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The attentional blink is governed by a temporary loss of control

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Identification of the second of two brief targets is impaired at intertarget lags of less than about 500 msec. We compared two accounts of this *attentional blink* (AB) by manipulating the number of digit distractors—and hence the lag—inserted among three letter targets in a rapid serial visual presentation stream of digit distractors. On the resource-depletion hypothesis, longer lags provide more time for processing the leading target, thus releasing resources for the trailing target. On the temporary-loss-of-control (TLC) hypothesis, intervening distractors disrupt the current attentional set, producing a trailing-target deficit. Identification accuracy for trailing targets was unimpaired not only at lag 1 (conventional lag 1 sparing) but also at later lags, if preceded by another target. The results supported the TLC hypothesis but not the resource-depletion hypothesis. We conclude that the AB is caused by a disruption in attentional set when a distractor is presented while the central executive is busy processing a leading target.

When two visual stimuli are presented in close temporal succession, identification is almost perfect for the first stimulus (T1) but substantially impaired for the second (T2). This second-target deficit, called the *attentional blink* (AB; Raymond, Shapiro, & Arnell, 1992), has been studied using a paradigm in which observers are required to identify two targets (e.g., letters) inserted in a stream of distractors (e.g., digits) displayed in rapid serial visual presentation (RSVP). All items in the RSVP stream are presented in the same spatial location at a rate of approximately 10 items/sec. The temporal lag between the two targets is manipulated by varying the number of intervening distractors. The second-target deficit is most pronounced at short intertarget lags, with performance improving progressively as the lag is increased, reaching an asymptote at about 500 msec.

Theoretical accounts of the AB have focused on the processing of T1 as the primary source of the second-target deficit. On these accounts (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1994), the requirement to process T1 is said to delay the allocation of attentional resources to T2 for several hundred milliseconds. As a result, if T2 is presented shortly after T1, its processing is delayed, and it becomes vulnerable to overwriting by subsequent stimuli (see, e.g., Giesbrecht & Di Lollo, 1998). At longer lags, resources initially deployed to T1 become available for T2 as T1 processing is nearing completion, and the AB is no longer in evidence. In brief, current theoretical accounts of the AB hold to the idea of resource depletion as the principal factor in the second-target deficit.

Findings inconsistent with a resource-depletion account have been reported by Di Lollo, Kawahara, Ghorashi, and Enns (2005) in a study in which observers were required to identify three consecutive target letters inserted in an RSVP stream of digit distractors. According to the resource-depletion hypothesis, identification accuracy should be highest for the leading target and decline progressively for each successive target as resources become more depleted. Instead, no progressive decrement (i.e., no AB deficit) was in evidence over the successive targets: The third target (T3) was identified as accurately as the first. A second, and even more revealing finding was that identification of T3 was substantially impaired—as in the conventional AB deficit—when the middle letter in the three-target string was replaced with a digit. This is all the more remarkable because the observers were required to report only two targets rather than three targets.

An account of these findings has been proposed by Di Lollo et al. (2005) in terms of a temporary loss of control (TLC) over the prevailing attentional set. The TLC account is based on two assumptions. First, that at the outset of the RSVP stream, the observer adopts an attentional set aimed at accepting targets and rejecting distractors. At this stage, the system acts as an input filter: Items that fit the filter's configuration gain access to a higher processing stage involving consolidation and response planning.

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All other items are excluded from further processing. The second assumption is that such an attentional set is not static but must be maintained by endogenous signals from a central executive that involves higher brain regions, such as prefrontal cortex. Maintenance signals are said to be issued without interruption in the period before T1, thus permitting efficient exclusion of leading distractors. The signals are discontinued, however, when processing of T1 begins. This is because the central executive cannot keep on issuing maintenance signals while, at the same time, orchestrating the processing of T1.

In the absence of endogenous maintenance signals, the attentional set becomes vulnerable to exogenous disruption by intervening distractors (Allport, Styles, & Hsieh, 1994). This occurs when the leading target is followed by an item from a different category, such as a distractor or a mask. Perception of the ensuing target is then impaired because the target-tuned attentional set has been disrupted by the intervening distractor. No such disruption occurs when the item intervening between the two targets is another target because it fits the current attentional set. It goes without saying that once T1 has been processed (i.e., at longer intertarget lags), the second-target deficit vanishes because the central executive is free to reestablish the initial attentional set and to resume issuing appropriate control signals.

