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Memory reloaded: Memory load effects in the attentional blink

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When two targets are presented in rapid succession, identification of the first is nearly perfect, while identification of the second is impaired when it follows the first by less than about 700 ms. According to bottleneck models, this attentional blink (AB) occurs because the second target is unable to gain access to capacity-limited working memory processes already occupied by the first target. Evidence for this hypothesis, however, has been mixed, with recent reports suggesting that increasing working memory load does not affect the AB. The present paper explores possible reasons for failures to find a link between memory load and the AB and shows that a reliable effect of load can be obtained when the item directly after T1 (Target 1) is omitted. This finding provides initial evidence that working memory load can influence the AB and additional evidence for a link between T1 processing time and the AB predicted by bottleneck models.

Keywords: Attentional blink; Working memory; Target 1 difficulty; Target 1 masking; Capacity limited.

We are often called upon to accurately perceive rapid sequences of visual input such as when driving a motor vehicle or reading words on a page. Nearly twenty years of research has shown that the success in such tasks relies upon efficient deployment of attention to each input and that failure to do so can result in startling impairments in conscious visual awareness (e.g., Mack & Rock, 1998; O'Regan, Rensink, & Clark, 1999; Raymond, Shapiro, & Arnell, 1992). Indeed, such a scenario is implicated in the now-all-too-familiar tale of drivers who cannot remember their journey while talking on their mobile phone.

In the laboratory, the critical role of attention in mediating awareness is illustrated by a phenomenon known as the attentional blink (AB; Raymond et al., 1992). In a typical AB experiment, observers are presented with a rapid serial visual presentation (RSVP) sequence of stimuli consisting primarily of nontarget distractors and two targets to be identified/detected. Under these conditions, identification of the first target (T1) is usually highly accurate. However, identification of the second target (T2) is greatly impaired when it follows T1 by 200–300 ms and then slowly improves to the level of T1 accuracy by about 700 ms.

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Theoretical accounts of the AB deficit have focused on the role of capacity limits (so-called "bottlenecks") in information processing (e.g., Chun & Potter, 1995; Jolicoeur, 1998). For example, in their two-stage model, Chun and Potter suggested that incoming stimuli are initially processed in parallel across the visual field. Although this analysis is relatively complex, extending to the level of semantics (e.g., Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997), resulting stimulus representations are short lived and vulnerable to decay or interference such as visual masking (e.g., Giesbecht & Di Lollo, 1998). Thus, for stimulus identification to occur, representations must be passed to a second capacity-limited stage for consolidation. On this account, the AB arises at brief T1–T2 intervals (lags) because T2 is likely to be presented while Stage 2 is processing T1, thus forcing T2 to remain at Stage 1, where it is vulnerable to decay or masking. On the other hand, at longer lags, T2 is likely to be presented after T1 processing has been completed, thus allowing it ready access to capacity-limited resources.

While the bottleneck account neatly explains the temporal profile of the AB deficit, it leaves open the issue of the exact nature of the capacity-limited resources involved. One oft-cited possibility is working memory (WM; e.g. Crebholder, Jolicoeur, & McIlwaine, 2002; Dell'Acqua & Jolicoeur, 2000; Jolicoeur, 1998; Jolicoeur & Dell'Acqua, 1998, 2000; Jolicoeur, Dell'Acqua, & Crebholder, 2001). Consistent with this viewpoint, Jolicoeur and Dell'Acqua (1998) found longer T2 response times (RTs) when T1 required three letters to be encoded in memory than when only a single letter was encoded. Similarly, event-related potential studies have shown modulations in the P3 component, which has been linked with WM consolidation, as a function of intertarget lag (e.g., Kranczioch, Debener, & Engel, 2003; Sergent, Baillet, & Dehaene, 2005; Vogel & Luck, 2002; Vogel, Luck, & Shapiro, 1998).

To further probe the link between WM and the AB, Akyürek and Hommel (2005, 2006) examined the effects of memory load on performance. On the basis of bottleneck theories, they reasoned that loading WM with items prior to an AB task should increase the duration needed to consolidate T1 and thus the magnitude of the AB. To test this notion, they presented observers with two, four, or six items to be remembered prior to the onset of an AB task in which two digit targets were presented amongst an RSVP stream of letter distractors (Akyürek & Hommel, 2005; Experiment 1).

In contrast to the expected results, although memory load impaired both T1 and T2 accuracy overall, it did not interact with T1–T2 lag, implying that load did not influence the mechanisms responsible for the AB. In subsequent experiments, Akyürek & Hommel (2005, 2006) replicated this null result across a variety of distractor and target types, varying levels of similarity between memory load items and targets and presence/absence of a verbal suppression task. On the basis of these findings, Akyürek and Hommel (2005) suggested that although the notion of a central bottleneck was consistent with their findings, it seemed unlikely that this bottleneck was at the level of WM.

As an alternative explanation for these findings, Akyürek, Hommel, and Jolicoeur (2007) proposed a distinction between capacity limitations with respect to WM storage and processing. Storage limitations arise from limits in the amount of information that can be held in WM. Processing limitations, on the other hand, arise from limits in the number of concurrent activities, such as scanning and updating, that can be carried on in WM. Akyürek et al. (2007) suggested that the processing bottleneck that causes the AB might not arise from limits in storage capacity, but instead from limits in processing capacity. This would account for the failure to find an effect of memory load, which was a storage capacity manipulation.

To test this hypothesis, Akyürek et al. (2007) asked observers to determine whether T1 was part of a memory set presented prior to each experimental trial. The size of the memory set varied from 1–4 letters, with larger sets presumably requiring more memory processing than smaller sets (due to greater numbers of stimulus–memory set comparisons). Consistent with their reasoning, the size of the memory set interacted with T1–T2 lag, implying that processing-capacity limits in WM played a role in the AB. These results are also consistent with demonstrations of a link between WM span and the AB (Colzato, Spape, Pannebakker, & Hommel, 2007).

Although the findings of Akyürek et al. (2007) provide a compelling demonstration of the effect that processing limitations in WM have on the AB, they do not conclusively show that limitations in storage capacity cannot influence the deficit as well. Thus, it is relevant to consider other possible reasons for Akyürek and Hommel's (2005, 2006) failure to find a link between memory load and the AB before rejecting the notion of such a link completely. One such reason may be their use of a masking item presented immediately following T1 in the same spatial location.

The use of a T1 mask is a nearly ubiquitous practice in AB experiments, largely motivated by Raymond et al. (1992)'s failure to find an AB in the absence of such a masking stimulus. However, recent work by Visser (2007) has suggested that this mask plays a critical role in modulating the impact of T1 difficulty manipulations. To illustrate, when T1 was masked, Visser (2007) found no effect of varying the difficulty of a T1 size judgement task on the AB. However, when the T1 mask was omitted, the identical T1 task reliably modulated the AB. Based on this pattern of results, Visser (2007) concluded that the mask interrupted T1 processing, thereby nullifying variations in processing time that would have otherwise arisen from the manipulation of T1 difficulty.

These findings are particularly relevant to the present inquiry because, in line with the bottleneck accounts, Akyürek and Hommel (2005) hypothesized that WM load would influence the AB by modulating T1 encoding time. Thus, memory load can be conceptualized as a type of T1 difficulty manipulation akin to those studied by Visser (2007) and others. Viewed from this perspective, it becomes clear that failures to find a link between WM load and the AB may stem from the same cause as earlier failures to find a link between T1 difficulty and the AB: the T1 mask. Couched in terms of the explanation given by Visser (2007), it may be that increased memory load increased T1 processing time, but not the AB because the T1 mask equated processing time across levels of the memory load manipulation.

