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T1 difficulty and the attentional blink: Expectancy versus backward masking

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According to bottleneck models of the attentional blink (AB), first-target (T1) processing difficulty should be related to AB magnitude. Tests of this prediction that have varied T1 difficulty in the context of a standard AB paradigm, however, have yielded mixed results. The present work examines two factors that may mediate the relationship between T1 difficulty and the AB: observer expectancy and backward masking of T1. In two experiments, omission of the backward mask consistently yielded the predicted relationship between T1 difficulty and the AB. In contrast, observer expectancy influenced target identification accuracy but did not mediate the relationship between T1 difficulty and the AB.

When two masked targets are presented in rapid succession, strikingly different patterns of identification accuracy are obtained. While first-target (T1) accuracy is nearly perfect, second-target (T2) accuracy varies as a function of intertarget interval (lag) with poorest performance at shorter lags (i.e., 200 ms) and gradual improvement until reaching asymptote at a lag of about 700 ms. This pattern of increasing T2 accuracy over lags has come to be known as the "attentional blink" (AB), in recognition of its phenomenological parallels with a physical eye blink.

Early investigations of the AB established that it was critically dependent on the requirement to attend to the first target. If the first target was omitted, or ignored, then the AB disappeared completely (Raymond, Shapiro, & Arnell, 1992). Beyond a general agreement that attention is involved in the AB, however, there has been little consensus about the specific mechanisms underlying the deficit. After much debate, two general theoretical frameworks have emerged: interference and bottleneck models.

Interference models (Raymond, Shapiro, & Arnell, 1994; Shapiro & Raymond, 1995) propose that rapid rates of stimulus input force incoming items to be stored in visual short-term memory (VSTM) while they await access to capacity-limited central resources. Access to VSTM is dependent upon a number of factors including: (a) how well an item matches a "target template" that is established based on task instructions; and (b) how closely in time an item is presented after a prior item that has already entered

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VSTM. After entering VSTM, items compete for access to attentional resources, with preference given to items that enter VSTM first. In the context of the AB, this means that when T1 and T2 (and accompanying masks) are presented in rapid succession, they both enter VSTM along with the masks. The ensuing competition for attentional access is usually won by T1 by virtue of the fact that it entered VSTM first, while T2 is forced to remain in VSTM where it gradually decays. On the other hand, when T1 and T2 are separated by a relatively long interval, T1 has already been selected from VSTM by the time T2 is presented. Thus, T2 can gain quick access to attentional processing and avoid decay.

According to bottleneck models, access to capacity-limited resources is also at the root of the AB. On these accounts (e.g., Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicœur, 1998, 1999a, 1999b), processing proceeds in two sequential stages. In the first precentral processing stage, stimuli are analysed in parallel across the visual field in order to identify potential targets. This analysis is relatively complex, extending to the level of semantics (e.g., Shapiro, Caldwell, & Sorensen, 1997b; Vogel, Luck, & Shapiro, 1998), but the resulting stimulus representations are vulnerable to decay and overwriting by subsequent sensory inputs (Giesbrecht & Di Lollo, 1998). Thus, potential targets must be transferred to a second capacity-limited central processing stage for consolidation, memory encoding, and response planning. With respect to the AB, at shorter lags T2 cannot gain access to central resources that are still occupied processing T1. As a result, T2 is delayed at the initial precentral stage where it decays or is overwritten by a subsequent mask. On the other hand, at longer lags, second-stage processing of T1 is complete by the time T2 is presented. This allows T2 quick access to central resources, thereby escaping masking or decay.

Clearly, the interference and bottleneck models possess broad similarities (Shapiro, Arnell, & Raymond, 1997a), and both provide excellent explanations for the basic AB phenomenon. However, the models do make different predictions with regard to some aspects of the AB. It is these differential predictions that have been the focus of attempts to determine which model provides a superior account of the AB. One prediction that has received much attention concerns the relationship between T1 difficulty and the AB. While interference models predict that no relationship should exist between these two factors, bottleneck models explicitly predict a link between "T1 processing difficulty" (Chun & Potter, 1995; Seiffert & Di Lollo, 1997) and AB magnitude. This follows from the fact that bottleneck models attribute poor identification of T2 to delays caused by processing of T1. Presumably, if processing difficulty were increased, T1 processing would take longer and would thus create a further delay for T2.

In the past, T1 processing difficulty has been operationalized in terms of T1 accuracy, with the implicit assumption that decreases in T1 accuracy reflect increased T1 processing time and thus should lead to a larger AB. Attempts to verify this prediction, however, have led to mixed results. For example, Shapiro, Raymond, and Arnell (1994) found a nonsignificant correlation between T1 accuracy and AB magnitude across the five studies in their paper. On the other hand, Seiffert and Di Lollo (1997) found a strong correlation between T1 accuracy and AB magnitude when analysing the results from about 20 experiments including Shapiro's and their own.

Direct examinations of the link between T1 difficulty and the AB have been similarly inconclusive. For example, Ward, Duncan, and Shapiro (1997) used a box-size judgment task for T1 and a letter identification task for T2. They adjusted the difficulty of the T1 task by varying the size difference between "large" and "small" T1 boxes. Although a hard size discrimination task yielded significantly poorer T1 accuracy, it did not result in a larger AB. Similarly, McLaughlin, Shore, and Klein (2001) asked observers to identify two successive masked letters. They varied T1 difficulty using a data-limited manipulation (Norman & Bobrow, 1975) to alter T1 discriminability. Specifically, they held constant the total duration from the onset of T1 to the offset of its mask and T1–mask interstimulus interval (ISI), while adjusting the duration of T1 (this effectively varied T1–mask stimulus onset asynchrony, SOA). Again, this manipulation produced variations in T1 accuracy but did not influence the AB.

On the other hand, Shore, McLaughlin, and Klein (2001) used the same masking procedure but varied T1 difficulty across separate blocks of trials. This produced reliable differences in T1 accuracy, as well as a commensurate increase in AB magnitude. Similarly, Christmann and Leuthold (2004) varied T1 difficulty by manipulating its contrast. To do this, they reciprocally varied T1 brightness and background luminance in separate blocks of trials. Like Shore et al. (2001), this led to reliable variations in the magnitude of the AB with lower contrast T1s yielding bigger ABs.

