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Task switching mediates the attentional blink even without backward masking

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When two targets are presented in rapid succession, perception of the second target is impaired at short intertarget lags (100–700 msec). This *attentional blink* (AB) is thought to occur only when the second target is backward masked. To the contrary, we show that task switching between the targets can produce an AB even without masking (Experiments 1 and 3). Further, we show that task switching produces an AB only when the second target does not belong to a class of overlearned stimuli such as letters or digits (Experiments 1 and 4). When the second target is masked, however, an AB is invariably obtained regardless of switching or overlearning. We propose that task switching involves a time-consuming process of reconfiguration of the visual system, during which the representation of the second target decays beyond recognition, resulting in an AB deficit. We suggest that overlearned stimuli are encoded in a form that, while maskable, decays relatively slowly, thus outlasting the delay due to reconfiguration and avoiding the AB deficit.

How does the visual system handle the ever-changing stream of images to which it is exposed in everyday experience? This issue has been studied in the laboratory by displaying a stream of rapidly sequential stimuli in a given spatial location using a technique known as *rapid serial visual presentation* (RSVP). In one application of this technique, subjects are required to report two targets (e.g., letters) embedded in a stream of distractors (e.g., digits). Under these conditions, accuracy is nearly perfect for the first target, but is substantially reduced for the second. This second-target deficit, known as the *attentional blink* (AB), is most pronounced when the temporal lag between the two targets is short (100–300 msec), with performance improving progressively as the lag is increased to about 700 msec (Raymond, Shapiro, & Arnell, 1992). The AB therefore points to an important limit on the rate at which successive visual images can be fully processed. In the present study, we examined the role of task switching in determining this limit. Earlier work had identified task switching as an important factor in the AB (Allport, Styles, & Hsieh, 1994; Potter, Chun, Banks, & Muckenhoupt, 1998), but its effects have not been explored systematically, especially in the absence of masking of the second target.

One of the factors considered essential in the AB is backward masking of the second target. In conventional studies of the AB, the second target is masked by the trailing distractors in the RSVP stream. It has been found that if the trailing items are omitted, so that the second target is the last item in the stream, the AB deficit is eliminated across all lags (Giesbrecht & Di Lollo, 1998). This is true even if accuracy is brought below a performance ceiling by degrading the second target with visual noise (Brehaut, Enns, & Di Lollo, 1999). The interpretation given to the critical role of backward masking is that while the system is occupied with processing the first target, processing the second target is delayed at an early stage where it is encoded in a form that makes it vulnerable to masking by trailing stimuli. When this happens, the mask replaces the second target as the internal representation to be identified, a process referred to as *object substitution* (Brehaut et al., 1999; Di Lollo, Enns, & Rensink, 2000; Giesbrecht & Di Lollo, 1998).

The necessity of backward masking for obtaining an AB deficit, however, has recently been questioned by Kawahara, Di Lollo, and Enns (1999). In that study, two targets were inserted in a stream of digit distractors. The first target was a letter, and the second was a circular array of uniformly oriented diagonal lines that contained an oddly oriented line on a random half of the trials. Subjects identified the first target and indicated whether the oddball line was present or absent. A pronounced AB deficit was obtained even when the second target was not followed by a mask.

In an attempt to resolve this inconsistency, we examined the procedural differences between the studies showing the

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importance of masking the second target (Brehaut et al., 1999; Giesbrecht & Di Lollo, 1998) and the study showing an AB even when the second target was not followed by a mask (Kawahara et al., 1999). Among the more salient differences was the relationship between the two targets. In the study of Kawahara et al. (1999), the two targets belonged to different classes of stimuli: One was a letter to be identified, the other an oddly tilted line to be detected. Given these differences, a task switch was clearly involved between the processing of the first and that of the second target. In contrast, no task switching was involved in the studies of Brehaut et al. and Giesbrecht and Di Lollo, where both targets were letters to be identified and, therefore, belonged to the same class of stimuli.

On the basis of these considerations, we formulated the hypothesis that the AB might be obtained either by backward masking of the second target, which capitalizes on the brief delay while the first target is being processed, or by implementing a task switch between the targets, which induces an even longer delay. It is known that task switching involves a time-consuming resetting of the system from a configuration optimally suited for performing one task to one best suited for another (Meiran, 1996; Monsell, 1996; Visser, Bischof, & Di Lollo, 1999). If the display sequence involves a task switch after the first target, the delay arising from system reconfiguration would combine with the delay due to first-target processing to yield a combined delay, during which the representation of the second target would continue to decay. By the end of the combined delay, the representation of the second target might have decayed beyond recognition, thus yielding an AB deficit even in the absence of a trailing mask.