To test this possibility, the present work varied memory load with and without the use of a mask displayed after T1. In Experiment 1, the results of Akyürek and Hommel (2005) were replicated using a similar paradigm with random-dot distractors and letter targets. In Experiment 2, the role of T1 masking was tested by replicating the first experiment, while omitting the T1 mask. To anticipate the results, omitting the T1 mask revealed a robust relationship between WM load and the AB. Experiments 3 and 4 extend this finding by showing similar effects of WM load when trials with and without a T1 mask were interleaved (Experiment 3) and when a spatial switch between T1 and T2 was required (Experiment 4). Finally, in Experiment 5, the influence of WM load on target processing times was demonstrated directly by requiring a speeded response to targets presented either with or without a trailing mask.

EXPERIMENT 1

Method

Participants

A total of 32 participants (26 female) were recruited through advertisements on university notice boards and web-based software. Informed consent was obtained from all participants as per standard ethical guidelines. All participants received a small honorarium of $10 or bonus credit towards their grade in a psychology course to compensate them for their time and effort, and all participants reported normal or corrected-to-normal vision.

Apparatus and stimuli

Stimuli were presented on a 19-inch (viewing size: 17.75 inch) NEC monitor (MultiSync FE992) running at a refresh rate of 100 Hz, attached to a Pentium computer running Presentation software (Version 9.82; Albany, CA: Neurobehavioral Systems). The software was also responsible for recording response times and accuracy from a computer keyboard.

Testing was conducted in a quiet, dark laboratory with only dim lighting provided by keys on an illuminated keyboard. All stimuli subtended a visual angle of approximately 1° at a viewing distance of 60 cm. Targets were shown in upper case Arial font (28 point; RGB, red/green/blue values: 70, 70, 70) and consisted of all letters of the English alphabet except I, O, Q, and Z, which were omitted due to their structural similarity to the digits 1, 0, 2, and 7. Random-dot distractors comprised 10 different patterns each consisting of 400 single-pixel dots distributed randomly within an imaginary square subtending 1° of visual angle. Target masks were symbols shown in Arial font (28 point; RGB: 250, 250, 250) that were chosen randomly from the set @, #, and %. Distractor and mask luminance was increased relative to targets in order to decrease target discriminability and to ensure accuracy was below a ceiling level of performance. The stimuli used in the memory load task were displayed in upper-case Arial font (28 point; RGB: 167, 167, 167), and consisted of all letters of the English alphabet except I, O, Q, and Z.

Procedure

The experiment comprised 240 trials, evenly divided between two levels of memory set (either two or six letters), and four T1–T2 stimulus onset asynchronies: 180, 270, 450, or 720 ms (Lags 2, 3, 5, and 7, respectively). This yielded a total of 30 trials at each combination of memory set and lag.

A schematic illustration of the sequence of events on a typical trial is presented in Figure 1. Each trial began with a fixation cross presented at the centre of the screen.

Participants focused their gaze at fixation and pressed the spacebar to initiate a trial. Following a 300-ms pause during which the display was blank, the memory load of either two or six letters was displayed at the centre of the screen for 1,000 ms (as in Akyürek & Hommel, 2005, 2006). Letters in the memory load were chosen randomly without replacement. After the memory load display disappeared, the fixation cross reappeared at the centre of the screen for 250 ms before the onset of an RSVP stream. Each item in the stream appeared for 60 ms and was followed by a 30-ms blank display. Distractors were chosen randomly with replacement with the proviso that identical distractors were never presented in succession. The first target was presented after five to eight distractors had been displayed. This target was chosen randomly from the set of possible letters. Depending on T1–T2 lag, T1 was followed by a randomly chosen symbol mask and one of the following: T2 (Lag 2); one random-dot distractor and T2 (Lag 3); three random-dot distractors and T2 (Lag 5); or five random-dot distractors and T2 (Lag 7). The second target was chosen randomly from the set of possible letters with the proviso that it must not be the same as T1. After T2, the last character presented in the RSVP stream was always a randomly chosen symbol mask.

After the mask disappeared, there was a 200-ms blank display, and then a single letter was presented in the centre of the screen. On half of trials, this letter was identical to one of the memory set, while on the other half of trials, a letter was randomly chosen that was not part of the memory set. Participants were instructed to press the left arrow key if the letter was part of the memory set, or the right arrow key if it was not. Once they had made this response, the letter disappeared and was replaced with a prompt ("T1 Letter?") that signalled participants to report the first letter presented during the trial by pressing the appropriate key on the keyboard. After this response, a second prompt ("T2 Letter?") appeared to signal participants to report the second letter in the same manner. Once this last response had been made, the fixation cross reappeared, and participants began the next trial at their leisure by pressing the spacebar.

Results

Mean accuracy on the memory load task was calculated separately as a function of memory set and T1–T2 lag. These means were then analysed using a 2 (memory set: 2 vs. 6) × 4 (T1–T2 lag:

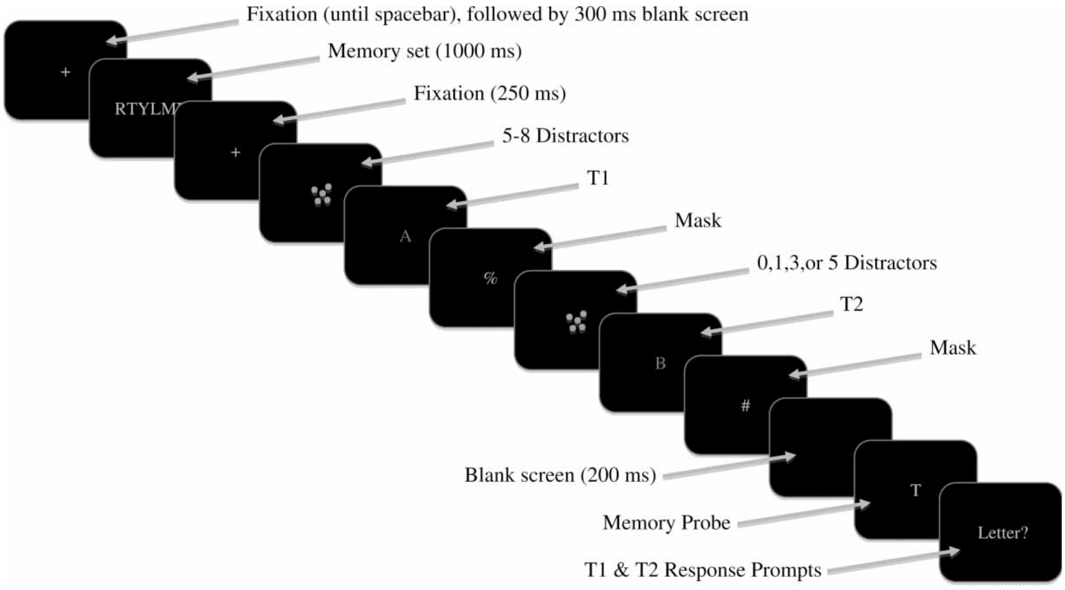

Figure 1. *Schematic illustration of the sequence of events on a Lag 3 trial in Experiment 1 (not to scale). Participants were expected to remember two or six letters presented at the beginning of each trial (working memory, WM, load) and then identify two letters (Target 1, T1, and Target 2, T2) presented amongst an ensuing stream of random-dot patches (distractors) and keyboard symbols (masks). At the end of each trial, participants were shown a single letter as a WM probe (present/absent) and were then prompted to report the identities of T1 and T2. In subsequent experiments in which the T1 mask was omitted, a blank screen replaced the keyboard symbol for the same duration.*

2, 3, 5, 7) within-subjects analysis of variance (ANOVA). This yielded a main effect of memory set, $F(1,\ 31) = 117.12$, $p < .001$, $\eta^2 = .79$, such that accuracy was significantly lower when the set consisted of six letters (74.08%) than when it consisted of two letters (93.39%). This suggests that memory consolidation was more difficult when there were six letters to remember. There was no main effect of lag or interaction between memory set and lag (ps > .07).

