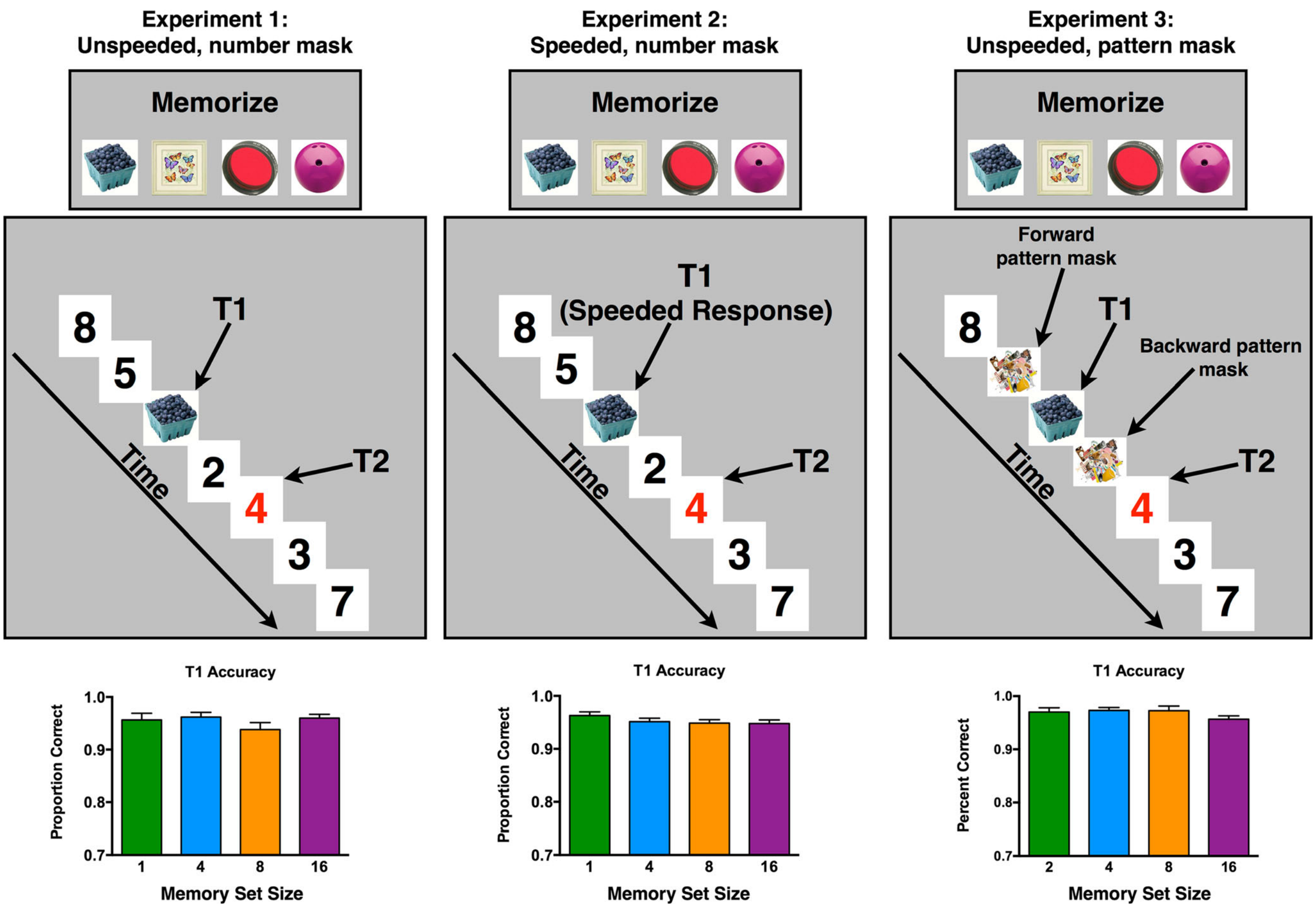
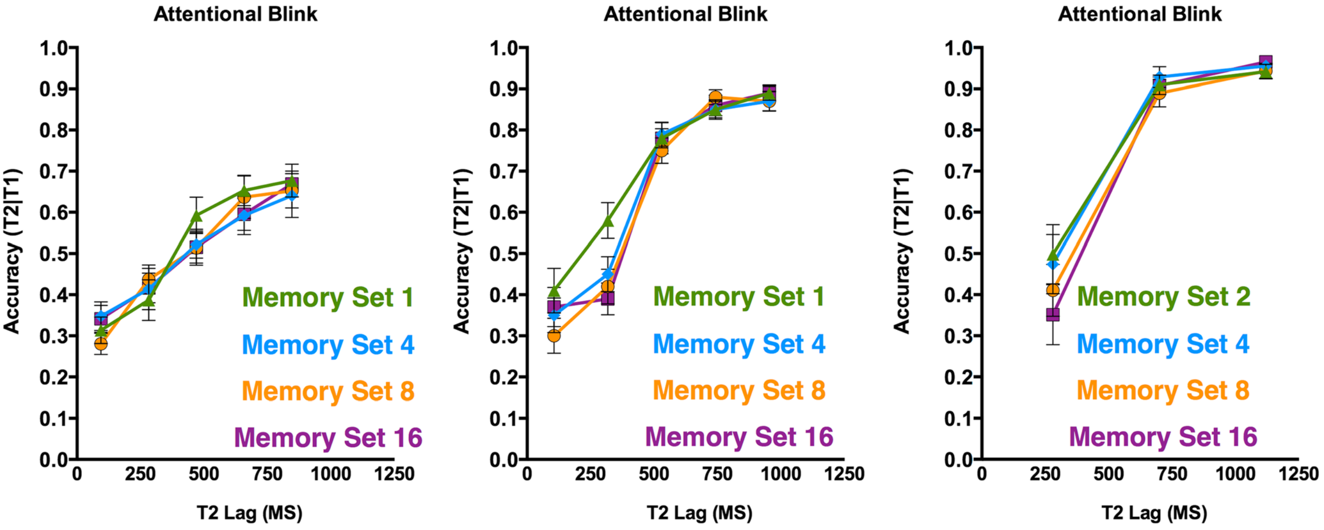