It is clear that the findings of Di Lollo et al. (2005) bring into question resource depletion as the sole source of deficit in the processing of rapidly sequential targets. It is equally clear, however, that the currently available evidence is not sufficient for establishing the TLC model as a valid account of the AB, because, by definition, the AB deficit depends critically on intertarget lag. However, in Di Lollo et al.'s study, the three targets were invariably presented in a continuous string, with no systematic variation of intertarget lag.

The importance of this issue is underscored by results reported by Nieuwenhuis, Gilzenrat, Holmes, and Cohen (2005), which have been said to be inconsistent with the TLC hypothesis. This conclusion is questionable, however, because in Nieuwenhuis et al.'s study, the lag between successive items in the RSVP stream was reduced by half in the critical condition. To wit, the lag between RSVP items was set at 100 msec except when one distractor was inserted between the two targets. In that case, the lag between three successive items (T1, distractor, T2) was halved to 50 msec, while it remained at 100 msec in the rest of the RSVP stream. This halving of the lag is important because it is known that the conventional AB results are not obtained when the lag is reduced to such short stimulus onset asynchronies (SOAs; Potter, Staub, & O'Connor, 2002). In that case, target identification is governed by factors other than those that underlie the conventional AB deficit.

One such factor is seen in the type of masking to which Bachmann and Hommuk (2005; see also Bachmann & Allik, 1976) refer as *mutual masking*, in which the first of two targets presented in rapid succession (i.e., at SOAs below about 70 msec) is impaired relative to the second target. In this case, the factors that underlie the leading-target impairment are likely to be those that also underlie metacontrast masking and the *plastic transformations* described by Kolers (1972) in motion perception. At SOAs beyond about 100 msec, however, it is the *trailing* target that is impaired, as in the conventional AB deficit. As noted above, the SOA employed by Nieuwenhuis et al. (2005) was within the range of the short SOAs discussed above. For this reason, the relative accuracy of identification of T1 and T2 obtained in their study cannot be ascribed unambiguously to factors underlying the conventional AB deficit. It goes without saying that, being a model of the AB and not of mutual masking or plastic transformations, the leading-target impairment obtained at short SOAs is beyond the scope of the TLC model.

Nevertheless, the conclusion reached by Nieuwenhuis et al. (2005) calls attention to the need to examine the TLC hypothesis under conditions in which the AB deficit is conventionally obtained—namely, under conditions in which the lag between successive targets in the RSVP stream is varied over a broad range. We did this in the present study by combining the three-target procedure with a systematic manipulation of the number of distractors intervening between T2 and T3 while maintaining a fixed SOA between successive items in the RSVP stream.

Predictions from the resource-depletion hypothesis and the TLC hypothesis were examined in the present work across a broad range of intertarget lags. According to the resource-depletion hypothesis, the main function served by the insertion of distractors between successive targets is to increase the period for which the leading target is processed before the onset of the trailing target. Increasing the number of intervening distractors is held to provide more time for processing the leading target, thus making more resources available for the trailing target when it arrives. The end result of increasing the number of intervening distractors is to produce a corresponding improvement in the identification of the trailing target. In contrast, the TLC hypothesis specifies that the insertion of distractors while the leading target is being processed will disrupt the prevailing attentional set and cause identification of the trailing target to be impaired.

Figure 1 illustrates the display sequences of targets and distractors. There were two conditions: TT and TxT. In Condition TT, the RSVP stream began with a variable number of digit distractors and continued with two target letters (T1 and T2) presented in direct succession. A third target letter (T3) was then presented at one of three lags after T2: lag 1 (in which T3 was presented directly after T2), lag 3 (in which two digit distractors were inserted between T2 and T3), and lag 7 (in which six digit distractors were inserted between T2 and T3). The RSVP stream ended with one digit distractor that acted as a mask after T3. Condition TxT was the same as Condition TT except that a distractor was always inserted between T1 and T2.