As is common in AB studies, responses to T1 and T2 were scored as correct regardless of order of report. Mean T1 accuracy levels were calculated as a function of memory set and lag only for trials on which the memory task was completed correctly.

These means are shown in Table 1. Accuracy scores for T1 were analysed using a 2 (memory set) × 4 (T1−T2 lag) within-subjects ANOVA. This analysis revealed a main effect of memory set, $F(1,\ 31) = 9.96$, $p < .01$, $\eta^2 = .24$, and a main effect of lag, $F(3,\ 93) = 7.04$, $p < .001$, $\eta^2 = .19$. Examination of Table 1 suggests that the main effect of memory set arose from the fact that T1 accuracy was lower when the memory set was larger, while the main effect of lag arose from the fact that performance increased slowly across lags. The interaction between memory set and lag was not significant ($p > .23$).

Mean T2 accuracy was calculated separately as a function of memory set and lag only for trials on which T1 was identified correctly in order to ensure that T1 had been attended.

These means are shown in Figure 2 (Panel A) and were analysed using a 2 (memory set) × 4 (lag) within-subjects ANOVA. This analysis revealed a significant main effect of memory set, $F(1,\ 31) = 4.72$, $p < .04$, $\eta^2 = .13$, indicating that T2 accuracy was significantly lower when the memory load was high. In addition, there was a significant main effect of lag, $F(3,\ 93) = 12.94$, $p < .001$, $\eta^2 = .29$. This significant

Table 1. *Mean T1 accuracy as a function of T1–T2 lag, memory set, and presence or absence of T1 mask for Experiments 1 and 2*

			Lag			
T1 mask	*Experiment*	*Memory set*	*2*	*3*	*5*	*7*
Present	1	2	85.29 (2.16)	85.97 (2.29)	88.42 (1.89)	91.19 (1.59)
		6	81.14 (2.22)	84.19 (2.21)	87.25 (2.16)	85.41 (1.94)
Absent	2	2	93.08 (1.17)	94.88 (1.07)	96.05 (0.84)	94.07 (1.08)
		6	89.12 (1.58)	90.36 (1.57)	92.99 (1.34)	92.57 (0.81)

Note: T1 = Target 1. T2 = Target 2. Numbers in parentheses represent one standard error of the mean. Scores are percentages.

increase in T2 accuracy across lags is the empirical signature of the AB. Critically, however, there was no significant interaction between memory set and lag, $F(3, 93) = 0.61$, $p > .61$, $\eta^2 = .02$.

The present findings replicate those of Akyürek and Hommel (2005, 2006) using a largely equivalent paradigm. Thus, on the face of it, failure to find an interaction between load and lag implies that WM capacity is not associated with the bottleneck implicated in the AB. However, Experiment 2 tested an alternative account—namely, that the influence of memory load on T1 processing and thus the AB were eliminated by the use of a T1 mask. To test this possibility, Experiment 1 was repeated but the mask after T1 was omitted.

EXPERIMENT 2

Method

Participants

A total of 32 participants (24 female) were recruited through advertisements on university notice boards and web-based software. Informed consent was obtained from all participants as per standard ethical guidelines. All participants received a small honorarium of $10 or bonus credit towards their grade in a psychology course to compensate them for their time and effort. All participants reported normal or corrected-to-normal vision, and none had participated in Experiment 1.

Apparatus and stimuli

Apparatus and stimuli were identical to those in Experiment 1.

Procedure

The procedure was identical to that in Experiment 2 with one exception. In this experiment, the distractor presented directly after T1 was omitted. Instead, participants were presented with a blank screen for an equivalent duration.

Results

Mean accuracy on the memory load task was calculated separately as a function of memory set and T1–T2 lag. These means were then analysed using a 2 (memory set) × 4 (T1–T2 lag) within-subjects ANOVA. As in Experiment 1, a main effect of memory set was obtained, $F(1, 31) = 67.22$, $p < .001$, $\eta^2 = .68$, such that accuracy was significantly lower when the set consisted of six letters (79.38%) than when it consisted of two letters (94.65%). This suggests that memory consolidation was more difficult when there were six letters to remember. There was no main effect of lag or interaction between memory set and lag (ps $> .09$).

Responses to T1 and T2 were recorded as correct regardless of order of report. Mean T1 accuracy levels were calculated separately as a function of memory set and lag only for trials on which the memory task was completed correctly. These means are shown in Table 1. Accuracy scores for T1 were analysed using a 2 (memory set) × 4 (T1–T2 lag) within-subjects ANOVA. This analysis revealed a main effect of memory set, $F(1, 31) = 17.11$, $p < .001$, $\eta^2 = .36$, and a main effect of lag, $F(3, 93) = 5.32$, $p < .01$, $\eta^2 = .15$. Examination of Table 1 suggests that the main effect of memory set arose from the fact that T1

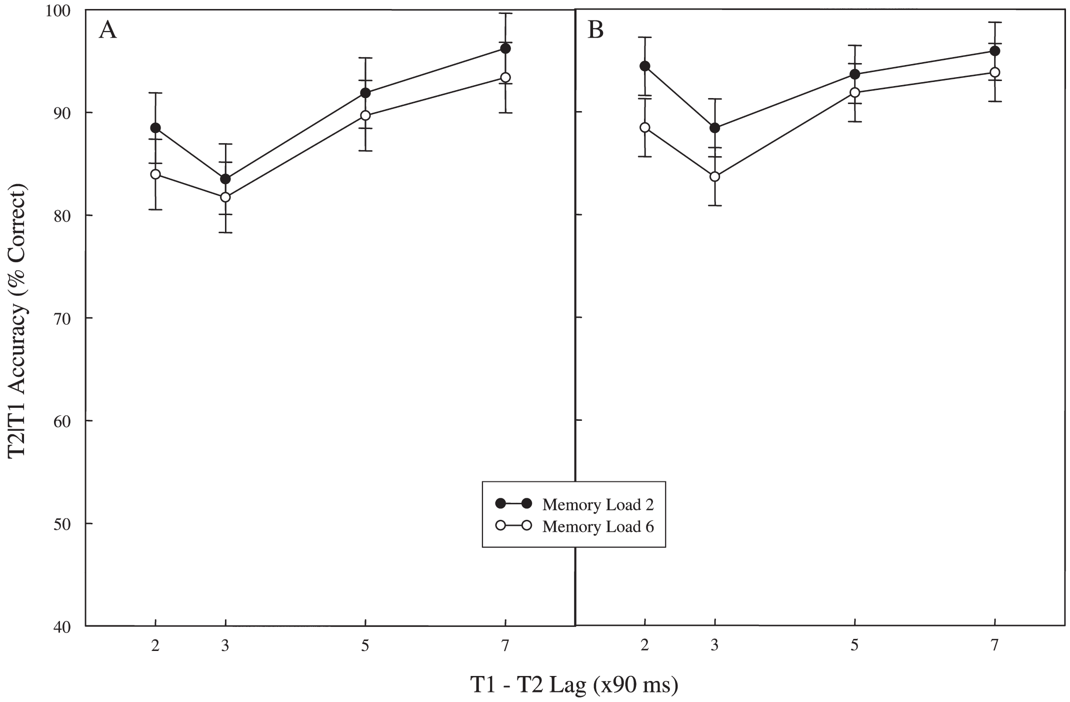

Figure 2. *Mean Target 2 (T2) accuracy as a function of intertarget lag and memory load. Panel A depicts performance from Experiment 1 with a Target 1 (T1) mask. Panel B depicts performance from Experiment 2 with no T1 mask. Error bars represent 95% within-subjects confidence intervals calculated as per Masson and Loftus (2003).*

accuracy was lower when the memory set was larger, while the main effect of lag arose from the fact that performance increased slowly across the first three lags and then levelled off at the longest lag. The interaction between memory set and lag was not significant ($p > .23$).