Fig. 1 Schematic illustration of paradigm and T1 results for Experiments 1–3. In Experiments 1 and 2, the items before and after the T1 item were black numbers, except on lag 1 trials, where a red number followed the target object. Error bars here and throughout the article represent standard errors of the means. T1 data here and in subsequent figures collapses across lag

In Experiments 1–3, the T1 item was the only intact object in the stream, and we therefore assumed that it was the only item that elicited a memory search. For these experiments, we report data from all trials, rather than focusing on trials where an item from the memory set was present, because a memory search should have been necessary even when the object in question was not a target. In each experiment, the qualitative pattern of results does not change if we restrict our analyses to only those trials where a target was present or if we examine all trials. Figure 2 shows mean accuracy of the T2 task given that the T1 question was correctly answered for Experiments 1–3. In Experiment 1, we observed a significant effect of lag on conditional T2 accuracy, $F(4, 40) = 43.89, p < .001, \eta_g^2 = .63$, but no effect of memory set size, $F(3, 30) = 0.49, p = .69, \eta_g^2 < .01$, and the two factors did not interact significantly, $F(12, 120) = 1.22, p = .27, \eta_g^2 = .05$. There is no evidence that the memory set influenced the AB, although the data show a robust AB.

Experiment 2

As in Experiment 1, performance on the memory test that preceded the AB phase of each block was very good: Only 2 % of all memory tested were failed. Experiments 2 and 3 were designed to determine whether forcing the T1 item to be processed online would result in an interaction between AB magnitude and memory set size. In Experiment 2, observers were asked to press the "present" button as soon as they were sure that they saw an object from the target set. This led to significant modulation of RT by memory set size. Here, we focus on trials where the observer correctly reported the presence of the target within 2 s of the object presentation. This RT criterion led to the rejection of less than 1 % of all trials. These trials were excluded from analysis of T2 responses. We observed a significant increase in RT as a function of memory set size, $\mathrm{F}(3, 39) = 15.41, p < .001, \eta_g^2 = .20$, with RT increasing from 462 to 523 to 551 to 572 ms as set size increased from 1 to 16 items. There was also a small but significant effect of lag, $F(4, 52) = 2.61, p = .05, \eta_g^2 = .006$. The two factors did not interact significantly, $F(12, 156) = 0.85, p = .60, \eta_g^2 < .01$. T1 accuracy data followed a similar pattern, with a significant main effect of lag, $F(4, 52) = 2.66, p = .043, \eta_g^2 = .04$, but no significant effect of memory set size, $F(3, 39) = 0.94, p = .43, \eta_g^2 = .02$, and no interaction between the two factors, $F(12, 156) = 1.68, p = .07, \eta_g^2 = .06$.