The principal objective of the present study was to explore the conditions under which task switching yields an AB in the absence of backward masking of the second target. In a series of five experiments, the first four revealed that task switching produces an AB, but not if the second target belongs to a class of overlearned stimuli such as letters or digits; the fifth experiment confirmed that, when the second target is masked, an AB is invariably obtained regardless of task switching or stimulus class. We conclude by describing a model capable of accounting for the effects of task switching and stimulus class within a single conceptual framework.

EXPERIMENT 1

The design of Experiment 1 was a factorial combination of the presence or absence of a task switch between the first and the second targets. Each target was either a letter to be identified or a diagonal line segment whose orientation was to be reported. It should be emphasized that the second target was never followed by a mask. We expected that if an AB can be produced by task switching in the absence of masking, the results would reveal AB deficits in the two conditions involving a switch (letter–line and line–letter) but not in the conditions not involving a switch (letter–letter and line–line).

Method

Subjects

Sixty-four undergraduate volunteers at the University of British Columbia participated for extra course credit. All reported normal or corrected-to-normal vision and were naive to the purpose of the experiment. They were assigned randomly to one of four conditions, each with 16 subjects.

Apparatus and Stimuli

All stimuli were displayed on a Tektronix 608 oscilloscopic point-plotter equipped with P15 phosphor. The stimuli consisted of digits, letters, and an oriented line segment. The digits and letters subtended approximately 1° of visual angle in height at a viewing distance of 57 cm, set by a headrest. The line segment was 1° in length and less than 0.1° in thickness. The luminance, as measured by a Minolta CS-100 luminance meter, was 20 cd/m^2 for the digits and letters, and 8 cd/m^2 for the line segment.

Procedure

At the beginning of each trial, a small fixation cross was presented in the center of the screen, indicating the location at which an RSVP stream was about to appear. The subjects initiated each trial by pressing the space bar. After a 500-msec delay, an RSVP stream was displayed, containing a variable number of digits (distractors) and two targets, each of which could be either a letter or an oriented line segment, as is illustrated in Figure 1. Each item was displayed for 30 msec and was separated from the next item by an interstimulus interval (ISI) of 70 msec, yielding a presentation rate of 10 items/sec.

The distractors on each trial 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 target letter was selected randomly from all letters of the English alphabet, except for I, O, Q, and Z, which were omitted because of their visual similarity with some of the digits. The number of distractors preceding the first target was determined randomly on each trial, and varied between 5 and 10. The subjects were instructed to ignore the distractors and to report the identity of the targets by pressing the corresponding keys on the keyboard. The second target was presented at one of five lags after the first target: 100, 200, 300, 500, or 700 msec. The stream of distractors continued to be displayed throughout the lag, as is illustrated in Figure 1. The display sequence ended with the second target.

Experimental Design

The design was a 4 × 5 factorial, with one between-subjects factor, condition (letter–letter, letter–line, line–letter, and line–line, where the items in each pair indicate the stimulus for the first and second targets, respectively), and one within-subjects factor, lag (100, 200, 300, 500, or 700 msec). The procedural details for each condition were as follows.

Letter–letter (no switch). The targets were two different letters inserted in the RSVP stream of digit distractors presented in the center of the screen. The subjects identified both letters by typing them on the keyboard.

In order to keep the level of identification of the second target below the ceiling level and above the floor level imposed by the response scale, we employed a dynamic adjustment procedure similar to that used by Kawahara et al. (1999). This involved degrading the perception of the target by embedding it in a variable number of noise dots. The average number of noise dots presented with the second target at the end of the session was 93.1.

Letter–line (task switch). This was the same as the letter–letter condition, except that the second target was an oriented line segment whose tilt was to be identified by pressing one of the arrow keys on the keyboard marked "\" or "/." In all the present experiments, the first target was masked by the next item in the RSVP stream. This meant that, at the shortest lag of 100 msec, the mask consisted of the

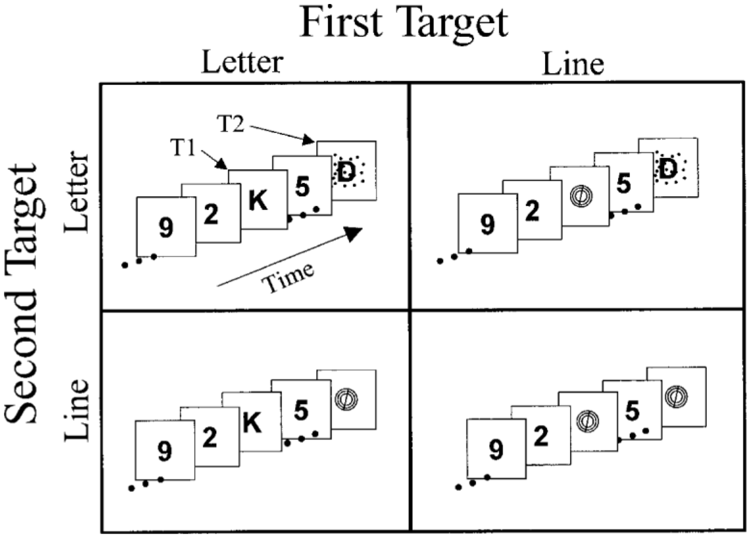

Figure 1. Schematic representation of the sequence of events in each of the four conditions in Experiment 1. T1, first target; T2, second target.