In analysing the differences between their experiments, Shore et al. (2001) posited that "the critical factor for observing a modulation of blink magnitude by T1 difficulty is the expectation, established before the trial, on how difficult T1 will be" (p. 321). This hypothesis neatly accounts for why the data-limited manipulation of difficulty that failed to influence the AB in McLaughlin et al. (2001) was effective when difficulty was manipulated between blocks of trials in Shore et al. (2001). It is also consistent with Christmann and Leuthold (2004) who used a data-limited manipulation of difficulty that was varied between blocks. Finally, it accounts for Ward et al.'s (1997) failure to obtain an influence of T1 difficulty because they mixed difficulty within blocks of trials, thus preventing observer expectancy from being established.

An alternative perspective on the issue of T1 difficulty and the AB has recently been offered by Visser (in press). He found that difficulty was reliably related to the AB when no mask was presented after T1, but never related when T1 was backward masked. To explain this, Visser (in press) suggested that the mask interrupted T1 processing in precentral stages (Jolicœur, 1998, 1999a, 1999b), thereby equating T1 processing time across levels of difficulty and producing equivalent AB deficits. This hypothesis neatly accounts for why increases in T1 difficulty led to decreased T1 accuracy, as interruption of perceptual processing would be more detrimental to accuracy in more difficult tasks. It also explains numerous failures to find a relationship between T1 accuracy and AB magnitude because all previous experiments had masked T1.

Of interest in the present work is a comparison of the effects of T1 backward masking and observer expectancy on the relationship between T1 difficulty and the AB. While both factors have been advanced as explanations for previous successes and failures to find this relationship it is unclear how or if they are related. Given that all previous studies that have failed to find a relationship between T1 difficulty and the AB have employed a T1 mask, it is possible that this is the critical factor, rather than expectancy. On this account, the magnitude of the AB should vary when T1 difficulty is manipulated when the T1 mask is omitted but not when the T1 mask is present, regardless of observer expectancy. Alternatively, it is equally possible that observer expectancy may be sufficient to produce a relationship between T1 difficulty and the AB regardless of the presence of a T1 mask. These alternatives were evaluated in Experiment 1 by varying both expectancy and masking in a 2 × 2 design.

EXPERIMENT 1

This experiment comprised a 2 × 2 factorial design in which T1 difficulty and T1 masking were varied. "Easy" T1 trials and "hard" T1 trials were presented across different blocks of trials or intermixed within the same block. Similarly, either T1 could be masked or the mask could be omitted. In all conditions, similar to the methodology of McLaughlin et al. (2001), both tasks were letter identification in order to eliminate the possible influence of task switches on performance. The T1 task was a visual search paradigm in which T1 was the letter "C" or "G" presented simultaneously with one or four other letters. The T2 task was to identify a single centrally presented letter.

Method

Participants

A total of 96 undergraduate students (72 female) at the University of British Columbia participated for course credit. All participants reported normal or corrected-to-normal vision. A total of 18 students participated in the condition in which T1 was masked, and difficulty was blocked (condition MB), 18 in the condition in which T1 was not masked, and difficulty was blocked (condition NMB), 18 in the condition in which T1 was masked, and difficulty was mixed (condition MM), and 18 in the condition in which T1 was not masked, and difficulty was mixed (condition NMM). An additional 24 participants were run in modified versions of each condition (6 per condition) in which the requirement to report the identity of T1 was eliminated.

Apparatus and stimuli

All stimuli had a luminance of 10 cd/m^2, as measured by a Minolta LS-100 luminance meter, and were displayed on a Tektronix 608 oscilloscope, equipped with fast P15 phosphor. The viewing distance, set by a headrest, was 57 cm. The background and surrounding visual field were dark, except for dim illumination of the keyboard. In the first display, T1 was always the letter "C" or "G", while distractors could be any letter in the English alphabet except for I, O, Q, Z, C, or G. These letters were omitted on the grounds that they either were confusable with digits (i.e., I, O, Q, Z) or were identical to the first target (i.e., C, G). The second target was any letter of the English alphabet except for I, O, Q, Z, C, or G. The same criterion for choosing T2 was used as that for choosing distractors in the first display. Masks consisted of digits from 1 to 9. Where present, the same digit was used to mask both T1 and T2. Targets, distractors, and masks all subtended an area of approximately 1° square of visual angle.

Procedure

Procedural details were similar across all four conditions. In conditions MB and MM, the T1 search display was followed by a mask display; in the NMB and NMM conditions, the T1 display was never masked. In conditions MB and NMB, trials were divided into two blocks in which the number of distractors presented along with the target numbered either one (set size 2), or four (set size 5). In conditions MM and NMM, T1 set size was varied within a single block of trials. For the purposes of creating the search display, the screen was divided into a notional 5 $\times$ 5 matrix of locations. The target and any accompanying distractors could appear at any location in this matrix with two constraints. First, no item could appear in the centre location. Second, items could not be directly adjacent to one another.

Each trial began with the presentation of a fixation point in the centre of the screen. Observers were instructed to press the space bar to start the sequence of stimuli. Following a random interval from 500 to 800 ms during which the screen was blank, the T1 search display was presented for 30 ms. In the conditions in which T1 was masked (MB, MM), this search display was followed by an ISI of 70 ms, during which the screen was blank, and then by a 30-ms presentation of a mask display. The mask display consisted of a digit presented at each location where a letter had been in the search display. The same digit was presented in all locations. In the condition in which T1 was not masked, there were no intervening items presented between T1 and T2.

The second target, which was a letter, was presented in the centre of the screen and followed T1 at one of four lags corresponding to T1–T2 SOAs of 200, 300, 500, or 700 ms. The target remained on the screen for 30 ms and was followed, after a 70-ms ISI during which the screen was blank, by a digit pattern mask that remained on the screen for 30 ms. Observers were instructed to make two responses. The first response was to indicate whether T1 was either a "C" or a "G", by pressing one of two appropriately marked keys on the keyboard. The second response was to identify the T2 letter by typing it into the keyboard. After making these two responses, the next trial began with the presentation of the central fixation point.