Experiment 1:
Unspeeded, number mask
SOA 94ms

Experiment 2:
Speeded, number mask
SOA 106ms

Experiment 3:
Unspeeded, pattern mask
SOA 140ms

Fig. 2 Identification accuracy for T2, given correct T1, as a function of stimulus onset asynchrony (SOA) between T1 and T2 for Experiments 1–3

Turning to the T2 data (Fig. 2b), we observed modulation of conditional T2 performance by both lag, $F(4, 52) = 79.5$, $p < .001$, $\eta_g^2 = .68$, and memory set size, $F(3, 39) = 3.96$, $p = .001$, $\eta_g^2 = .01$. In contrast to Experiment 1, we also observed a significant interaction between lag and memory set size on conditional T2 performance, $F(12, 156) = 1.8$, $p = .004$, $\eta_g^2 = .04$.

Experiment 3

Experiment 3 was identical to Experiment 1, but the T1 item was preceded and followed by a colorful pattern mask. As in Experiments 1 and 2, performance in the memory test that preceded the AB phase of each block was very good: Only 2 % of all memory tested were failed. T1 accuracy data followed a pattern that was consistent with those in Experiments 1 and 2. We did not observe a significant main effect for memory set size, $F(3, 30) = 2.26$, $p = .10$, $\eta_g^2 = .05$, or lag, $F(2, 20) = 2.73$, $p = .09$, $\eta_g^2 = .05$, in the T1 accuracy data. More important, lag and memory set size did not significantly interact, $F(6, 60) = 0.94$, $p = .47$, $\eta_g^2 = .02$.

The T2 data exhibit a clear modulation of AB depth as a function of memory set size. As is shown in Fig. 2c, there was a significant effect of both lag, $F(2, 20) = 72.9$, $p < .001$, $\eta_g^2 = .74$, and memory set size, $F(3, 30) = 5.82$, $p < .005$, $\eta_g^2 = .02$, and a significant interaction between the two factors, $F(6, 60) = 7.28$, $p < .001$, $\eta_g^2 = .04$. The AB becomes deeper as the memory set gets larger.

Discussion

In all three experiments, we manipulated the size of the memory set. On the basis of previous work (Drew & Wolfe, 2014; Wolfe, 2012), this manipulation was predicted to have a large effect on the T1 processing time. Despite a number of recent studies that have suggested that a key factor in determining whether T1 difficulty interacts with AB magnitude is T1 processing time, in Experiment 1 there was no effect of memory set size on AB magnitude (Akyürek et al., 2007; Visser, 2007; Visser & Ohan, 2007).

We suspected that this could be due to observers processing the target object offline: holding the object identity in WM until the end of the trial when it was necessary to make a decision about whether it was a target object. In an effort to eliminate this possibility, we conducted two follow-up experiments. Experiment 2 was a replication of Experiment 1, with the added requirement that observers respond to the T1 task online. This manipulation resulted in a significant interaction between lag and memory set size. This interaction was replicated in Experiment 3, when we increased the masking of the T1 item with forward and backward pattern masks even though we removed the necessity to respond online to T1. What Experiments 2 and 3 seem to have in common is that they required relatively complete handling of T1 before subsequent items could be processed. In the case of Experiment 2, the actual response to T1 was required. In the case of Experiment 3, the information required for a T1 response was only fleetingly available, due to the masking. These manipulations tie up resources that could otherwise be used to process subsequent items, deepening the AB. As can be seen in the T1 RTs for Experiment 2, the additional memory search time is about 100 ms as memory set increases from 1 to 16. As a result, the impact of forcing observers to deal with T1 is seen at the short lags. By the time the T2 occurs at a longer lag, the memory search effects have abated.

Visser (2010) has argued that masking interrupts high-level processing of target information, which effectively eliminates the influence that T1 difficulty has on blink magnitude under certain circumstances. Here, we appear to find the opposite: Increased masking led to a more reliable interaction with AB magnitude. Perhaps masking plays a fundamentally different role depending on whether the task is data limited or resource limited. In our resource-limited manipulation, masking served to force online processing, thereby leading to the observed interaction. We will return to this issue in the General Discussion section.