second target, which, in the letter–line and line–line conditions, was a single oriented line. In pilot studies, we found that a single line segment was insufficient to mask the first target at the shortest lag of 100 msec. Therefore, the line was superimposed on a pattern of three concentric circles, which formed a more effective mask. The diameter of the smallest circle was 0.2°, that of the medium-sized circle was 0.6°, and that of the largest circle was 1°. The degree of tilt of the diagonal line was determined individually for each subject by the dynamic adjustment method described above. At the beginning of the session, the tilt of the line was 3° of geometrical angle, which was adjusted in steps of ±0.5°, depending on performance. At the end of the session, the mean tilt of the line, averaged across subjects, was 1.41°.

Line–letter (task switch). This was the same as the letter–line condition, except that the sequential order of the two targets was reversed. The tilt of the first target was fixed at 15°. At the beginning of the session, the second target was degraded with 30 noise dots. At the end of the session, the number of noise dots, averaged across subjects, was 48.1.

Line–line (no switch). In this condition, both targets were oriented line segments, as described for the letter–line condition above. The tilt of the first target was fixed at 15°. At the beginning of the session, the tilt of the second target was 3° of geometrical angle, which was adjusted in steps of ±0.5°, depending on performance. At the end of the session, the mean tilt of the line, averaged across subjects, was 2.6°.

At the beginning of each session, the subjects were given 20 practice trials. These were followed by 360 experimental trials that lasted approximately 40 min. The subjects were allowed several brief rest periods during the session.

Results and Discussion

In this and all subsequent experiments, estimates of second-target identification were based on only those trials in which the first target had been identified correctly. This procedure is commonly adopted in AB experiments on the grounds that, on trials in which the first target is identified incorrectly, the source of the error is unknown, and, thus, its effect on second-target processing cannot be estimated. Correct identifications of the first target, averaged across lags separately for each condition, were letter–letter (88.8%), line–letter (86.0%), letter–line (95.9%), and line–line (91.2%). Figure 2 shows the percentages of correct responses on the second target as a function of lag, averaged over all subjects, separately for each condition.

Mean individual scores were analyzed in to a two-way analysis of variance (ANOVA) with one between-subjects factor, condition (letter–letter, letter–line, line–line, letter–letter) and one within-subjects factor, lag (100, 200, 300, 500, and 700 msec). The analysis revealed a significant effect of lag [$F(4,240) = 3.92, MS_e = 28.90, p < .01$] and a significant interaction between lag and condition [$F(12,240) = 2.02$, $MS_e = 28.90$, $p < .05$]. Separate tests aimed at examining the interaction revealed that the effect of lag was significant in the letter–line condition [$F(4,60) = 8.09$, $MS_e = 26.40$, $p < .001$] but not in any of the remaining three conditions [letter–letter, $F(4,60) = 1.66, MS_e = 27.17$, $p > .17$; line–line, $F(4,60) < 1$; line–letter, $F(4,60) < 1$].

The results of the two conditions that did not involve task switching are clear-cut. No AB was obtained in either the letter–letter or the line–line condition (Figures 2A and 2D, respectively), confirming earlier findings that the AB does not occur when neither task switching nor backward masking of the second target is involved (Giesbrecht & Di Lollo, 1998). In contrast, the results of the two conditions involving task switching revealed a mixed picture: An AB was found when the task involved a switch from a letter to a line (Figure 2C), but not when it involved the converse switch from a line to a letter (Figure 2B).

On the face of it, the absence of an AB in the line–letter condition (Figure 2B) appears to disconfirm the proposition, proffered in the foregoing, that a task switch might be sufficient to produce an AB deficit even if the second target is not masked. Before abandoning that propo-