Within each blocked condition (MB, NMB), difficulty was counterbalanced such that half of observers received set size 5 trials first, while the other half began with set size 2. Each block began with 10 practice trials, followed by 120 experimental trials. These experimental trials consisted of equal numbers of trials with "C" or "G" as T1. Trials were divided evenly across T1–T2 lags yielding 30 trials at each of the four lags. Within each mixed condition (MM, NMM), there was single block of 240 experimental trials, preceded by 20 practice trials. The experimental trials were divided evenly between difficulty level and lag, yielding 30 trials per lag and difficulty level. Trials in all conditions were self-paced, and participants were encouraged to take a short rest break between trials when necessary.

Because variations in T1 difficulty were always associated with changes in T1 displays, it is possible that performance differences across conditions could be due to these display changes rather than variations in task difficulty per se. To examine this possibility, 6 additional participants were run in modified versions of each condition in which the displays were identical but the requirement to report T1 was eliminated. If variations in the T1 display are the primary determinant of T2 accuracy, performance in these control conditions should be similar to that when T1 must be reported. On the other hand, if T1 difficulty is the primary determinant of T2 accuracy, omitting the requirement to report T1 should lead to near-perfect T2 accuracy in all conditions.

Results

Mean accuracy was calculated for T1 and for T2 conditional on correct identification of T1 separately as a function of set size, T1–T2 lag, T1 masking, and observer expectancy. Conditional accuracy scores were calculated for T2 on the grounds that correct identification of T1 ensured that it had been attended. Data were then submitted to a preliminary 2 (set size: 2, 5) × 4 (T1–T2 lag: 200, 300, 500, 700 ms) × 2 (T1 mask: present vs. absent) × 2 (expectancy: yes vs. no) mixed-design analysis of variance (ANOVA) with T1 mask and expectancy as between-subjects variables. The purpose of this analysis was to determine whether T1 masking and/or expectancy reliably modulated the influence of T1 difficulty on target accuracy. For T1, only two interactions involving these factors were significant: Set size × Expectancy, $F(1, 68) = 8.35$, $p < .005$, $MSE = 109.39$, and Lag × T1 Mask, $F(3, 204) = 2.67$, $p < .05$, $MSE = 41.69$. Examination of the data suggested that the Set Size × Expectancy interaction arose because increasing set size impaired T1 accuracy more when difficulty was mixed than when it was blocked. The interaction between lag and T1 masking was due to the fact that accuracy remained stable across lag when T1 was masked, while it increased across lag when T1 was not masked.

For T2, the critical issue was whether the influence of T1 difficulty on the AB, as seen in Figure 1 (Panels B and D) and indicated by a significant Set Size × Lag interaction, $F(3, 204) = 11.69$, $p < .001$, $MSE = 93.04$, would be modulated by T1 masking or expectancy. The results indicated that masking did modulate the influence of T1 difficulty, as indicated by a significant Set Size × Lag × T1 Mask interaction, $F(3, 204) = 6.01$, $p < .01$, $MSE = 93.04$, while expectancy did not, as indicated by a nonsignificant Set Size × Lag × Expectancy interaction, $F(3, 204) = 0.31$, $p > .81$, $MSE = 93.04$. Further analysis of the data was conducted by examining each of the four conditions individually.

Condition MB (T1 masked, blocked T1 difficulty)

Mean T1 accuracy was analysed in a 2 (set size: 2, 5) × 4 (T1–T2 lag: 200, 300, 500 and 700 ms) repeated measures ANOVA. The analysis revealed a significant effect of set size, $F(1, 17) = 46.77$, $p < .001$, $MSE = 217.38$, confirming that overall T1 accuracy declined significantly as the number of distractors presented simultaneously with T1 increased. All other effects were nonsignificant ($p > .83$).

Mean T2|T1 accuracy (see Figure 1, Panel A) was analysed in a 2 (set size) × 4 (T1–T2 lag) repeated measures ANOVA. Confirming the presence of an AB, the analysis indicated a significant