METHOD

Observers

Seventeen adults (13 males, 4 females; mean age, 20.9 years) from the subject pool of the National Institute of Advanced Indus-

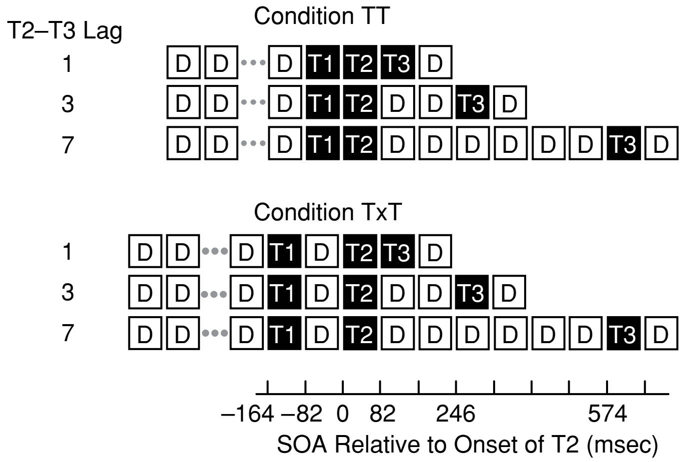

Figure 1. Schematic representation of the display sequences in Experiment 1. D, distractor; T1, first target; T2, second target; T3, third target; SOA, stimulus onset asynchrony. All targets were letters; all distractors were digits. See text for explanation.

trial Science and Technology participated for payment. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus and Stimuli

The stimuli were white digits and letters displayed on the black screen of a computer monitor. They subtended approximately 1º of visual angle in height at a viewing distance of 57 cm.

Experimental Design

The experimental design was a 2 (condition: TT, TxT) × 3 (lag: 1, 3, 7) within-subjects factorial. There were 192 trials comprising 32 presentations of the six combinations of condition and lag, ordered randomly, independently for each observer, preceded by 20 practice trials.

Procedure

At the beginning of each trial, a small fixation cross was presented in the center of the screen. The observers initiated each trial by pressing the space bar. After a 500-msec delay, an RSVP stream was displayed, containing a variable number of digit distractors and three letter targets. Each item was displayed for 82 msec with no interstimulus interval, yielding a presentation rate of approximately 12 items/sec. On each trial, the distractors were selected randomly with replacement from the digits 0–9, with the constraint that the selected digit was not one of the two immediately preceding items. The targets were selected randomly without replacement from all uppercase letters of the English alphabet, except I, O, Q, and Z. The number of distractors preceding T1 was determined randomly on each trial and varied between 5 and 10. The observers were instructed to report the identity of all three targets, regardless of order, by pressing the corresponding keys on the keyboard.

RESULTS AND DISCUSSION

The results, illustrated in Figure 2, were analyzed in a 2 (condition: TT, TxT) × 3 (target: T1, T2, T3) × 3 (T2–T3 lag: 1, 3, 7) within-subjects ANOVA. The analysis revealed significant effects of condition [$F(1,16) = 7.87$, $MS_e = 70.63$, $p < .05$], target [$F(2,32) = 3.49$, $MS_e = 307.50$, $p < .05$], and T2–T3 lag [$F(2,32) = 29.19$, $MS_e = 54.59$, $p < .001$]. There were two significant interaction effects: between condition and target [$F(2,32) = 104.80$, $MS_e = 108.17$, $p < .001$] and between target and T2–T3 lag [$F(4,64) = 36.66$, $MS_e = 93.19$, $p < .001$]. No other effects were significant.

Additional analyses were performed to examine how the results in Figure 2 matched specific predictions made by the resource-depletion hypothesis and the TLC hypothesis. First, we analyzed the results denoted by the two dotted oval shapes in Figure 2. These data represent the accuracy of identifying T3 when it was presented either directly after T2 (upper oval) or when two distractors intervened between T2 and T3 (lower oval).

According to the resource-depletion hypothesis, T3 should be identified more accurately when it is presented after two distractors (SOA = 246 msec) than when it is presented directly after T2 (SOA = 82 msec). This is because more processing of T2 can be accomplished during the longer SOA, making more resources available for processing T3. The TLC hypothesis makes the opposite prediction. When T3 is presented directly after T2, identification accuracy for T3 should remain high because there is no intervening distractor to disrupt the current system configuration optimally tuned to accepting letter targets and excluding digit distractors. By the same token, identification accuracy for T3 should be lower when two distractors are inserted between T2 and T3 because the intervening distractors would disrupt the current attentional set with consequent impairment in T3 identification.