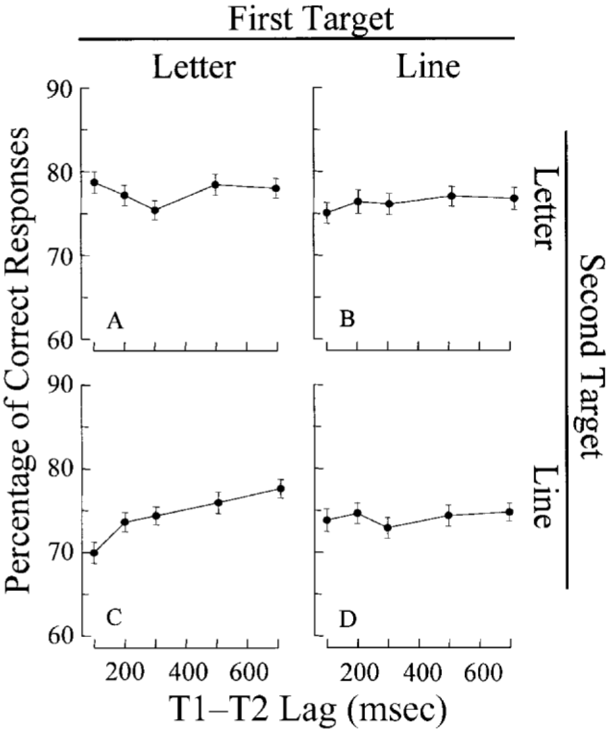

Figure 2. Mean percentages of correct identifications of the second target, given correct identification of the first target, in each of the four conditions of Experiment 1. T1, first target; T2, second target. Error bars represent 1 standard error of the mean.

sition, however, it is well to consider other possible reasons why an AB failed to appear in the line–letter condition despite a task switch. There are at least two options.

First, it is possible that the task of identifying the orientation of a line might not tax the system's processing resources to any significant extent. Therefore, the orientation task could be performed easily and rapidly. Processing resources would then be available for identifying the trailing letter immediately, regardless of the intertarget lag, and the AB deficit would be obviated. In a sense, this would be functionally equivalent to omitting the first target from the RSVP stream, a procedure known to effectively eliminate the AB deficit (Raymond et al., 1992).

A second option is that the internal representations of a letter might decay more slowly than that of a line, perhaps because the former is more meaningful, more complex, or overlearned. In that case, the representation of a letter might still be available after the additional processing delay caused by a task switch, whereas that of a line might have decayed beyond recognition. This would produce an AB deficit when the second target is a line but not when it is a letter.

The first option was examined in Experiment 2, and the second in Experiments 3 and 4.

EXPERIMENT 2

Experiment 2 was designed to test the hypothesis that in the line–letter condition of Experiment 1 the first target might have been processed very rapidly, thus obviating an AB deficit. We tested this hypothesis by replicating the line–letter condition of Experiment 1, with one important difference: Instead of measuring accuracy, we measured the time to respond (reaction time, RT) to the second target as a function of intertarget lag. The rationale for the test was based on the hypothesis that while the system is busy with the first target, processing of the second target must be postponed until the system is again free. If the time required to process the first target is very short, as might be the case for a line segment, processing resources should be promptly available for identifying the second target even if it arrives shortly after the first target. In this case, RT to the second target should exhibit a flat function across lags. If, on the other hand, the time required to process the first target is relatively long, RT to the second target should be long at the shorter lags and should diminish progressively as lag is increased. In general, the temporal course of RT over lags should index the amount of time required for processing the line's orientation before resources can be devoted to identifying the trailing letter.

An intrinsic requirement in measuring RT is that the response be made immediately upon target presentation. To this end, the subjects were required to respond to the second target (the letter) as quickly as possible when it appeared on the screen and to respond to the first target later, at their leisure. This reversal of the order of report is known not to affect response accuracy or the nature of the lag-dependent effects in AB studies (Kawahara, Di Lollo, & Enns, 2001).

Method

A new group of 16 subjects participated in Experiment 2. The stimuli and procedures were the same as in the line–letter condition of Experiment 1, with the following exceptions: The first target was an oriented line segment as in Experiment 1; the second target consisted of the letter C or G, one of which was presented randomly on each trial. The subjects were required to identify the first target and to make a speeded response to the second. However, to measure RT to the second target, the order of report was reversed. The subjects were instructed to respond as quickly as possible to the second target by pressing either the "Z" or the "X" key on the keyboard, which were marked "C" and "G," respectively, and then to indicate the orientation of the first target by pressing one of two arrow keys marked "\" and "/." The second target was not degraded by noise dots.

Results and Discussion

The median RT was computed separately for each subject. Figure 3 shows the mean of the median RT scores to the second target as a function of lag. Correct identifications of the first target, averaged across subjects and lags, was 93.2%. A one-way within-subjects ANOVA, conducted on median individual RT scores, revealed a significant effect of lag [$F(4,60) = 24.30$, $MS_e = 4,866.98$, $p < .001$].