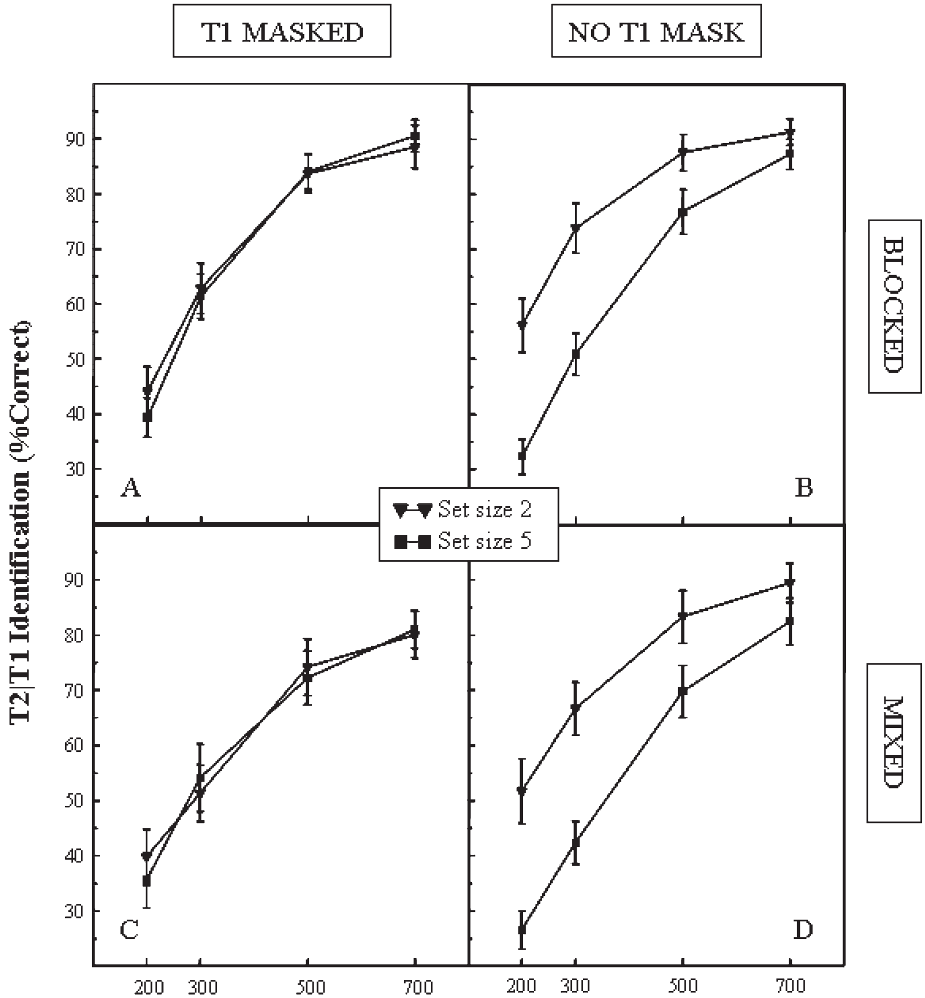

Figure 1. *Mean accuracy of T2 identification, given correct identification of T1, as a function of the temporal lag between T1 and T2. Closed inverted triangles represent scores when T1 set size was 2. Closed squares represent scores when T1 set size was 5. Error bars represent one standard error of the mean. Panel A depicts T2 accuracy in condition MB (T1 masked, blocked difficulty). Panel B depicts T2 accuracy in condition NMB (no T1 mask, blocked difficulty). Panel C depicts T2 accuracy in condition MM (T1 masked, mixed difficulty). Panel D depicts T2 accuracy in condition NMM (no T1 mask, mixed difficulty).*

effect of lag, $F(3, 51) = 86.35$, $p < .001$, $MSE = 199.72$. However, there was no significant effect of set size ($p = .71$) or Set Size × Lag interaction ($p = .35$), indicating that AB magnitude was unaffected by T1 difficulty.

Condition NMB (no T1 mask, blocked T1 difficulty)
Mean T1 accuracy was analysed in a 2 (set size) × 4 (T1–T2 lag) repeated measures ANOVA, which revealed a significant effect of lag, $F(3, 51) = 5.40$, $p < .001$, $MSE = 22.86$, but no main effect of set size ($p > .23$) or Set Size × Lag interaction ($p > .29$). Inspection of the data suggested that the main effect of lag arose from a slight increase in T1 accuracy from 93.6% at Lag 2 to 97.5% at Lag 7.

Mean T2|T1 accuracy (see Figure 1, Panel B) was analysed in a 2 (set size) × 4 (T1–T2 lag) repeated measures ANOVA. Confirming the presence of an AB, the analysis indicated a significant effect of lag, $F(3, 51) = 139.01$, $p < .001$, $MSE = 107.10$. Confirming that performance varied as a function of T1 difficulty, the analysis also revealed a significant effect of set size, $F(1, 17) = 36.67$, $p < .001$, $MSE = 231.96$, and a significant interaction between lag and set size, $F(3, 51) = 8.86$, $p < .001$, $MSE = 94.25$. Inspection of Panel B suggests that this arose from a gradual decline in the T2 accuracy difference between set sizes 2 and 5 as lag increased.

Condition MM (T1 masked, mixed T1 difficulty)

Mean T1 accuracy was analysed in a 2 (set size) × 4 (T1−T2 lag) repeated measures ANOVA. The analysis revealed only a significant effect of set size, $F(1, 17) = 152.93$, $p < .001$, $MSE = 113.55$, confirming that overall T1 accuracy declined significantly as the number of distractors presented simultaneously with T1 increased. All other effects were nonsignificant ($p > .64$).

Mean T2|T1 accuracy (see Figure 1, Panel C) was analysed in a 2 (set size) × 4 (T1−T2 lag) repeated measures ANOVA. Confirming the presence of an AB, the analysis indicated a significant effect of lag, $F(3, 51) = 57.39$, $p < .001$, $MSE = 238.81$. However, there was no significant effect of set size ($p > .81$) or Set Size×Lag interaction ($p > .39$), indicating that the magnitude of the AB did not vary with T1 difficulty.

Condition NMM (no T1 mask, mixed T1 difficulty)

Mean T1 accuracy was analysed in a 2 (set size) × 4 (T1−T2 lag) repeated measures ANOVA, which revealed significant effects of set size, $F(1, 17) = 14.90$, $p < .01$, $MSE = 84.10$, and lag, $F(3, 51) = 4.05$, $p < .02$, $MSE = 25.95$, but no Set Size × Lag interaction ($p > .84$). The main effect of lag seems to have arisen because accuracy at Lag 1 (89.98%) and Lag 7 (92.76%) was lower than that at Lag 3 (93.78%) and Lag 7 (93.24%).

Mean T2|T1 accuracy (see Figure 1, Panel D) was analysed in a 2 (set size) × 4 (T1−T2 lag) repeated measures ANOVA. Confirming the presence of an AB, the analysis indicated a significant effect of lag, $F(3, 51) = 182.43$, $p < .001$, $MSE = 88.75$. Confirming that performance varied as a function of T1 difficulty, there was also a significant effect of set size, $F(1, 17) = 37.86$, $p < .001$, $MSE = 291.09$, and a Lag × Set Size interaction, $F(3, 51) = 5.44$, $p < .01$, $MSE = 126.94$.

Control conditions

In order to determine whether the performance differences reported above were due simply to variations in the T1 displays, mean T2 accuracy was calculated in each control condition in which participants viewed the same stimuli but did not have to report T1. As can be seen in Table 1, T2 accuracy is uniformly high across conditions. Consistent with this impression, a 2 (set size)×4 (T1−T2 lag) × 2 (T1 mask)×2 (expectancy) mixed-design ANOVA yielded only main effects of lag, $F(3, 60) = 12.48$, $p < .001$, $MSE = 0.002$, and set size, $F(1, 20) = 5.44$, $p < .04$, $MSE = 0.001$, and expectancy, $F(1, 20) = 5.11$, $p < .04$, $MSE = 0.003$. Examination of the data suggested that the main effect of lag stemmed from the fact that performance was slightly lower at Lags 2 and 3 than at Lags 5 and 7, the main effect of set size stemmed from the fact that accuracy was slightly higher at Set Size 5 than at Set Size 2, and the main effect of expectancy arose because accuracy was slightly higher when T1 set size was predictable than when it was not. Most importantly, however, T2 results in the control condition looked very different from those in the experimental conditions in which participants completed a T1 task. This confirms that differences in task difficulty influenced T2 accuracy in the above experiments, rather than simply changes in the T1 display.