While we have argued that the AB magnitude × memory set size interaction observed by Akyürek and colleagues (2007) may have been due to a combination of processing and storage bottlenecks, these first experiments extend these findings by demonstrating that interaction can also be observed in a consistent mapping context where the memory set size places a minimal load on storage capacity. Importantly though, this interaction was present only when we discouraged offline processing of the T1 item via either online speeded response (Experiment 2) or stronger masking (Experiment 3). How general is this effect? Perhaps the interaction observed in Experiments 2 and 3 was due in part to the task switch (target set categorization followed by identifying a red number) that was necessary in this paradigm. In Experiments 4 and 5, we sought to replicate the interaction between memory set size and lag in versions of this paradigm that do not necessitate a task switch (Experiment 4) and that are closer to the typical AB paradigm with a stream of letter and numbers (Experiment 5).

Experiment 4: Objects among objects

Introduction

In Experiments 1–3, the RSVP stream was composed of items that were categorically different than the target set item, with the exception of a single target or distractor item. We argue that the interaction observed between memory set size and AB magnitude in Experiments 2 and 3 is driven by the increased time associated with searching the potential target set. Importantly, since there was just one item from the target category (i.e., objects), observers needed to conduct only one memory search. In Experiment 4, the entire RSVP stream was made up of items drawn from the same category as the target, thereby necessitating memory searches for each item prior to T1. In previous work from our lab, observers were instructed to determine whether any member of a stream of objects was an item from the memory set. They could do this task at presentation rates of up to roughly 7.7 Hz (130 ms per object) with a memory set size of 16 (Drew & Wolfe, 2014). What remains unclear, however, is how the act of conducting a memory search for each item in a stream influences the ability to encode subsequent information. The AB paradigm is well equipped to address this question.

Method

In Experiment 4, we used RSVP streams consisting entirely of real objects. Sixteen observers (12 women; average age of 26.2 years) memorized the objects in the same manner as that described in the General Method section. The four test blocks contained 20 practice trials and 300 test trials. On each trial, an RSVP stream of 19 pictures with an SOA of 201 ms was shown. Within the stream, a single object would appear with a red frame around it. As in the previous experiments, the T1 task was to report the presence of a member of the memory set. T2 was an object surrounded by a red frame. The T2 task was to identify whether an object, presented after the end of the RSVP stream, was the red-framed object. As in Experiments 2 and 3, observers were encouraged to respond as quickly as possible to the presence of a target object and were told to try to go faster if they did not respond to a T1 target item within 2.5 s of presentation. The position of T1 varied from 5 to 7. T2 appeared two, five, or eight objects after the presentation of T1.

Results

As in previous experiments, performance on the memory test prior to the AB portion of each block was very good. Observers failed in just 4 out of 132 memory tests (3 %). Overall, the results of Experiment 4 (see Fig. 3) are similar to those of Experiment 3. T1 accuracy was influenced by memory set size, $F(3, 45) = 8.92$, $p < .001$, $\eta_g^2 = .17$, but not by lag, $F(2, 30) = 2.39$, $p = .11$, $\eta_g^2 = .005$, and the two factors did not interact, $F(6, 90) = 0.58$, $p = .74$, $\eta_g^2 = .005$. When T1 was absent, the lag variable was no longer meaningful, because a memory search was necessary for every item in the stream preceding T2. Accordingly, we focused subsequent analyses on trials where T1 was present. T1 RT increased significantly with memory set size, $F(3, 45) = 4.34$, $p < .01$, $\eta_g^2 = .09$, but was unaffected by lag, $F(2, 30) = 0.4$, $p = .67$, $\eta_g^2 < .001$, and factors did not interact, $F(6, 90) = 0.49$, $p = .81$, $\eta_g^2 < .001$.

The critical data for the AB are the T2 responses where T1 was present and correctly identified. These T2 data showed a strong effect of both memory set size, $F(3, 45) = 17.86$, $p < .001$, $\eta_g^2 = .22$, and lag, $F(2, 30) = 160.8$, $p < .001$, $\eta_g^2 = .79$. Most important, as in Experiments 2 and 3, the two factors interacted significantly, $F(6, 90) = 2.97$, $p < .05$, $\eta_g^2 = .08$, indicating that a larger memory set size led to a larger AB.