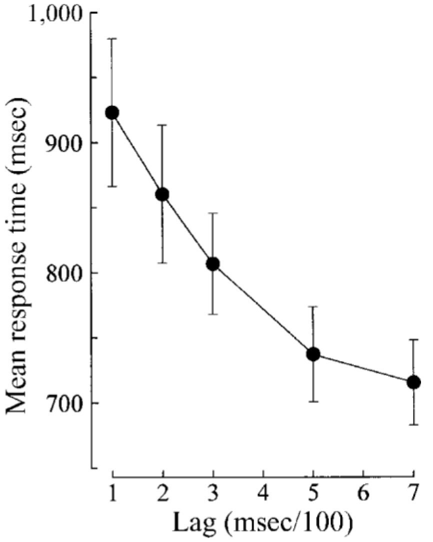

Figure 3. Mean median response times in relation to intertarget lag in Experiment 2. Error bars represent 1 standard error of the mean.

As is illustrated in Figure 3, RTs to the second target decreased progressively as the intertarget lag was increased. This is consistent with the hypothesis that identification of the line's orientation in the line–letter condition in Experiment 1 required an extended temporal interval, which caused a corresponding delay in the processing of the second target. The evidence in Figure 3 is important for the present purpose because it rules out one of the alternative hypotheses for the absence of an AB deficit in the line–letter condition in Experiment 1 (Figure 2B)—namely, it disconfirms the hypothesis that the line's orientation might have been processed so rapidly as not to cause any significant additional delay in the processing of the second target.

This general argument is based on the assumption that the pattern of delays seen in Figure 3 is of the same approximate magnitude as would be obtained if the order of the two targets were to be reversed—namely, if the first target were a letter and the second a tilted line. This assumption is supported by the studies of Jolicœur and Dell' Acqua (1998, 1999), who used a letter as first target and found delays comparable to those illustrated in Figure 3. A similar pattern of delays has been reported by Kawahara et al. (2001, Experiment 3) when the first target was a letter and the second a tilted line.

What is still in need of explanation is why an AB was obtained in the letter–line but not in the line–letter condition in Experiment 1. Both conditions involved a task switch that required some time to complete. According to our hypothesis, task switching added to the delay due to first-target processing, yielding a combined delay during which the representation of the second target decayed beyond recognition, giving rise to an AB deficit. On this hypothesis, an AB should have been obtained in both conditions that involved a task switch. Yet, a deficit was found only when the task involved a switch from a letter to a line (Figure 2C). The question that needs to be asked is, Why did a second-target deficit fail to appear when the task involved the converse switch from line to letter?

One of the options considered in the Discussion section of Experiment 1 was that letters might belong to a class of overlearned stimuli that are encoded in a form that decays relatively slowly. Given this option, the representation of the second target in the line–letter condition in Experiment 1 would have outlasted the combined delays arising from first-target processing and task switching, thus avoiding an AB deficit. This option was tested in Experiments 3 and 4. In Experiment 3, we introduced task switching between two sets of stimuli that were unlikely to be overlearned: the oriented line segment used in Experiment 1, and a rectangular outline box that could be either vertical or horizontal. In Experiment 4, the task switch was between two sets of overlearned stimuli: letters and digits.

EXPERIMENT 3

The design of Experiment 3 was a 2 × 2 factorial in which the stimulus object in the first target (line or box) was crossed with the stimulus object in the second target (line or box). On the basis of our reasoning outlined above, we expected to find an AB deficit in the two conditions that involved a task switch (line–box and box–line) but not in the no-switch conditions (line–line and box–box). The results confirmed this expectation.

Method

A new group of 16 subjects served in Experiment 3. The stimuli, apparatus, and procedures were the same as in Experiment 1, with the following exceptions. The letter stimuli in Experiment 1 were replaced with rectangular box outlines in Experiment 3, as is illustrated in Figure 4. The box was displayed as either a vertical or a horizontal rectangular outline. The subjects were instructed to report whether the box appeared to be vertical or horizontal by pressing the up arrow or the down arrow key on the keyboard, which had been appropriately marked with vertical or horizontal rectangles, respectively. The box was embedded with 30 noise dots in order to make it a more effective mask for the preceding item in the RSVP stream (see Experiment 1). When the box was displayed in the first-target position within the RSVP stream (box–line and box–box conditions), the vertical–horizontal aspect ratio of the box was .75° × .50°. When the box was displayed in the second-target position within the RSVP stream (line–box and box–box conditions), the vertical–horizontal aspect ratio was varied individually for each subject by the dynamic adjustment method described in Experiment 1 in order to maintain an average level of between 70% and 80% correct responses. At the beginning of the session, the aspect ratio was 0.65° × 0.50°. At the end of the session, the mean aspect ratio, averaged across subjects, was 0.54° × 0.50°. The thickness of the outline of the rectangular figure was less than 0.1°.