Mean T2 accuracy was calculated separately as a function of memory set and lag only for trials on which T1 was identified correctly in order to ensure that T1 had been attended. These means are shown in Figure 2 (Panel B) and were analysed in a 2 (memory set) × 4 (lag) within-subjects ANOVA. This analysis revealed a significant main effect of memory set, $F(1, 31) = 8.21$, $p < .01$, $\eta^2 = .21$, indicating that T2 accuracy was significantly lower when load was high. In addition, there was a significant main effect of lag, $F(3, 93) = 10.42$, $p < .001$, $\eta^2 = .25$. This significant increase in T2 accuracy across lags is the empirical signature of the AB. Most importantly, in contrast to previous experiments, there was also a significant interaction between memory set and lag, $F(3, 93) = 3.00$, $p < .05$, $\eta^2 = .08$. This interaction suggests that memory load interacted with the magnitude of the AB deficit and, in turn, implicates WM capacity in the bottleneck associated with the AB. Confirming this interpretation, t tests were conducted to compare T2 accuracy as a function of memory set separately at each lag. These analyses revealed significant differences at Lag 2, $t(31) = 3.37$, $p < .01$, and Lag 3, $t(31) = 2.42$, $p < .03$, but not at Lags 5 or 7 ($p > .13$).

In comparing the current results with those of Experiment 1 and earlier studies that have examined the influence of memory load on the AB, it seems that the relevant difference is the presence of a masking distractor following T1. On the assumption that the influence of memory load is to vary the speed with which T1 can be consolidated, this finding is consistent with the results of Visser (2007) showing that T1 difficulty effects are reliably obtained only when the T1 mask is omitted.

Although sensible, before concluding that memory load does indeed influence the AB, it is desirable to evaluate alternative interpretations of the present findings. One possibility is that the present results might only be found when masked and nonmasked T1 trials are presented to separate participants or in a blocked design. This would imply that attentional set is a critical factor in determining whether memory load influences the AB. To test this possibility, in Experiment 3, a single group of participants was presented with randomly interleaved trials in which the T1 mask was presented or omitted. In addition, digit distractors were used along with letter targets in order to increase target–distractor similarity.

EXPERIMENT 3

Method

Participants
A total of 40 participants (31 female) were recruited through advertisements on notice boards and web-based software. Informed consent was obtained from all participants as per standard ethical guidelines. All participants received a small honorarium of $10 or bonus credit towards their grade in a psychology course to compensate them for their time and effort. All participants reported normal or corrected-to-normal vision, and none had participated in previous experiments.

Apparatus and stimuli
Apparatus and stimuli were identical to those in Experiment 1 except that dot distractors were replaced with digits. These digit distractors were shown in Arial font (28 point; RGB: 250, 250, 250) and consisted of all single digits except 1, 0, 2, and 7, which were omitted due to their similarity to the letters I, O, Q, and Z.

Procedure
The procedure was identical to that in Experiment 1 with two exceptions. First, there were 400 trials evenly divided between those in which a distractor was presented after T1 and those in which the distractor was omitted. In turn, these trials were divided equally between the two levels of memory load and four lags. This yielded a total of 25 trials at each combination of these three factors. Trial types were presented to participants in random order. In addition, digit distractors were used in the RSVP stream, rather than random-dot distractors.

Results

Mean accuracy on the memory load task was calculated separately as a function of memory set, T1–T2 lag, and presence/absence of T1 mask. These means were then analysed using a 2 (memory set) × 2 (T1 mask: present vs. absent) × 4 (T1–T2 lag) within-subjects ANOVA. This yielded a main effect of memory set, $F(1, 39) = 131.28$, $p < .001$, $\eta^2 = .77$, indicating that overall performance was lower when the memory set consisted of six characters (67.73%) than when it consisted of two characters (87.04%). No other main effects or interactions were significant (ps $> .19$).

Responses to T1 and T2 were recorded as correct regardless of order of report. Mean T1 accuracy levels were calculated as a function of memory set, lag, and presence/absence of T1 mask only for trials on which the memory task was completed correctly. These means are shown in Table 2. Accuracy scores for T1 were analysed using a 2 (memory set) × 2 (T1 mask) × 4 (T1–T2 lag) within-subjects ANOVA. This analysis revealed main effects of memory set, $F(1, 39) = 9.27$, $p < .01$, $\eta^2 = .19$, mask, $F(1, 39) = 39.45$, $p < .001$, $\eta^2 = .48$, and lag, $F(3, 117) = 9.01$, $p < .001$, $\eta^2 = .19$. As can be seen in Table 2, the main effect of memory set confirmed that T1 accuracy was higher when only two letters had to be encoded. The main effect of mask indicated that accuracy was higher when the T1 mask was omitted, replicating differences between Experiments 1 and 2. Finally, the main effect of lag confirmed that accuracy was somewhat

Table 2. *Mean T1 accuracy as a function of T1–T2 lag, memory set, and presence or absence of T1 mask for Experiment 3*

		Lag			
T1 mask	*Memory set*	*2*	*3*	*5*	*7*
Present	2	81.89 (3.30)	83.21 (2.89)	84.41 (2.97)	86.52 (2.87)
	6	75.93 (3.30)	78.61 (3.36)	82.19 (3.07)	83.31 (2.99)
Absent	2	87.71 (2.93)	85.75 (2.80)	90.42 (2.58)	89.45 (2.76)
	6	83.35 (3.38)	85.75 (2.78)	88.46 (2.91)	86.19 (2.81)

Note: T1 = Target 1. T2 = Target 2. Numbers in parentheses represent one standard error of the mean. Scores are percentages.

lower at the first two lags than at the last two lags. No interactions involving these factors were significant (all ps > .16).

Mean T2 accuracy was calculated separately as a function of memory set and lag only for trials on which T1 was identified correctly in order to ensure that T1 had been attended.