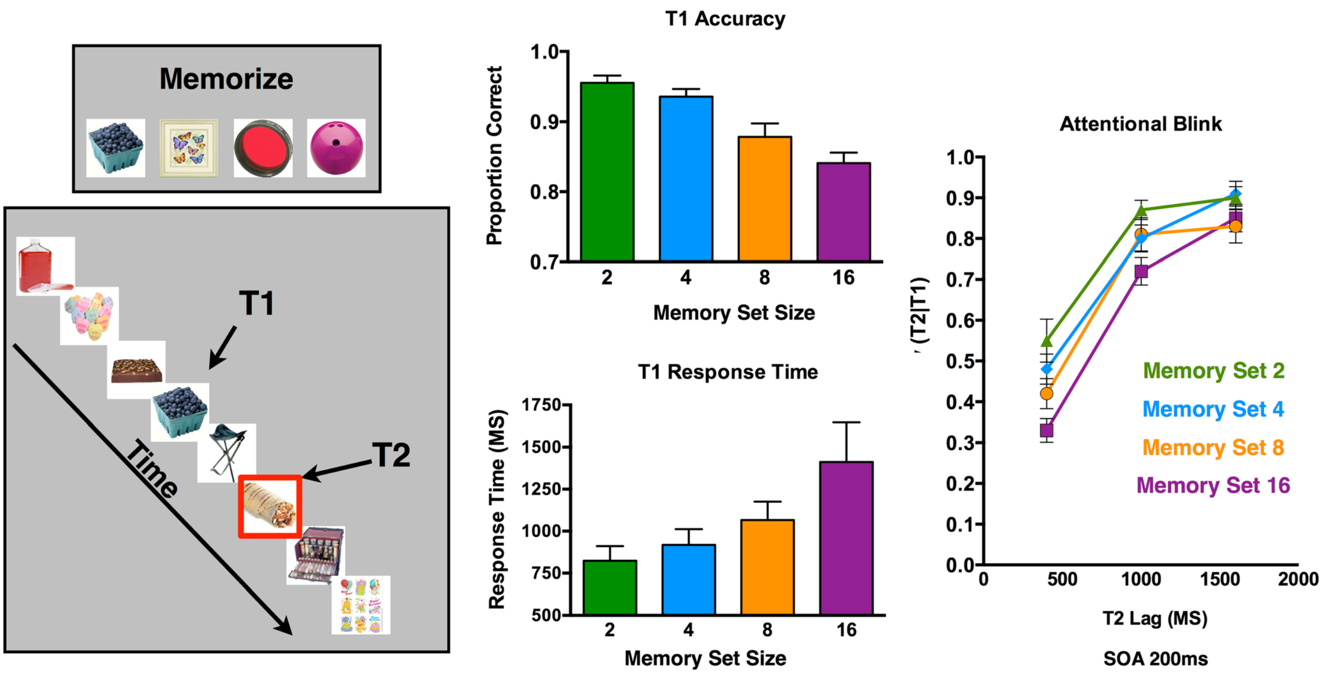


Fig. 3 Schematic illustration of paradigm and results from Experiment 4

Discussion

The results of Experiment 4 demonstrate that memory search load devised in the first set of experiments is capable of eliciting an interaction with blink magnitude even when the T1 and T2 were equated in order to minimize the task switching cost.

One might imagine that the design of Experiment 4 would produce a much more dramatic blink than Experiment 3 because each object in the stream should elicit a memory search. In fact, the two experiments produced similar results in terms of the strength of the interaction. It is important to note the different SOAs used in Experiments 3 and 4. In pilot testing, we found that, not surprisingly, the T1 task was much more difficult with a full stream of objects and slowed the RSVP stream down accordingly. The difference in SOA makes it difficult to directly compare across experiments. However, the fact that T2 performance was not more dramatically influenced by the need to perform a series of memory searches in an RSVP stream is consistent with previous work from out lab that shows that observers are surprisingly good at this temporal version of the hybrid search task (Drew & Wolfe, 2014).

Experiment 5: Letters among letters

Introduction

Previously, Akyürek and colleagues (2007) demonstrated that increasing the number of possible letters that could be T1 resulted in a larger AB, a finding that was one of the primary motivations for the present study. While the authors concluded that this result indicates that scanning memory modulates AB magnitude, an alternative explanation is that the increased AB magnitude was due to a combination of both the increased number of possible targets and the WM load imposed by the inconsistent mapping design. The purpose of the present Experiment 5 was to determine whether the memory set size × AB interaction observed by Akyürek (2007) would replicate when the target set was successfully encoded into ALTM, rather than being continually updated in WM. To anticipate the results, Experiment 5 provides converging evidence with Experiment 4, showing that memory set size influences the blink when all of the RSVP items are of the same type, including T1.