Results and Discussion

Figure 5 shows the percentages of correct responses to the second target as a function of lag, averaged over all subjects, separately for each condition. Correct identifi-

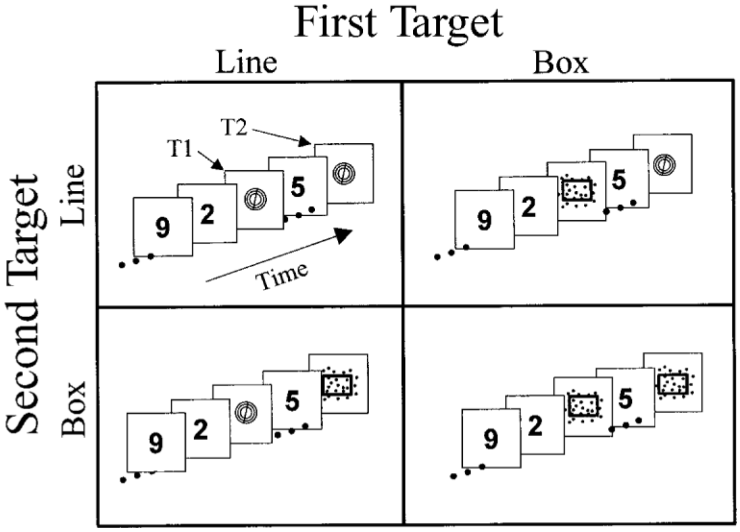

Figure 4. Schematic representation of the sequence of events in each of the four conditions in Experiment 3. T1, first target; T2, second target.

cations of the first target, averaged across lags, separately for each condition, were line–line (90.0%), box–line (95.2%), line–box (94.1%), and box–box (94.8%).

Mean individual scores were analyzed in a two-way ANOVA with one between-subjects factor (condition: line–line, box–line, line–box, and box–box) and one within-subjects factor (lag: 100, 200, 300, 500, and 700 msec). The analysis revealed a significant effect of lag [$F(4,240) = 4.63$, $MS_e = 34.19$, $p < .01$] and a significant interaction between lag and condition [$F(12,240) = 2.53$, $MS_e = 34.19$, $p < .01$]. Separate tests aimed at examining the interaction revealed that the effect of lag was significant in the box–line condition [$F(4,60) = 4.34$, $MS_e = 34.47$, $p < .01$] and in the line–box condition [$F(4,60) = 4.86$, $MS_e = 39.06$, $p < .01$], but not in the remaining two conditions [line–line, $F(4,60) = 1.43$, $MS_e = 33.67$, $p > .24$, and box–box, $F(4,60) = 1.03$, $MS_e = 29.56$, $p > .40$].

The results are unambiguous. An AB deficit is fully evident in the conditions involving task switching (Figures 5B and 5C) but not in the no-switch conditions (Figures 5A and 5D). These results are consistent with the hypothesis that task switching delays the processing of the second target to such an extent that by the time the first target has been processed, the decayed representation of the second target is no longer legible.

The pattern of results shown in Figure 5 replicates and builds on the results of Experiment 1 (Figure 2). In both experiments, an AB was obtained only when task switching was involved. The exception to this rule was the line–letter condition in Experiment 1 (Figure 2B). In that condition, no AB deficit was obtained, despite a task switch. In accounting for that exception, we surmised that letters might belong to a class of overlearned stimuli that are encoded in a form that decays relatively slowly. Thus, in the line–letter condition, a legible representation of the second target might still have been available after the combined delay arising from task switching and first-target processing.

We pursued this hypothesis in Experiment 4 by implementing a task switch between two sets of overlearned

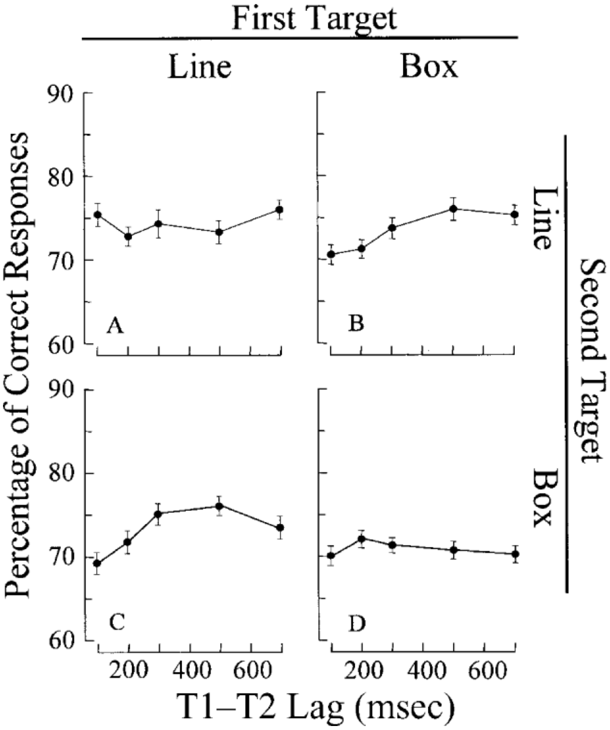

Figure 5. Mean percentages of correct responses to the second target, given correct identification of the first target, in each of the four conditions of Experiment 3. T1, first target; T2, second target. Error bars represent 1 standard error of the mean.

stimuli: letters and digits. In keeping with the results of the line–letter condition in Experiment 1, we expected to find no AB deficits in Experiment 4, regardless of task switching. The outcome confirmed our expectation.