These means are shown in Figure 3 and were analysed using a 2 (memory set) × 2 (T1 mask) × 4 (lag) within-subjects ANOVA. This analysis revealed main effects of memory set, $F(1, 39) = 5.52$, $p < .03$, $\eta^2 = .12$, mask, $F(1, 39) = 41.99$, $p < .001$, $\eta^2 = .52$, and lag, $F(3, 117) = 89.00$, $p < .001$, $\eta^2 = .70$. As suggested by an examination of Figure 3, overall T2 accuracy was greater when the memory set was smaller and when the T1 mask was omitted, replicating differences between Experiments 1 and 2. In addition,

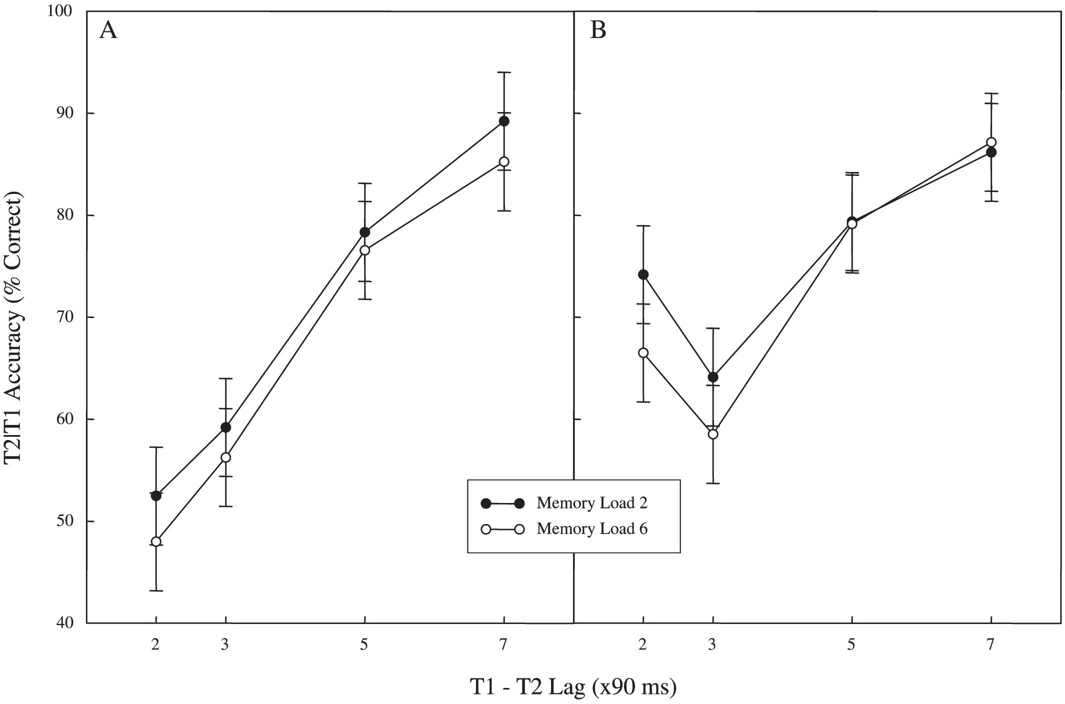

Figure 3. *Mean Target 2 (T2) accuracy as a function of intertarget lag and memory load in Experiment 3. Panel A depicts performance with a mask after T1. Panel B depicts performance when the mask after T1 was omitted. Error bars represent 95% within-subjects confidence intervals calculated as per Masson and Loftus (2003).*

consistent with the presence of an AB, accuracy improved across lags. In addition to the main effects, there was a significant interaction between T1 mask and lag, $F(3, 117) = 20.16$, $p < .001$, $\eta^2 = .34$. Inspection of the graph suggests that this interaction arose because performance increased linearly across lag when there was a T1 mask but displayed a nonlinear function when the mask was omitted. This marks a departure from the results obtained in Experiments 1 and 2 and implies that attentional set may influence the overall pattern of the AB obtained in these earlier experiments.

Although no other interactions were significant ($ps > .17$), based on a priori hypotheses about differences between performances when the T1 mask was present or absent, separate 2 (memory set) × 4 (lag) within-subject ANOVAs were conducted for these two types of trial. When the mask was present, as in Experiment 1, this analysis revealed a main effect of memory set, $F(1, 39) = 4.56$, $p < .04$, $\eta^2 = .11$, and lag, $F(3, 117) = 81.40$, $p < .001$, $\eta^2 = .68$, but no interaction between memory set and lag, $F(3, 123) = 0.19$, $p > .90$, $\eta^2 = .01$.

In contrast, when the T1 mask was omitted, as in Experiment 2, there was a significant main effect of memory set, $F(1, 39) = 4.15$, $p < .05$, $\eta^2 = .10$, and lag, $F(3, 117) = 43.91$, $p < .001$, $\eta^2 = .53$, consistent with an effect of memory load on T2 accuracy and the presence of an AB, and, most importantly, a significant interaction between memory set and lag, $F(3, 117) = 3.03$, $p < .04$, $\eta^2 = .07$, indicating that load affected the processing stage responsible for the AB. To confirm this interpretation, *t* tests were again conducted to compare T2 accuracy as a function of memory set separately at each lag. These analyses revealed significant differences at Lag 2, $t(39) = 2.36$, $p < .03$, and Lag 3, $t(39) = 2.10$, $p < .04$, but not at Lags 5 or 7 ($p > .58$). Taken together, these analyses suggest that a reliable influence of memory load on the AB can be found even when observers cannot predict whether a T1 mask will occur.

Although the results of Experiment 3 dovetail nicely with those from Experiment 2, before concluding that memory load influences AB magnitude, another alternative interpretation must also be considered. Examination of the data in conditions where the T1 mask is omitted reveals that the appearance of memory load effects is accompanied by an overall improvement in T2 at Lag 2 relative to Lag 3. This pattern of performance is reminiscent of so-called “Lag 1 sparing” in which T2 accuracy is relatively improved when it follows T1 directly compared to when T1 and T2 are separated by at least one distractor (e.g., Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). Although the experiments here did not contain a Lag 1 position, it may have been that omitting the mask after T1 mimicked the conditions necessary for Lag 1 sparing to occur when T2 was at the Lag 2 position. This is particularly relevant because it has been argued that Lag 1 sparing and the AB reflect separable mechanisms (Visser et al., 1999). Thus, it may be possible that the memory load effects found here do not interact with the mechanisms responsible for the AB, but instead those responsible for Lag 1 sparing.

To test this option, in Experiment 4, T1 and T2 were presented in different spatial locations. In their review of the Lag 1 sparing literature, Visser et al. (1999) found that experiments that contained a spatial location switch between T1 and T2 reliably failed to show Lag 1 sparing. On this account, by presenting targets in different locations in Experiment 4, any effect of memory load on T2 performance may be confidently attributed to the mechanisms underlying the AB and not to those underlying Lag 1 sparing.

EXPERIMENT 4

Method

Participants

A total of 43 participants (31 female) were recruited through advertisements on web-based software. Informed consent was obtained from all participants as per standard ethical guidelines. All participants received a small honorarium of

$10 or bonus credit towards their grade in a psychology course to compensate them for their time and effort. All participants reported normal or corrected-to-normal vision, and none had participated in previous experiments.

Apparatus and stimuli

Stimuli were presented on a 19-inch (viewing size: 17.99 inch) monitor (Acer AC 713) running at a refresh rate of 100 Hz, on a Pentium computer. Stimuli were identical to those in Experiment 3.

Procedure

The procedure was identical to that in Experiment 1 with one exception. The second target and its trailing mask were presented randomly above, below, left, or right of the central stream. The centre-to-centre separation between the peripheral items and the central stream was approximately 1°.

Results

Mean accuracy on the memory load task was calculated separately as a function of memory set, T1–T2 lag, and presence/absence of T1 mask. These means were then analysed using a 2 (memory set) × 2 (T1 mask: present vs. absent) × 4 (T1–T2 lag) within-subjects ANOVA. This yielded a main effect of memory set, $F(1, 42) = 124.15$, $p < .001$, $\eta^2 = .75$, indicating that overall performance was lower when the memory set consisted of six characters (71.90%) than when it consisted of two characters (88.25%). No other main effects or interactions were significant (ps > .20).