Method

In Experiment 5, 12 observers (10 women; average age, 28.6 years) memorized 2, 4, or 8 letters in the manner described in the General Method section. At the beginning of the experiment, 14 letters were set aside as items to be placed in the target sets throughout the three blocks of the experiment. Distractor items were randomly drawn from the remaining 12 letters, with the restriction that the same distractor letter was never displayed twice in a row. Each of the three test blocks consisted of 300 trials. On each trial, an RSVP stream of 16 letters with an SOA of 189 ms was displayed. Each stream contained 15 black letters on a gray background and a single red letter. The T1 task was to report the presence of a member of the memory set, and the T2 task was to identify the red letter in the stream. Observers were instructed to respond to T1 as quickly as possible, and the program impelled them to respond faster if they did not respond to the T1 item within 2.5 s of presentation. The position of T1 varied from 5 to 7. T2 appeared two, five, or eight positions after the presentation of T1.

Results

In pilot testing, we found that memorizing a target set of letters was more difficult than memorizing unique objects. As a result, in the memory-learning phase of each block of the experiment, we required observers to successfully pass our memory test with at least 80 % correct on four, rather than two, tests in a row. Still, despite the increased similarity between the target set and distractor set in this experiment, performance on the memory tests was very good. Observers failed the test only 3 out of 148 (2 %) of the time. Broadly speaking, the results of Experiment 5, summarized in Fig. 4, mirror those of Experiments 2, 3, and 4. As in Experiment 4, we focused our analyses on trials when the T1 target item was present, aside from T1 accuracy, where we examined all trials. The most relevant result for present purposes is that lag and memory set size did not interact for T1 accuracy, $F(4, 44) = 0.82$, $p = .51$, $\eta_g^2 = .004$, or T1 RT, $F(4, 44) = 0.93$, $p = .46$, $\eta_g^2 < .001$. While there was a significant effect of lag in the T1 accuracy data, $F(2, 22) = 4.98$, $p < .05$, $\eta_g^2 = .007$, this result did not replicate in the T1 RT data, $F(2, 22) = 0.24$, $p = .79$, $\eta_g^2 < .001$. On the other hand, there was a reliable effect of memory set size in both measures [T1 accuracy, $F(2, 22) = 9.06$, $p < .005$, $\eta_g^2 = .21$; T1 RT, $F(2, 22) = 4.63$, $p < .05$, $\eta_g^2 = .003$]: Larger memory set size led to slower, less accurate responses.

Conditional T2 accuracy exhibited a reliable effect of both lag, $F(2, 22) = 51.69$, $p < .001$, $\eta_g^2 = .53$, and memory set size, $F(2, 22) = 6.62$, $p < .01$, $\eta_g^2 = .11$, and a significant interaction between the two, $F(4, 44) = 2.7$, $p < .05$, $\eta_g^2 = .05$. In sum, as in Experiments 3 and 4, blink magnitude appeared to increase with memory set size.

Discussion

Experiment 5 produces a pattern of results similar to that in Akyürek's previous work (Akyürek et al., 2007) and Experiments 2, 3, and 4 in the present study. Unlike in Akyürek et al., our observers held the same set of letters in memory for an entire block. In all of these experiments, increasing the number of potential T1 target items led to a larger blink. Clearly, the Akyürek finding does not rely entirely on a WM load imposed by changing the target set from trial to trial. The fact that this change does not appear to be the driving force behind the interaction is consistent with other work that has shown that the size of a WM load does not interact with AB magnitude (Akyürek & Hommel, 2005, 2006). Together, our data strongly suggest that the observed interaction is driven by the increased processing time associated with determining whether an item is a member of a larger target set.