EXPERIMENT 4

The design of Experiment 4 was a 2 × 2 factorial in which the stimulus item in the first target (letter or digit) was crossed with the stimulus item in the second target (letter or digit).

Method

A new group of 16 subjects served in Experiment 4. The stimuli, apparatus, and procedures were the same as in Experiment 1, with the following exceptions. The oriented-line targets in Experiment 1 were replaced with single-digit targets in Experiment 4. The digits were the Arabic numerals 1–9, of the same angular size as the letters. The 2 × 2 factorial design yielded the following four conditions: letter–letter, letter–digit, digit–letter, and digit–digit, where the first item in each pair denotes the first target and the second item the second target. Given the nature of the targets, neither letters nor digits could be used as distractors in the RSVP stream. Instead, we used false-font characters such as those illustrated in Figure 6. The sequence of events on any given trial in the four experimental conditions is presented schematically in Figure 6.

Results and Discussion

Figure 7 shows percentages of correct responses on the second target as a function of lag, averaged over all subjects, separately for each condition. Correct identifications of the first target, averaged across lags for each condition, were letter–letter (88.5%), digit–letter (96.1%), letter–digit (90.2%), and digit–digit (94.9%). Mean individual scores on the second target were analyzed in a two-way ANOVA with one between-subjects factor (condition: letter–letter, digit–letter, letter–digit, and digit–digit) and one within-subjects factor (lag: 100, 200, 300, 500, and 700 msec). The analysis revealed no significant effects [lag, $F(4,60) < 1$; lag × condition, $F(4,60) < 1$]. Separate analyses carried out in each of the four conditions yielded F ratios smaller than unity in every case.

No AB deficit was found in any of the four conditions in Experiment 4 (see Figure 7). This finding replicates the results of the line–letter condition in Experiment 1 (see Figure 2B) and is consistent with the hypothesis that letters and digits belong to a class of overlearned stimuli that are encoded in a form that outlasts the combined delays arising from task switching and first-target processing.

Two Stimulus Classes

A cautionary note is in order regarding the relationship between the two classes of stimuli in the present experiments. Letters and digits (e.g., in Experiment 4) differ from lines and boxes (e.g., in Experiment 3) along dimensions other than overlearning. For example, letters and digits are more meaningful and more complex than lines or boxes. Any one—or any combination—of these attributes might have been responsible for the absence of an AB in Experiment 4 (Figures 7B and 7C) and Experiment 1 (Figure 2B). The fact that we singled out overlearning as an important factor does not mean that we consider it to be the only factor. Rather, we use that term partly as a shorthand way of denoting the variety of attributes that distinguish the two classes of stimuli and partly because overlearning appears to be an especially promising factor.

Perceptual learning experiments strongly suggest that overlearned stimuli are encoded differently than nonoverlearned stimuli. For example, in a study by Walsh, Ashbridge, and Cowey (1998), observers received extensive training on a visual search task that initially yielded inef-

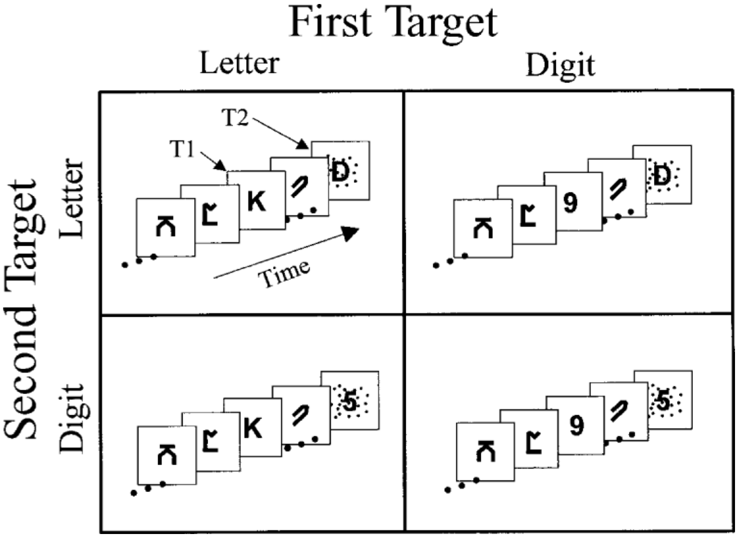

Figure 6. Schematic representation of the sequence of events in each of the four conditions in Experiment 4. T1, first target; T2, second target.