Discussion

Experiment 1 directly compared the effect of observer expectancy and T1 masking on the relationship between T1 difficulty and AB magnitude. The outcome was clear-cut. Inspection of the results from conditions NMM and NMB (Panels B and D) shows that increases in T1 difficulty reliably increased AB magnitude as long as the

Table 1. *Mean T2 accuracy as a function of observer expectancy, set size, lag, and T1 masking in the control conditions*

		T1 masked				*No T1 mask*			
		Lag				*Lag*			
Expectancy	*Set size*	*2*	*3*	*5*	*7*	*2*	*3*	*5*	*7*
Blocked	2	97.09	96.03	100.00	100.00	94.52	93.04	100.00	100.00
		(1.32)	(1.27)	(0.00)	(0.00)	(2.02)	(2.62)	(0.00)	(0.00)
	5	96.11	100.00	100.00	100.00	96.99	94.25	100.00	98.72
		(2.78)	(0.00)	(0.00)	(0.00)	(2.10)	(2.24)	(0.00)	(1.28)
Mixed	2	98.15	87.64	95.94	97.22	92.17	91.70	98.81	100.00
		(1.85)	(2.72)	(2.82)	(1.90)	(3.52)	(2.93)	(1.19)	(0.00)
	5	97.50	94.78	100.00	95.39	99.02	94.73	96.59	98.48
		(1.60)	(1.90)	(0.00)	(3.51)	(0.98)	(2.64)	(2.30)	(1.52)

Note: Numbers in parentheses represent one standard error of the mean.

T1 mask was omitted. On the other hand, with a backward mask after T1 (conditions MM and MB; Panels A and C), T1 difficulty and AB magnitude were unrelated, regardless of whether T1 difficulty was blocked or mixed. This suggests that of the two factors—expectancy and T1 masking—the latter was the more important determinant of whether a relationship between T1 difficulty and AB magnitude occurred in the present experiment.

Examination of Table 1 shows that T1 masking had a significant influence on T1 accuracy as well—namely, when T1 was masked, T1 accuracy declined with an increase in T1 difficulty more steeply than when T1 was not masked. Visser (in press) has argued that this difference stems from the fact that the mask interrupts T1 processing (Breitmeyer, 1984; Di Lollo, Enns, & Rensink, 2000). On this account, greater T1 difficulty leads to an increase in T1 processing time. When T1 is not masked, this increase allows accurate identification of T1, but results in a larger AB due to delayed processing of T2. However, when T1 is masked, the mask interrupts T1 processing before stimulus recognition can occur. This greatly impairs T1 accuracy, but allows T2 to be processed earlier, thereby avoiding processing delays that lead to a larger AB when the T1 mask is omitted.

Although it appears that masking is the critical factor mediating the relationship between T1 difficulty and the AB, observer expectancy did influence both T1 and T2 accuracy. For T1, inspection of the mean accuracy levels suggests that interspersing hard and easy T1 trials reduced identification accuracy at Set Size 5 across conditions. For T2, accuracy was generally lower across both set sizes when T1 difficulty was mixed versus when it was blocked. One interpretation of this pattern of results is that blocking trials allowed observers to establish attentional control settings (e.g., Folk & Remington, 1998; Folk, Remington, & Johnston, 1992) that aided efficient T1 processing. The results suggest that this not only yielded an improvement in T1 accuracy, but also reduced T1 processing time, thus resulting in a smaller AB.

This interpretation is also consistent with recent demonstrations by Folk, Leber, and Egeth (2002) and Visser, Bischof, and Di Lollo (2004) that distractors that share target characteristics such as colour (Folk et al., 2002) or visual features (Visser et al., 2004) can capture attention and prolong the AB. This capture has been attributed to attentional control settings (or, alternatively, "visual input filters"—Ghorashi, Zuvic, Visser, & Di Lollo, 2003; Visser et al., 2004) that are established based on target characteristics in order to limit access to attentional resources. When target–distractor similarity is high, the input filters will sometimes pass distractors, thereby prohibiting attentional access to actual targets.

Before concluding that expectancy does not influence whether a relationship between T1 difficulty and AB magnitude is obtained, it is important to consider other possible explanations for our failure to find a modulating effect of expectancy. In Shore et al. (2001), the authors employed a data-limited (Norman & Bobrow, 1975) manipulation of T1 difficulty in which the perceptual salience of T1 was reduced using a masking procedure. Moreover, they were careful to eliminate attentional switches such as those in location, task, or target type. In contrast, the present experiment varied T1 difficulty using a resource-limited manipulation—namely, visual search. Moreover, there was also a location shift involved as T1 and T2 were always presented in different spatial locations. These procedural differences may account for why Shore et al. (2001) found a strong mediating influence of expectancy on the relationship between T1 difficulty and the AB, while no such relationship was obtained in Experiment 1. To evaluate this possibility, in Experiment 2, a data-limited manipulation of T1 difficulty was employed, and both T1 and T2 were presented in the same spatial location. In one condition, T1 was masked, while the mask was omitted in the other.

EXPERIMENT 2

The goal of Experiment 2 was to determine whether expectancy would modulate the relationship between T1 difficulty and the AB, or whether backward masking of T1 would be a more crucial factor. To test these options, performance was compared across two conditions. In one, T1 difficulty was varied by degrading T1 with simultaneous noise dots and by varying its luminance. In the other, the same procedure was used, in addition to the presentation of a backward mask after T1. If expectancy is the only factor that determines whether T1 difficulty will influence the AB, there should be a relationship between T1 difficulty and AB magnitude in both conditions. On the other hand, if T1 masking is the only critical factor, there should be a relationship between T1 difficulty and AB magnitude only when the T1 mask is omitted.

Method

Participants

A total of 52 undergraduate students (39 female) at the University of Victoria and the University of British Columbia Okanagan participated for course credit. All participants reported normal or corrected-to-normal vision. A total of 40 participants were run in conditions requiring identification of both T1 and T2 (20 in conditions in which T1 was masked; 20 in conditions in which the T1 mask was omitted). An additional 12 control participants viewed the same stimuli were but were required to report only T2 (6 in conditions in which T1 was masked; 6 in conditions in which the T1 mask was omitted).