Our data support bottleneck theories of the AB, which postulate that increasing the processing time of T1 will lead to increased deficits on T2 accuracy (Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998, 1999). Memory search through larger memory set sizes takes more time, and our data suggest

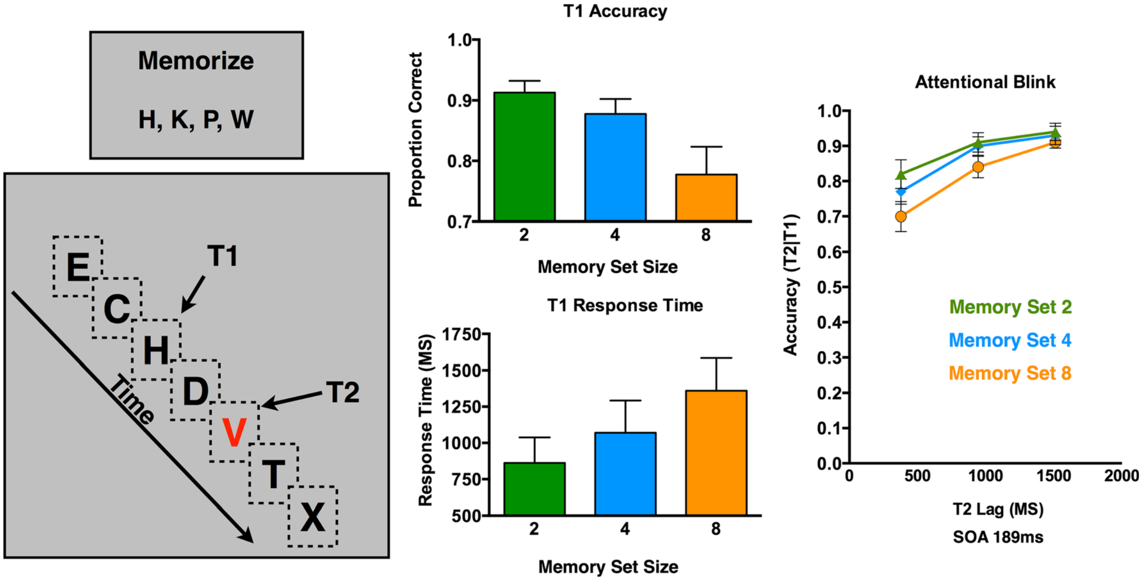


Fig. 4 Schematic illustration of paradigm and results from Experiment 5. Squares in the schematic are for display purposes only. Letters appeared in the center of the gray screen

that the size of memory search influenced the magnitude of the AB. While these results are consistent with bottleneck theories of the AB, they appear to be inconsistent with the boost and bounce theory (Olivers & Meeter, 2008). According to this model, the AB is caused by the presence of a distractor immediately after the T1 item that triggers inhibitory processing that impairs T2 processing. This theory proposes that processing capacity limitations have little influence on the AB. In fact, since this model ascribes a limited role for T1 processing in the generation of the AB, it is not clear how it could account for the present results. Furthermore, it proposes that one of the primary functions of storage capacity (WM) in the AB is to help selectively enhance items that appear similar to the target set so that they receive additional processing. This emphasis on the role of WM may help explain the variable-mapping results of Akyürek and colleagues (2007), but the present results represent a more fundamental challenge to this model, given a consistent mapping design that minimizes the role of WM.

General discussion

When given the task of identifying the presence or absence of a single target item in an RSVP stream, we have previously shown that increasing the memory set size increases the amount of time necessary to carry out the task (Drew & Wolfe, 2014). In the present set of experiments, we found that when this item served as T1 in an attentional blink paradigm, successful T1 detection led to a large decrement in performance for T2 items. However, in Experiment 1, we were surprised to find that the magnitude of the AB did not increase with the memory set size. This suggests that observers were capable either of completing a memory search for the T1 item while simultaneously monitoring the stream or of postponing the memory search until the end of the trial.

By increasing the effectiveness of the T1 mask and/or requiring a speeded T1 response, our subsequent experiments strongly suggest that when observers were not allowed to perform the memory search offline, increasing the size of the memory set size led to a larger AB. On the surface, this finding of no interaction with poor masking and an interaction when the observer is forced to process information seems to be at odds with recent findings from Visser and colleagues (Visser, 2007, 2010; Visser & Ohan, 2007). For instance, Visser (2007) found that when the T1 task was a size judgment task, there was no interaction between T1 difficulty when T1 was masked but that when it was unmasked, an interaction emerged. More relevant for the present study, Visser (2010) found that size of a WM load interacted with AB magnitude, but only when T1 was not masked. On the basis of these results, and a number of instances where the difficulty of well-masked T1 items did not interact with AB magnitude (i.e., McLaughlin, Shore, & Klein, 2001), Visser concluded that under certain circumstances, masking interrupts the processing of T1, so that difficulty manipulations that would otherwise influence total processing time are no longer capable of doing so. Therefore, when the mask is removed, it enables processing time of T1 to vary with difficulty, which in turn leads to interaction with AB magnitude. In sum, Visser has suggested that it is T1 processing that is the driving force behind the interaction between T1 difficulty and AB magnitude (Visser, 2007).