Responses to T1 and T2 were recorded as correct regardless of order of report. Mean T1 accuracy levels were calculated as a function of memory set, lag, and presence/absence of T1 mask only for trials on which the memory task was completed correctly. These means are shown in Table 3. Accuracy scores for T1 were analysed using a 2 (memory set) × 2 (T1 mask) × 4 (T1–T2 lag) within-subjects ANOVA. This analysis revealed main effects of memory set, $F(1, 42) = 10.56$, $p < .01$, $\eta^2 = .20$, and lag, $F(3, 126) = 8.09$, $p < .001$, $\eta^2 = .16$. As can be seen in Table 3, the main effect of memory set confirmed that T1 was identified more accurately when two letters had to be encoded, rather than six letters. The main effect of lag reflects that overall performance was better at the last two lags than at the first two lags. No other main effects or interactions were significant (all ps > .34).

Mean T2 accuracy was calculated separately as a function of memory set and lags only for trials on which T1 was identified correctly in order to ensure that T1 had been attended. These means are shown in Figure 4 and were analysed using a 2 (memory set) × 2 (T1 mask) × 4 (lag) within-subjects ANOVA. This analysis revealed main effects of memory set, $F(1, 42) = 28.82$, $p < .001$, $\eta^2 = .41$, lag, $F(3, 126) = 56.88$, $p < .001$, $\eta^2 = .58$, and mask, $F(1, 42) = 4.39$, $p < .05$, $\eta^2 = .10$. This confirms that overall T2 accuracy was greater when the memory set was smaller, that a significant AB was obtained across conditions, and that T2 accuracy was lower when T1 was masked. No other main effects or interactions were significant (all ps > .13), except a significant

Table 3. *Mean T1 accuracy as a function of T1–T2 lag, memory set, and presence or absence of T1 mask for Experiment 4*

		Lag			
T1 mask	*Memory set*	*2*	*3*	*5*	*7*
Present	2	85.22 (1.85)	85.96 (1.88)	89.30 (1.50)	90.84 (1.48)
	6	80.04 (2.46)	80.47 (2.33)	85.17 (2.49)	82.06 (2.18)
Absent	2	85.28 (2.61)	84.89 (2.60)	87.52 (2.54)	86.25 (2.50)
	6	81.88 (3.09)	80.88 (2.99)	83.41 (2.74)	83.39 (2.96)

Note: T1 = Target 1. T2 = Target 2. Numbers in parentheses represent one standard error of the mean. Scores are percentages.

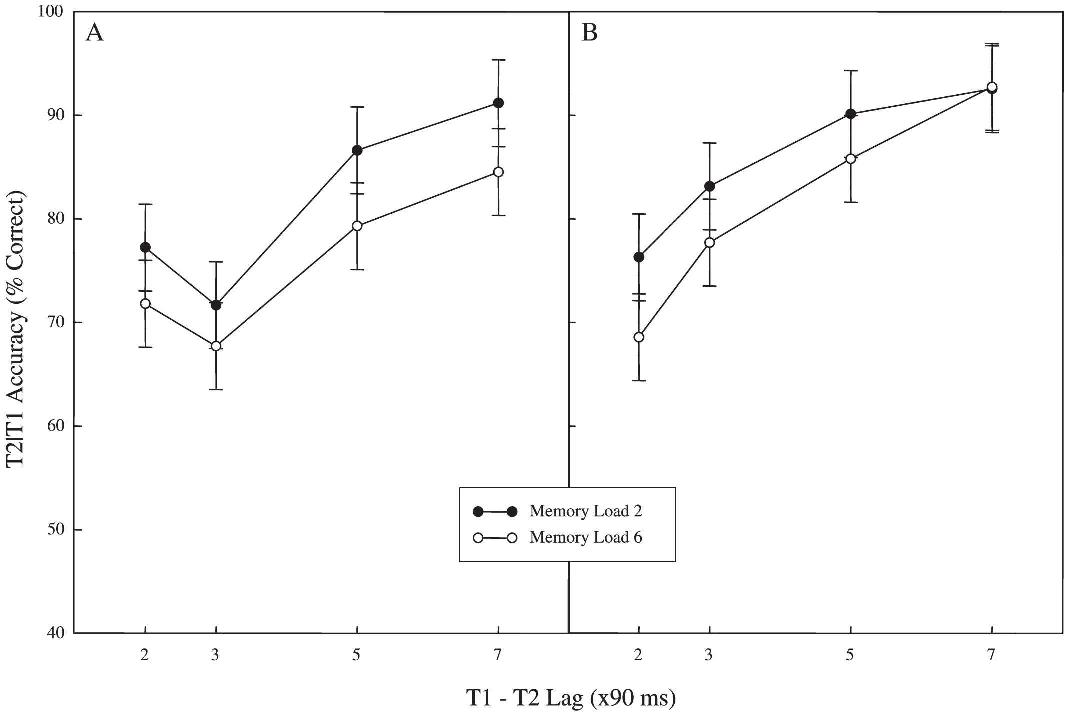

Figure 4. *Mean Target 2 (T2) accuracy as a function of intertarget lag and memory load in Experiment 4. Panel A depicts performance with a mask after T1. Panel B depicts performance when the mask after T1 was omitted. Error bars represent 95% within-subjects confidence intervals calculated as per Masson and Loftus (2003).*

interaction between T1 mask and lag, $F(3, 126) = 6.99$, $p < .001$, $\eta^2 = .14$, indicating that the AB differed as a function of T1 masking. Examination of Figure 4 shows that when T1 was masked, T2 accuracy was better at Lag 2 than Lag 3 and then improved steadily over lags; in contrast, when the mask was omitted, T2 accuracy improved linearly across lags. This "sparing" pattern is the opposite of that obtained in Experiment 3 and argues strongly against a link between the memory load effects obtained here without a T1 mask and the mechanisms underlying Lag 1 sparing.

As in Experiment 3, although the three-way interaction between memory set, mask, and lag was not significant, based on a priori predictions, separate 2 (memory set) × 4 (lag) within-subject ANOVAs were conducted for trials on which the T1 mask was present or absent. When the T1 mask was present, there was a main effect of memory set, $F(1, 42) = 25.35$, $p < .001$, $\eta^2 = .38$, and lag, $F(3, 126) = 30.20$, $p < .001$, $\eta^2 = .42$, but no interaction between memory set and lag, $F(3, 126) = 0.35$, $p > .79$, $\eta^2 = .01$. In contrast, when the T1 mask was omitted, a main effect of memory set, $F(1, 42) = 12.44$, $p < .01$, $\eta^2 = .23$, and lag was obtained, $F(3, 126) = 38.00$, $p < .001$, $\eta^2 = .48$, as well as a significant interaction between memory set and lag, $F(3, 126) = 3.74$, $p < .02$, $\eta^2 = .08$. To deconstruct the interaction, separate *t* tests were conducted to compare T2 accuracy as a function of memory set at each lag. The analyses revealed significant differences at Lag 2, $t(42) = 3.52$, $p < .01$, and Lag 3, $t(42) = 2.61$, $p < .02$, and a marginal difference at Lag 5, $t(42) = 1.98$, $p < .06$, but no difference at Lag 7, $t(42) = 0.22$, $p > .82$. The fact that T2 "sparing" occurred with a T1 mask, that there was an interaction between memory set and lag in the presence of a spatial switch, and that there were consistent differences in T2 accuracy as a function of memory set at Lag 3 all compellingly demonstrate that WM capacity can influence the AB in the absence of a T1 mask and when the conditions necessary for Lag 1 sparing are eliminated.