Apparatus and stimuli

Stimuli were presented on a 17-inch Sony Multiscan monitor (Model E240) running at a refresh rate of 100 Hz, slaved to a Pentium-4 computer running Presentation software (Version 0.81; Neurobehavioral Systems, 2002). The background and surrounding visual field were dark, except for dim indirect illumination of the keyboard. All stimuli subtended approximately 1° of visual angle at a viewing distance of 60 cm. Targets were upper-case letters from the English alphabet, except for I, O, Q, Z, and P, which were omitted because they were structurally similar to digits (I, O, Q, Z) or because they would pause the experimental software (P). In the "hard" condition, the RGB colour coordinates of the T1 were 90, 90, 90, which yielded a dark grey; in the "easy" condition, the RGB coordinates of T1 were 105, 105, 105, which yielded a lighter grey. The RGB coordinates of T2 were always 105, 105, 105. Digit masks consisted of all digits from 0–9 except 1, 0, 2, and 7, which were omitted due to their similarity to the letters I, O, Q, and Z. The RGB coordinates of the digit masks were 95, 95, 95, yielding a grey midway between the "hard" and "easy" T1. T1 was presented simultaneously with a noise-dot mask that consisted of approximately 400 dots randomly distributed in an area of about 1° square. Dots had RGB coordinates of 108, 108, 108.

Procedure

The experiment consisted of two conditions in which T1 was backward masked or the backward mask was omitted. Within each condition, there were two blocks of trials in which T1 was a letter that was "hard" or "easy" to identify. In both blocks, T1 was presented along with a simultaneous dot mask. In the hard condition, the luminance of T1 was also reduced to decrease its perceptual salience. In the condition in which T1 was backward masked, a single digit mask was presented in the same location as T1 after an SOA of 100 ms. In the condition in which T1 was not masked, no stimuli were presented on the screen between the onsets of T1 and T2.

Each trial began with the presentation of a fixation cross in the centre of the screen. Observers were instructed to press the space bar to start the sequence of stimuli. Following a random interval from 500 to 800 ms during which the screen was blank, the T1 letter and dot mask were presented simultaneously for 30 ms at the centre of the screen. In the condition in which T1 was backward masked, the target was followed by an ISI of 70 ms during which the screen was blank, and then by a 30-ms presentation of a mask display. The mask display consisted of a digit presented in the same location as T1. In the condition in which T1 was not masked, there were no intervening items presented between T1 and T2.

The second target, which was a letter, was also presented in the centre of the screen and followed T1 at one of four lags corresponding to T1−T2 SOAs of 200, 300, 500, or 700 ms. The target remained on the screen for 30 ms and was followed, after a 70-ms ISI during which the screen was blank, by a digit pattern mask that remained on the screen for 30 ms. The digit mask after T2 was always different from that presented after T1 (if there was one). Observers were instructed to indicate the identities of the two letters presented during the trial by pressing the appropriate key on the keyboard. They were also told that order of response was unimportant and to guess at the letter identities if they were unsure. After making these two responses, the next trial began with the presentation of the central fixation cross.

Within each condition, the order of the blocks was completely counterbalanced. Each block consisted of 75 trials at each T1−T2 lag, for a total of 300 trials. Trials in all conditions were self-paced, and participants were encouraged to take a short rest break between trials when necessary.

In the control conditions, stimuli were identical to those described above. However, the requirement to report the identity of T1 was omitted. As in Experiment 1, this control condition was designed to determine the effects of varying the T1 stimulus display on T2 accuracy.

Results

No T1 mask

Mean percentages of correct identifications of T1 were 77.2 and 61.8 for the "easy" and "hard" blocks, respectively. The results were analysed in a 2 (T1 difficulty: easy, hard) × 4 (T1−T2 lag: 200, 300, 500, and 700 ms) repeated measures ANOVA. The analysis revealed significant effects of T1 difficulty, $F(1, 19) = 44.42$, $p < .001$, $MSE = 213.41$, confirming that overall T1 accuracy declined significantly as T1 difficulty increased, as well as lag, $F(3, 57) = 19.14$, $p < .001$, $MSE = 30.37$, indicating that T1 accuracy improved over lags. The T1 Difficulty × Lag interaction was nonsignificant ($p > .24$).

Estimates of T2 identification were based exclusively on trials in which T1 had been identified correctly. Mean percentages of correct T2 identification as a function of T1 difficulty and T1−T2 lag are illustrated in Panel A of Figure 2. An inspection of this figure suggests that an AB occurred whether T1 was hard or easy. Moreover, it appears that the AB was larger on the "hard" T1 trials. To verify these impressions, the data were analysed in a 2 (T1 difficulty) × 4 (T1−T2 lag) repeated measures ANOVA. Confirming the presence of an AB,

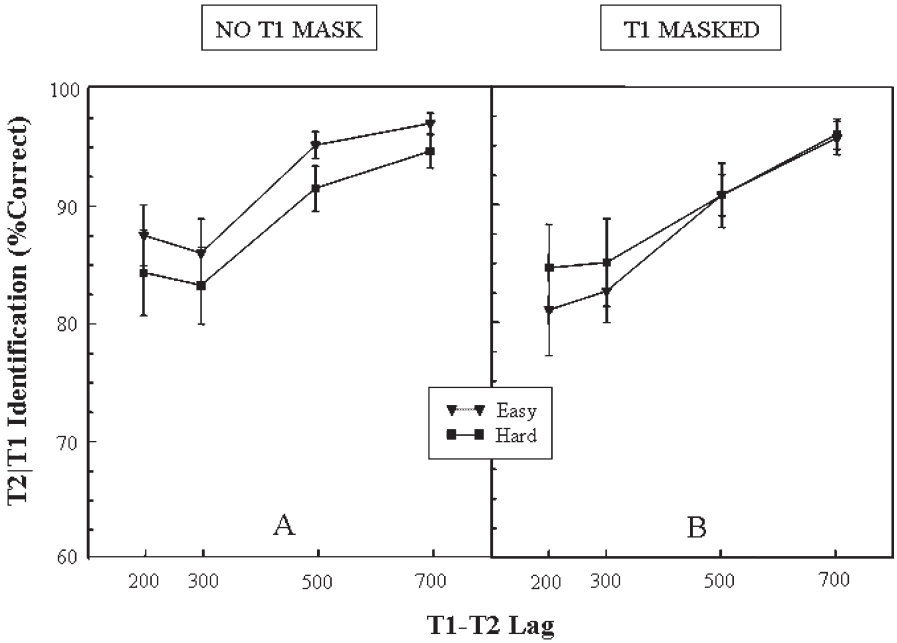

Figure 2. *Mean accuracy of T2 identification, given correct identification of T1, as a function of the temporal lag between T1 and T2. Closed inverted triangles represent scores when T1 was "easy". Closed squares represent scores when T1 was "hard". Error bars represent one standard error of the mean. Panel A depicts T2 accuracy when the T1 mask was omitted. Panel B depicts T2 accuracy when T1 was backward masked.*