These predictions were examined in a 2 (condition: TT, TxT) × 2 (T2–T3 lag: 1, 3) ANOVA, which revealed a significant effect of T2–T3 lag [$F(1,16) = 83.09$, $MS_e = 126.00$, $p < .001$] and a significant interaction effect [$F(1,16) = 7.58$, $MS_e = 159.44$, $p < .05$]. The effect of condition was not significant. This confirms that accuracy of T3 identification was significantly higher when T3 was preceded by another target (Figure 2, upper oval) than

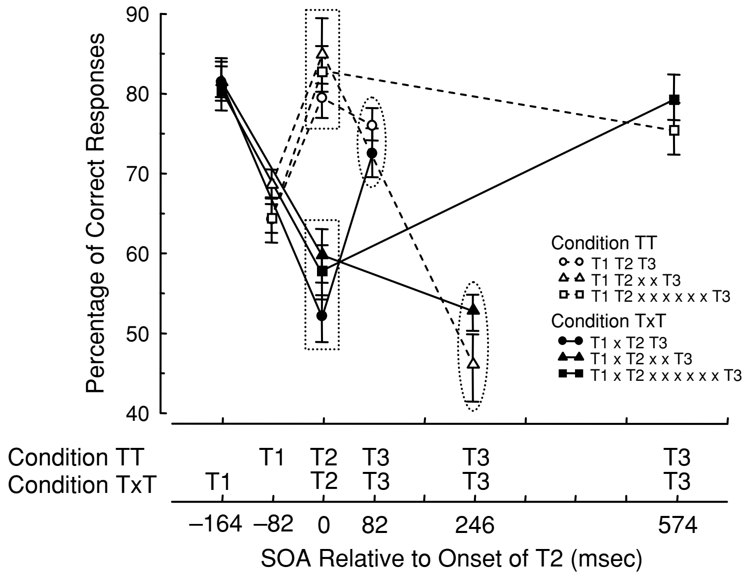

Figure 2. Percentage of correct responses for each of the three targets. T1, first target; T2, second target; T3, third target; SOA, stimulus onset asynchrony. All targets were letters; all distractors were digits. In the legend, the symbol "x" denotes a distractor. See text for an explanation of the dotted oval and rectangular shapes.

when it was preceded by two distractors (Figure 2, lower oval) [Fs(1,32) $>$ 35.5, ps $<$ .001]. This pattern of results is clearly consistent with the TLC hypothesis but not with the resource-depletion hypothesis, which would predict the opposite outcome.

Other aspects of the results are also inconsistent with the resource-depletion hypothesis but are explained naturally within the TLC framework. One concerns the relative accuracy for T2 and T3 in the TxT condition at SOAs of 82 and 246 msec (Figure 2, filled circles and filled triangles). First, consider an SOA of 246 msec. Figure 2 shows that at an SOA of 246 msec, performance for T3 was lower than performance for T2 (filled triangles) [$t(16) = 1.8, p < .05$, one-tailed]. According to the resource-depletion hypothesis, T3 performance was impaired because the resources required for T3 were preempted by T2. In other words, at end of the 246-msec period, processing resources were still deployed mostly to T2 to the detriment of T3. But this account runs afoul of the finding that accuracy for T3 was substantially higher than for T2 when T3 was presented only 82 msec after T2 (Figure 2, filled circles) [$t(16) = 7.4, p < .001$]. What needs to be explained is why there were ample resources for processing T3 when it arrived only 82 msec after T2 but not when it arrived as long as 246 msec after T2. Clearly, the resource-depletion hypothesis would predict the opposite result. In contrast, this pattern of results is entirely consistent with predictions from the TLC hypothesis. At an SOA of 246 msec, T3 suffered because it was preceded by two distractors, which disrupted the prevailing attentional set. In contrast, accuracy for T3 was much higher at an SOA of 82 msec because the preceding item was not a distractor but another target, which reset the system's configuration exogenously so as to be optimally tuned to passing letters and excluding digits.