To this point, it has been assumed both here and in earlier work (Akyürek & Hommel, 2005, 2006) that memory load modulates the time required to encode T1. Further, it has been assumed here that these modulations are eliminated by the presence of the T1 mask. If these assumptions are accurate, it should be the case that T1 processing times will be longer when memory load is increased, but only if T1 is not masked. To test this prediction, in Experiment 5, participants were presented with a memory set of 2 or 6 letters, followed by an RSVP stream and a single target that was either a "C" or a "G". This target was either masked, or the mask was omitted. Participants were asked to report target identity as quickly as possible and then to determine whether a subsequent letter was part of the memory set. These presentation and response requirements closely mimicked those used for T1 in previous experiments. If the assumption that memory load increases T1 processing time is accurate, response times should be greater with a larger memory load. Further, if the assumption that the T1 mask interrupts target processing is correct, differences in T1 RTs as a function of memory load should only occur when the T1 mask is omitted.

EXPERIMENT 5

Method

Participants

A total of 32 participants (27 female) were recruited through advertisements on university notice boards and web-based software. Informed consent was obtained from all participants as per standard ethical guidelines. All participants received a small honorarium of $10 or bonus credit towards their grade in a psychology course to compensate them for their time and effort. All participants reported normal or corrected-to-normal vision, and none had participated in previous experiments.

Apparatus and stimuli

Apparatus and stimuli were identical to those in Experiment 1.

Procedure

The experiment comprised 240 trials evenly divided between two levels of memory set (either two or six letters) and the presence/absence of a T1 mask. This yielded a total of 60 trials at each combination of these factors.

Each trial was similar to those in Experiments 1 and 2, except that only a single target was presented in the RSVP following five to eight random-dot distractors. The target was equally likely to be the letter "C" or "G". Participants were instructed to press an appropriate response key as soon as they were able to identify the target letter (or guess if they were not sure). As in earlier experiments, following this speeded response, there was a 200-ms pause during which the display was blank, and then participants completed the memory recall task without time pressure.

Results

Mean accuracy on the memory load task was calculated separately as a function of memory set and presence/absence of a T1 mask. These means were then analysed using a 2 (memory set) × 2 (target mask: present vs. absent) within-subjects ANOVA. This analysis revealed only a significant main effect of memory set, $F(1, 31) = 34.92$, $p < .001$, $\eta^2 = .53$, such that accuracy was significantly lower when the memory set consisted of six letters (81.44%) than when it consisted of two letters (91.27%). This finding replicates earlier results and validates that the memory task was more difficult when the number of items to be remembered was increased. No other main effects or interactions were significant (ps $> .34$).

Mean target identification accuracy was calculated separately as a function of memory set and the presence/absence of a T1 mask. These means (see Figure 5) were then analysed using a 2 (memory set) × 2 (target mask) within-subjects ANOVA. Only the main effect of T1 mask was significant, $F(1, 31) = 43.33$, $p < .001$, $\eta^2 = .58$, indicating that target accuracy was lower when the target was masked (80.31%) than when it was not (88.59%). No other main effects or interactions were significant (ps $> .25$).

Mean target RTs were calculated separately as a function of memory set and the presence/absence of a T1 mask only on trials in which the target was correctly identified.

These means are presented in Figure 5 and were analysed using a 2 (memory set) × 2 (target mask) within-subjects ANOVA. This revealed a main effect of target mask, $F(1, 31) = 30.06$, $p < .001$, $\eta^2 = .49$, indicating that responses were slower when the target was masked (547 ms) than when it was not (513 ms). This finding is consistent with the accuracy data and suggests that no speed–accuracy trade-offs occurred in the experiment. Although the main effect of memory set was not significant ($p > .21$), importantly, there was a significant interaction between memory set and target mask, $F(1, 31) = 6.76$, $p < .02$, $\eta^2 = .18$. Examination of Figure 5 suggests that this interaction arose from the fact that RTs were unaffected by memory load when the target was masked, but slower with a larger memory load when the mask was omitted. Consistent with this interpretation, follow-up tests showed no difference in RTs as a function of memory load when the target was masked, $t(31) = 0.11$, $p > .90$, but a significant difference when the target mask was omitted, $t(31) = 2.57$, $p < .02$.

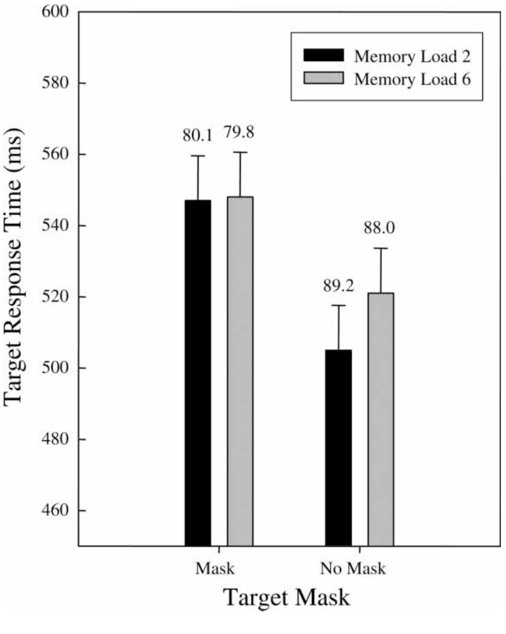

Figure 5. *Mean target response times as a function of the presence/absence of a trailing mask and memory load in Experiment 5. Error bars represent 95% within-subjects confidence intervals calculated as per Masson and Loftus (2003). Numbers above columns denote target identification accuracy (in percentages) in that experimental condition.*

The present results support two assumptions made in previous experiments: An increase in memory load increases T1 processing time, and this increase is eliminated when T1 is masked. This finding is consistent with results from T1 difficulty experiments reported by Visser (2007) and supports the hypothesis advanced here that failures to find an impact of memory load on the AB are the result of using a T1 mask, rather than because WM capacity does not influence the mechanisms responsible for the AB.

GENERAL DISCUSSION

When two targets are presented in rapid succession, identification of the first target is nearly perfect, while identification of the second target is impaired when it follows the first target by less than about 700 ms. This attentional blink has often been attributed to capacity limits in working memory (e.g., Jolicoeur, 1998). On this notion, if the second target is presented while the first target is being consolidated in WM, it cannot also gain access to WM, leaving it vulnerable to masking or decay. While prior studies have shown that AB magnitude is related to the processing capacity of WM (Akyürek et al., 2007; Colzato et al., 2007), other studies have failed to find a similar relationship between the AB and storage capacity in WM (Akyürek & Hommel, 2005, 2006). The present study examined whether these failures stemmed from the use of a mask after T1 (Visser, 2007). Consistent with this hypothesis, manipulation of memory load presented prior to the AB task modulated performance when the T1 mask was omitted, but not when the mask was present.

The findings here suggest that the bottleneck associated with T2 errors in the AB may be at least partially related to the need to store T1 in WM. This is not to say, of course, that WM capacity is the only limiting factor in T2 performance as demonstrated by numerous other stimulus and task manipulations that are unrelated to WM but also interact with AB magnitude—for example, difficulty of size discrimination task (Ward, Duncan, & Shapiro, 1997; Visser, 2007); T1 masking (Shore, McLaughlin, & Klein, 2001; Visser & Ohan, 2007). Rather, the present findings delineate one possible source of T2 delays in the AB, which may be added to the growing list of factors that are implicated in the deficit.