the analysis indicated a significant effect of lag, $F(3, 57) = 17.77$, $p < .001$, $MSE = 67.88$. Consistent with the impression that the magnitude of the AB differed between "easy" and "hard" trials, there was also a significant effect of difficulty, $F(1, 19) = 4.53$, $p < .05$, $MSE = 79.32$. The T1 Difficulty × Lag interaction was not significant ($p > .92$).

T1 masked

Data from 3 participants were excluded from analysis because they scored at chance levels on the T1 task. For the remaining 17 participants, mean percentages of correct identifications of T1 were 48.3 and 35.3 for the "easy" and "hard" blocks, respectively. The results were analysed in a 2 (T1 difficulty) × 4 (T1−T2 lag) repeated measures ANOVA, which revealed significant effects of T1 difficulty, $F(1, 16) = 19.96$, $p < .001$, $MSE = 287.09$, confirming that overall T1 accuracy declined significantly as T1 difficulty increased, as well as lag, $F(3, 48) = 7.28$, $p < .001$, $MSE = 22.48$, confirming an increase in T1 accuracy as lag increased. The T1 Difficulty × Lag interaction was nonsignificant ($p > .70$).

Estimates of T2 identification were based exclusively on trials in which T1 had been identified correctly. Mean percentages of correct T2 identification as a function of T1 difficulty and T1−T2 lag are illustrated in Panel B of Figure 2. An inspection of this figure suggests that an AB occurred at both levels of difficulty. Moreover, it appears that the AB was similar in magnitude in both conditions. To verify these impressions, the data were analysed in a 2 (T1 difficulty) × 4 (T1−T2 lag) repeated measures ANOVA. Confirming the presence of an AB, the analysis indicated a significant effect of lag, $F(3, 48) = 11.05$, $p < .001$, $MSE = 115.46$. However, consistent with the impression that T1 difficulty did not influence the AB, there was no effect of T1 difficulty ($p > .41$) or T1 Difficulty×Lag interaction ($p > .80$).

Control conditions

Mean percentages of T2 correct identification were calculated separately as a function of lag, T1 difficulty, and the presence or absence of T1 backward masking. As can be seen in Table 2, when T1 was not backward masked, T2 accuracy was very high and was unaffected by lag or difficulty. This was confirmed by a 2 (T1 difficulty) × 4 (T1−T2 lag) ANOVA, which showed no significant effects (all *p*s $>$ .07). On the other hand, when T1 was backward masked, T2 accuracy was also very high and showed a tendency to increase slightly as the interval between T1 and T2 increased. Consistent with this impression, a 2 (T1 difficulty) × 4 (T1−T2 lag) ANOVA revealed a significant effect of lag, $F(3, 15) = 3.91$, $p < .04$, $MSE = .001$. As in Experiment 1, results from the control condition results confirm that T2 accuracy was principally influenced by changes in T1 task difficulty and not merely by changes in the T1 display.

Discussion

In Experiment 2, T1 difficulty was manipulated between blocks of trials by varying T1 luminance—a data-limited manipulation (Norman & Bobrow, 1975). Of interest was whether establishing observer expectancy about T1 difficulty via the blocking manipulation would lead to a relationship between T1 difficulty and AB magnitude as in Shore et al. (2001), or if this relationship would emerge only when T1 was not backward masked. Like Experiment 1, in which a resource-limited manipulation of T1 difficulty was used, the present results showed that T1 difficulty was related to the AB only when T1 was not backward masked. When such a mask was present, difficulty impacted T1 accuracy, but had no effect on the AB.

Given the failure to find a relationship between T1 difficulty and the AB when T1 was backward masked, an obvious question is why Shore et al. (2001) did find such a relationship when they used a mask that was presented after T1. A likely explanation for the difference between their study and the present one is in the temporal characteristics of the masks employed. The mask in the present work followed T1 at an SOA of 100 ms. Such a target−mask SOA is optimally placed for it to interrupt T1 processing, while minimizing contour integration between T1 and the mask (Breitmeyer, 1984). On the other hand, the masking procedure employed in Shore et al. (2001; see also McLaughlin et al., 2001) consisted of much shorter SOAs ranging from 30 to 60 ms. Such temporal parameters may have limited the mask's ability to interrupt T1 processing, while increasing contour integration between T1 and the mask (see McLaughlin et al., 2001, p. 183, for a discussion of this issue).

GENERAL DISCUSSION

The present work compared the potential mediating influence of observer expectancy and T1 backward masking on the relationship between T1

Table 2. *Mean T2 accuracy as a function of lag, T1 difficulty, and T1 masking in the control conditions*

	T1 masked				*No T1 mask*			
	Lag				*Lag*			
T1 Difficulty	*2*	*3*	*5*	*7*	*2*	*3*	*5*	*7*
Easy	93.33	97.50	98.33	98.33	95.00	98.33	95.83	100.00
	(2.47)	(1.71)	(1.67)	(1.67)	(2.24)	(1.67)	(2.39)	(0.00)
Hard	97.50	98.33	100.00	100.00	100.00	98.33	98.33	100.00
	(1.71)	(1.05)	(0.00)	(0.00)	(0.00)	(1.67)	(1.67)	(0.00)

Note: Numbers in parentheses represent one standard error of the mean.

difficulty and AB magnitude. The results were clear. Whether T1 difficulty was manipulated via resource limitations (Experiment 1) or data limitations (Experiment 2), AB magnitude was influenced only when T1 was not backward masked. When T1 was backward masked, no relationship was found between T1 difficulty and the AB.