Finally, the results denoted by the dotted rectangular shapes in Figure 2 are a replication of the earlier finding that identification accuracy for T2 is substantially higher if T2 is presented directly after T1 (Figure 2, upper rectangle) than if a distractor intervenes between T1 and T2 (Figure 2, lower rectangle). We have noted that this finding is consistent with the TLC hypothesis but not with the resource-depletion hypothesis (Di Lollo et al., 2005).

Two secondary aspects of the results in Figure 2 deserve comment. First, at an SOA of 574 msec, T3 identification was highly accurate. This finding is consistent with both the resource-depletion hypothesis and the TLC hypothesis. According to the resource-depletion hypothesis, an SOA of 574 msec was sufficient for completing the processing of T2, thus allowing adequate resources to be deployed to T3. According to the TLC hypothesis, completion of T2 processing allowed the central executive to reconfigure the system optimally for the task at hand and to resume the endogenous maintenance signals. The second aspect of the results that deserves comment is that accuracy of T1 identification was decidedly higher when T1 was followed by a distractor (Figure 2, filled symbols) than when it was followed by another target (Figure 2, open symbols). This result has been reported earlier by Di Lollo et al. (2005) and, on the face of it, seems to be related more to memory processes than to resource depletion or loss of endogenous control. It is possible, for example, that memory consolidation of T1 occurs more readily when the processing demands of the next item in the RSVP stream are low (because it is a distractor) than when they are high (because it is another target to be encoded and consolidated). Although potentially important, further investigation of this finding is beyond the scope of the present work.

An additional potential account should be discussed. The results of Condition TT might be explained by the "gating" hypothesis invoked recently by Li, Lin, Chang, and Hung (2004). An attentional gate is said to open at the onset of T1 and to close sluggishly, allowing several items after T1 to enter cognitive processing. According to this hypothesis, T3 performance in the T1–T2–T3 sequence was relatively high because the gate remained open for at least three items (i.e., at least 246 msec) after T1 onset.

This account is disconfirmed, however, by the corresponding results in the TxT condition. Given a T1–distractor–T2 sequence, accuracy for the third item should have been the same as for the third item in the T1–T2–T3 sequence because both were presented within 246 msec. In fact, third-item accuracy was much lower in the T1–distractor–T2 sequence than in the T1–T2–T3 sequence (Figure 2, open circle in upper oval vs. filled circle in lower rectangle). Clearly, the present results are beyond what can be explained solely on the basis of the gating hypothesis.

CONCLUDING REMARKS

The major objective of the present work was to determine whether the TLC model (Di Lollo et al., 2005) offers a plausible account of the AB deficit. Part of that objective was to examine an ostensible failure of the TLC hypothesis reported by Nieuwenhuis et al. (2005). To this end, we used a paradigm in which three targets were inserted in an RSVP stream of distractors over a broad range of intertarget lags. The results were consistent with predictions from the TLC hypothesis but not with those of the resource-depletion hypothesis or the attentional-gating hypothesis.

The consistent pattern of AB deficit obtained in the present work over a broad range of lags strongly suggests that Nieuwenhuis et al.'s (2005) findings represent the effect of competitive intertarget processes that take place at very short SOAs (Bachmann & Hommuk, 2005; Potter et al., 2002) rather than a conventional AB deficit. Although a full account of Nieuwenhuis et al.'s findings is beyond the scope of the present article, it seems clear that those findings do not disconfirm the TLC model, which was designed to account for conventional AB findings.

Perhaps more important, the present results demonstrate that the same loss of control occurs between T2 and T3 as was previously shown between T1 and T2 (Di Lollo et al., 2005). This same conclusion is supported by a reanalysis of the data from Chun and Potter's (1995) Experiment 2, kindly supplied to us by Marvin Chun. This reanalysis revealed a pattern virtually identical to those in Figure 2. These findings are important for the definition of the phenomenon known as *lag 1 sparing* in which the AB deficit is found to be much reduced or entirely absent when T2 is presented directly after T1—namely, in the lag 1 position within the RSVP stream.

The present results show that lag 1 sparing occurs not only at lag 1 but at any lag in the RSVP stream, provided that the "spared" target is preceded not by a distractor but by another target. This is inconsistent with the gating hypothesis commonly invoked to account for lag 1 sparing, because the sparing can occur unabated even at lags (such as lag 3) at which the gate is presumed to be closed. In contrast, this finding is entirely consistent with the TLC hypothesis.

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