The effect of T1 difficulty on the AB

One of the central tenets of bottleneck theories is that processing time for T1 should be related to AB magnitude (Chun & Potter, 1995). This hypothesis has been examined in numerous AB studies that have found evidence both for this relationship (e.g., Chun & Potter, 1995; Ouimet & Jolicoeur, 2007; Seiffert & Di Lollo, 1997; Shore et al., 2001) and against it (e.g., McLaughlin, Shore, & Klein, 2001; Ward et al., 1997). In analysing these mixed results, Visser (2007) suggested two possible explanations for this puzzling inconsistency. One possibility stems from the fact that experiments have consistently varied T1 difficulty using a variety of manipulations without verifying whether difficulty actually influenced T1 processing time. Thus, failures to find a relationship between T1 difficulty and the AB might reflect a failure of the experimental manipulation rather than a fault with bottleneck theories.

A second possibility, and one more relevant for the present work, lies in the use of T1 masking. As noted above, while such masking is commonplace in AB experiments, there is substantial empirical literature (e.g., Breitmeyer, 1984; Breitmeyer & Öğmen, 2006; Turvey, 1973) to suggest that one function of backward masking is to interrupt high-level processing of prior targets. Visser (2007) argued that such interruption might effectively eliminate the effect of T1 difficulty on processing time. On this reasoning, while more difficult tasks should increase processing time, the interruption of T1 processing by the mask would eliminate this difference, by simply halting target processing before accurate identification could occur. This explanation not only accounts for failures to find T1 difficulty effects, but also explains why these difficulty manipulations still routinely influence T1 accuracy (i.e., accuracy is lower when the T1 task is more difficult).

How might processing interruption have occurred in the present experiments? While this is clearly a complex issue, it seems likely that the impact of the memory load manipulation employed here on T1 might be functionally equivalent to the influence of T1 processing on T2. That is, the memory load occupied central resources, thereby interfering with T1 processing and leaving it vulnerable to pattern masking in the same fashion as T2 in the AB (Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998). To the extent that this conjecture is correct, the impact of the trailing mask on T1 processing may be akin to the influence of object-substitution masking thought to underlie the AB (Dell'Acqua, Pascali, Jolicoeur, & Sessa, 2003; Di Lollo, Enns, & Rensink, 2000; Marti, Paradis, Thibeault, & Richer, 2006). Object-substitution masking arises when the representation of the mask replaces that of the target as the focus of perceptual hypothesis-testing mechanisms. This replacement effectively limits the duration of target processing to the interval between target and mask onset in the case where the target and mask are presented sequentially.

The present work can be seen as a further test of Visser's alternative accounts for the uncertainty surrounding the influence of T1 difficulty on the AB. With respect to the possibility that manipulations of difficulty do not affect T1, Experiment 5 provides strong evidence that memory load modulates T1 processing time as is the case with other T1 difficulty manipulations such as integration masking (Visser & Ohan, 2007). With respect to the role of T1 masking, two aspects of the results reported here are consistent with Visser's account. First, when the T1 mask was omitted, WM load modulated the AB as predicted by bottleneck accounts. Second, direct examinations of T1 processing time in Experiment 5 showed that the mask eliminated differences in T1 processing time arising from variations in WM load.

An additional point should also be noted here. While the use of a T1 mask has conventionally been viewed as a prerequisite for finding an AB (Martin & Shapiro, 2007; Raymond et al., 1992; Seiffert & Di Lollo, 1997), the experiments here show that a robust AB can be obtained without using a T1 mask. Why have previous experiments failed to find an AB without a mask? An explanation may be found in closer examination of bottleneck theories of the AB. These accounts make a critical link between the duration of T1 processing time and AB magnitude. Notably this implies that an AB should be found whenever T1 processing time is sufficient to overlap with T2 presentation, not simply when a T1 mask is used. However, because many AB experiments employ relatively simple stimuli and tasks, masking may also interfere with the encoding of T1 sufficiently long for an AB to be obtained, thus creating the illusion of a "requirement" for a T1 mask.

Relationship to other theories of the AB

While the results reported here are clearly consistent with bottleneck accounts of the AB, the importance of WM capacity is also compatible with the theory of Shapiro, Raymond, and Arnell (1994), which suggests that the AB arises from a competition amongst items stored in visual short-term memory (VSTM). On this account, both targets and the immediately trailing item enter VSTM. As a result, at short lags, T1, T2, and their immediately trailing items all compete in VSTM for access to central resources—a competition that is usually lost by T2 by virtue of its relatively late entry into VSTM. In contrast, at longer lags, by the time T2 is presented, T1 and the immediately trailing item have already been selected from VSTM, thus reducing the competition for T2.

To the extent that items from the memory load set are also stored in VSTM and thus compete with targets for attentional selection, this account neatly explains why both T1 and T2 accuracy are reduced by an increase in the size of the memory load. Similarly, when the T1 mask was omitted in Experiments 2–4, T2 accuracy was greater than when the T1 mask was included. This fits nicely with the notion that omission of the mask should reduce competition for T2 and thus increase the likelihood that it would be selected for attentional processing.

Another alternative account of the AB is the TLC (temporary loss of control) model proposed by Di Lollo and colleagues (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Kawahara, Enns, & Di Lollo, 2006a; Kawahara, Kumada, & Di Lollo, 2006b; see also Olivers & Nieuwenhuis, 2005, 2006). Di Lollo et al. (2005) suggested that the AB arises from a temporary loss of attentional control due to processing of the first target. Specifically, the distractor presented after T1 "resets" a perceptual input filter initially set to pass targets and reject distractors. As a result, when a second target is presented, the input filter has to be reconfigured, slowing T2 processing and leaving it vulnerable to masking or decay. A similar idea has been proposed by Olivers and Meeter (2008) in their "boost and bounce" theory, which suggests that an incompatible distractor interposed between two targets triggers inhibitory processes that impair second-target accuracy.

Consistent with these suggestions, Di Lollo et al. (2005) presented observers with two letter targets separated by a confusable distractor, or three consecutive letter targets. In the former case, detection of the second letter was severely impaired as is commonly found in AB experiments. Interestingly, however, when three consecutive letters were presented, detection of the third letter, which was in the same temporal position as the second target in the first condition, was considerably improved. This suggested that the distractor played an important role in triggering the AB.

The present findings provide mixed support for the hypotheses of Di Lollo et al. (2005) and Olivers and Meeter (2008). For example, one piece of relevant data for the purposes of testing the TLC account comes from a comparison between T2 accuracy at Lag 2 with and without a T1 mask. According to the TLC account, T2 accuracy at Lag 2 should be greater when the mask is omitted because there is no distractor present that could errantly reset the input filter or trigger inhibition. Indeed, examination of this comparison across experiments is consistent with this prediction.

At the same time, however, the results do not unambiguously support the TLC option. One reason this is true is that T1 performance is also often higher when the mask is omitted (although see Experiment 4). This opens up the possibility that the beneficial effect of the mask stemmed from decreased processing time for T1, and consequent benefits for T2, rather than because of any effects on input filters or inhibition (see also Dux, Asplund, & Marois, 2008, for a discussion of how trade-offs may explain the advantage found in three-target paradigms more generally). In addition, to the extent that the TLC and boost-and-bounce theories represent alternatives to conventional bottleneck models of the AB, the evidence for a relationship between capacity-limited WM mechanisms and the AB—something clearly not predicted by the boost-and-bounce account—suggests that conventional models may provide a more comprehensive account of the AB.

Concluding comments

In sum, the present findings show that WM capacity influences the same stage of processing as the AB, but only when the mask following T1 is omitted. This qualifies earlier failures to find a link between WM capacity in which a T1 mask was used (Akyürek & Hommel, 2005, 2006) and extends recent findings that WM processing influences the AB (Akyürek et al., 2007). It also highlights the important role that the T1 mask plays in modulating the AB and the fact that a robust AB can be obtained in the absence of such masks (Visser, 2007).

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