This outcome strongly suggests that expectancy is not the critical variable mediating the relationship between T1 difficulty and AB magnitude. Rather, the more important factor is the presence of a backward mask that interrupts T1 processing. Consistent with this suggestion, previous failures to obtain such a relationship have all come from paradigms that masked T1 (McLaughlin et al., 2001; Ward et al., 1997). However, that is not to say that expectancy does not influence target identification accuracy. In Experiment 1, T1 and T2 accuracy was generally higher when difficulty was blocked. This was probably due to the fact that observers could develop an appropriate attentional control setting (e.g., Folk & Remington, 1998; Folk et al., 1992), or alternatively an "input filter" (Ghorashi et al., 2003; Visser, Bischof, & Di Lollo, 1999; Visser et al., 2004) that allowed processing mechanisms to be optimally tuned for target processing.

It should also be noted that the present results do not exclude the possibility that a relationship between T1 difficulty and the AB can occur when a mask is presented after T1. Shore et al. (2001) found such a relationship when they presented a mask after T1, although as noted earlier, their masking procedure probably included a significant integration masking component. The same is true for Christmann and Leuthold (2004), although again their use of a relatively fast presentation rate combined with low-contrast first targets may have introduced significant integration masking of T1. Finally, Seiffert and Di Lollo (1997)'s review of the AB literature showed a significant correlation between AB magnitude and T1 accuracy in studies that all employed backward masking of T1. What is clear from the present work and that of Visser (in press), however, is that omission of the T1 backward mask reliably leads to a relationship between T1 difficulty and AB magnitude under experimental conditions where no such relationship emerges when T1 is backward masked.

Implications for AB models

The present demonstration of a robust relationship between T1 difficulty and AB magnitude clearly supports predictions of bottleneck models (e.g., Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicœur, 1998, 1999a, 1999b). On these accounts, the AB occurs because T2 is presented while capacity-limited central resources are still processing T1. This prevents T2 from gaining access to these resources and leaves it vulnerable to masking and/or decay. It follows from this framework that increased T1 processing difficulty (Chun & Potter, 1995; Seiffert & Di Lollo, 1997) should increase the duration of T1 processing in capacity-limited central stages, thereby leaving T2 vulnerable to masking and/or decay for longer and yielding a bigger AB.

As they are currently conceptualized, interference models (Raymond et al., 1995; Shapiro & Raymond, 1994) do not predict a relationship between T1 difficulty and AB magnitude and thus do not incorporate this factor into their architecture. Thus, on the face of it, the present results contradict these models. That said, it is clear that interference models could be modified to incorporate the effect of T1 difficulty in any of a number of ways. One possibility is simply to adjust the weighting assigned to "hard" targets in VSTM, such that they receive a higher priority for selection by capacity-limited mechanisms. Such an adjustment would presumably aid target identification by allowing "hard" targets earlier access to attentional resources. Moreover, by biasing competition further in favour of T1, at shorter lags, this change would presumably decrease T2's chances of being selected from VSTM and thus reduce its identification accuracy, thereby yielding a relationship between T1 difficulty and the AB.

A final comment should also be made regarding the implications of the present results for the loss-of-control model proposed by Di Lollo, Kawahara, Ghorashi, and Enns (2005). On this account of the AB, observers are said to establish an attentional set that allows them to selectively attend to targets while ignoring distractors. However, maintenance of this set requires resources that become unavailable when T1 is presented. Thus, if a dissimilar distractor is introduced after T1 (i.e., a T1 mask), the set is disrupted, with a consequent decrease in processing efficiency for an immediately subsequent target (i.e., T2). In contrast to the predictions of this model, in the present work, overall T2 accuracy was similar whether T1 was masked or not. One possible reason for this discrepancy is that targets here were not embedded in a confusable distractor stream, which, in turn, may have discouraged observers from adopting a strong attentional set when performing the task. Without an attentional set to disrupt, the presence of the mask would do little to influence the AB. If that is the case, however, the robust effects shown here imply that an AB can occur in the absence of disruptions to attentional sets and thus that these disruptions cannot be the sole cause of the AB (see also Akyürek & Hommel, 2005).

Is backward masking of T1 necessary for the AB?

As noted above, all previous studies directly examining the relationship between T1 difficulty and AB magnitude have employed a mask presented after T1. This followed from Raymond et al. (1992)'s demonstration that the AB was eliminated when the mask after T1 was omitted (see also Seiffert & Di Lollo, 1997). In contrast to this early work, the present findings (see also Visser, in press) show robust ABs in the absence of a backward mask and, in the case of Experiment 1, in the absence of any sort of T1 mask. From the perspective of the bottleneck models, this is not necessarily surprising. Recall, that the AB is said to arise when T2 is presented during the time period that T1 is occupied in capacity-limited central stages. From this, it follows that an AB will occur any time that T1 processing is sufficiently lengthy to overlap with the presentation of T2. In principle, such conditions may arise with or without a backward mask after T1, as long as the T1 task is sufficiently time consuming.

It is notable that in many AB tasks, including Raymond et al. (1992), T1 requires identification of a single letter presented at a central location that has been fixated prior to the beginning of the trial (e.g., Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Jolicœur, 1999a, 1999b; Seiffert & Di Lollo, 1997). Such conditions probably engender optimal processing conditions because the target is the sole exemplar of a highly overlearned category (i.e., letters) presented in a known spatial location at the centre of gaze. Because of this, backward masking of T1 is probably necessary in order to increase T1 processing time to a point where it is sufficient to overlap with the onset of T2. On the other hand, in Experiment 1, T1 was presented in an unpredictable location along with distractors, while in Experiment 2, T1 was quite dim and highly degraded by a simultaneous mask. Given the AB that was found in both conditions, it must be concluded that these manipulations were sufficient to increase T1 processing time to the point where an AB could be found without the need for a backward mask.

Concluding comments

The present work highlights the role of T1 masking in modulating a robust relationship between T1 difficulty and AB magnitude. This outcome not only aids us in distinguishing between models of dual-task performance, but also underscores the need to reexamine the role of T1 masking in generating the AB phenomenon. Future work needs to more fully elucidate the role of T1 masking in order to better understand its relationship to T1 difficulty, as well as to determine how data-limited and resource-limited manipulations of T1 difficulty might produce similar or different effects on the AB.

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