We chose the memory set size manipulation for T1 in a deliberate attempt to influence processing time, based on the recent work in our lab which has delineated the time-course of memory search from 1 to 100 items for these real-world objects (Drew & Wolfe 2014). As noted above, we were surprised to find no hint of interaction in our first experiment despite a very large AB and a much larger memory set size manipulation than in previous work (Akyürek et al., 2007; Visser, 2010). Like Visser, we hypothesized that the T1 difficulty manipulation was not having the predicted effect because our paradigm allowed the effect of T1 processing time to be negated. In our case, because we used highly memorable real-world objects that were very different from all the other items in the stream, observers may have been able to store the identity of the object in question in WM while delaying the memory search until after the T2 task had been completed. It seems that the unique conditions of Experiment 1 may have led to the surprising result: When we took steps to discourage offline processing of T1, the anticipated interaction was reliably observed. Therefore, while Visser and colleagues uncovered an interesting situation where masking of the T1 item essentially obscures the effect of T1 difficulty, the present study suggests that the effect of T1 difficulty may also be obscured in situations where T1 can be processed offline. In sum, despite differences in methods and stimuli employed, the present study is broadly consistent with the idea that T1 processing time is the driving force behind the interaction between T1 task and AB magnitude.

Interestingly, while previous research has suggested that eliminating the T1 mask allows manipulations that influence T1 processing time to more reliably influence AB magnitude, here we found that stronger T1 masking evoked an interaction with our manipulation, whereas weak masking did not. This apparent discrepancy may have to do with the type of processing necessary to fulfill the T1 task. While Visser and colleagues' studies simply required that T1 be accurately identified (Visser, 2007, 2010; Visser & Ohan, 2007), in the present study and in Akyürek and colleagues' (2007) study, it was necessary to identify the item and then determine whether the item in question was a member of the memory set. This suggests that the critical distinction is the stage of processing that is being manipulated. While Visser's manipulations seem to tax a relatively early identification stage, memory scanning to determine whether the identified item is a member of the target necessarily occurs at a later stage of processing. Our data suggest that either requiring an online response (Experiment 2) or masking (Experiment 3) discourages performing the memory search offline, thereby allowing the time it takes to scan memory to have an effect on the processing of subsequent stimuli. Future research may further delineate under what circumstances observers are capable of identifying information (T1) and then turning attention to a pressing task (T2) before returning to fully processing previously identified information (T1) offline.

In contrast to the present results, Akyürek and colleagues (2007) found that whether or not the T1 task was speeded had little influence on the memory set size × AB interaction that they observed. This suggests that the observers were performing the memory scanning task for the T1 item online, rather than encoding T1 into WM and processing it offline. Akyürek speculated that observers might not have been able to postpone the memory scan. While our own data cannot directly address this result, we see two promising possibilities that could be explored in future work. One possibility is that observers in the Akyürek et al. (2007) study were unable to encode the T1 item because it was strongly masked. This interpretation predicts that there would be no interaction between WM set size and AB magnitude if T1 was not masked in Akyürek's paradigm. Another possibility is that scanning the contents of WM might be easier and more efficient than scanning through the contents of ALTM. While limited in capacity, the contents of WM are thought to be actively maintained to serve the needs of ongoing tasks (Luck & Vogel, 2013). On the other hand, ALTM has a much higher capacity but is not actively maintained (Cowan, 1995, 2001). We speculate that scanning through a store of information that is being actively maintained should be more efficient than for one that is merely "activated," but more work is necessary to determine whether this is the case.

Conclusions

The present experiments clearly demonstrate that, when T1 must be attended online, processing limitations, imposed on the T1 task, consistently influence AB magnitude. These results generalized across a variety of different stimulus sets, from a stream of unique objects to the more traditional stream of single letters. The data demonstrate that, even when employing a consistent mapping paradigm with little emphasis on storage capacity, the act of internally searching one's memory for a target reliably influences the ability to accurately perceive temporally proximal information.

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