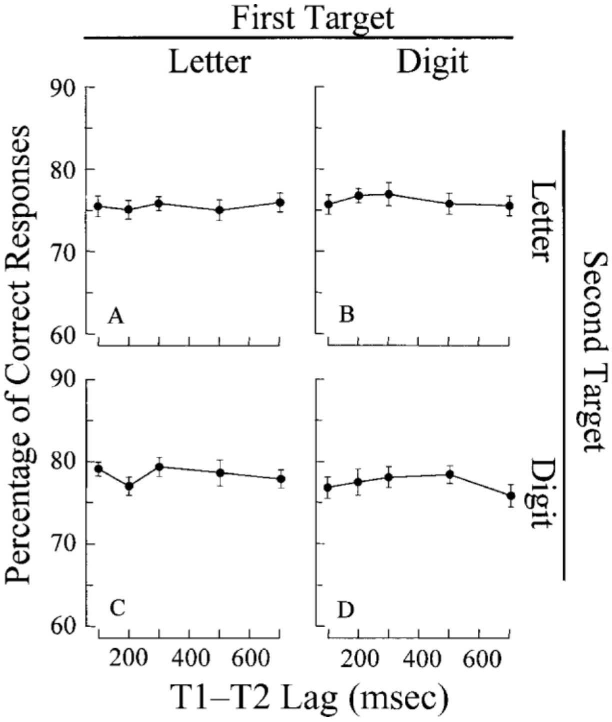

Figure 7. Mean percentages of correct responses to the second target, given correct identification of the first target, in each of the four conditions of Experiment 4. T1, first target; T2, second target. Error bars represent 1 standard error of the mean.

ficient search slopes suggestive of serial search. By the end of training, the search was performed efficiently, as is evidenced by flat slopes suggestive of parallel search. The important finding was that application of transcranial magnetic stimulation over parietal visual cortex disrupted search performance before but not after training. This prompted the hypothesis that overlearned and nonoverlearned stimuli are coded in different ways through processes that involve different brain regions.

It seems reasonable to conjecture that the representations of overlearned stimuli are not only established more rapidly, as has been suggested by the visual search studies noted above, but might also decay more slowly. At any rate, whether the critical variable is overlearning, meaningfulness, or complexity, what matters for the present purpose is that the class of stimuli exemplified by digits and letters can be separated pragmatically from the class of stimuli exemplified by lines and boxes. Upon a task switch, the latter class yields an AB, but the former does not. In the remainder of this paper, *overlearning* is used as a purely descriptive term to denote the differences between these two classes of stimuli.

Task Switching and Backward Masking

Considered collectively, the experiments reported thus far strongly suggest that task switching is sufficient to produce an AB even when the second target is not masked, provided that the second target is not overlearned. This conclusion, however, must not be taken to imply that masking of the second target is irrelevant to the AB. On the contrary, the AB literature shows that when the second target is masked, substantial AB deficits are obtained even when the two targets belong to the same category (i.e., when no task switching is involved). Therefore, the evidence indicates that the AB can be obtained by at least two distinct procedures: backward masking of the second target, and task switching between the targets.

A question now arises regarding the equivalence of the two procedures. Is the AB obtained with task switching the same as that obtained with backward masking? There are hints in the present results that the two procedures yield AB deficits that, although fundamentally similar, might be nonidentical. For example, the magnitude of the AB obtained in the present experiments seems smaller than that obtained in conventional studies in which the second target is backward masked.

Comparison between the present work and earlier studies, however, is complicated by procedural and methodological differences. Among the more notable procedural differences is the dynamic adjustment used in the present work to maintain the level of identification of the second target within a measurable range. Clearly, if masking and task switching are to be compared directly, all other factors, notably procedural and methodological details, must remain constant. In Experiment 5, we took a first step toward this objective by replicating Experiment 1 with a single critical modification: In each of the four conditions, the second target was followed by a mask.

EXPERIMENT 5

Method

A new group of 16 subjects served in Experiment 5. The stimuli, apparatus, and procedures were the same as in Experiment 1, with the key exception that the second target was followed by a mask consisting of a digit, drawn from the same item pool as the distractors. The sequence of events on any one trial is illustrated in Figure 8. The level of performance on the second target was kept within a measurable range by the dynamic adjustment procedure used in Experiment 1.

Results and Discussion

Figure 9 shows the percentages of correct responses on the second target as a function of lag, averaged across subjects, separately for each condition. Correct identifications of the first target, averaged across lags for each condition, were letter–letter (85.8%), line–letter (88.0%), letter–line (93.9%), and line–line (92.7%). Mean individual scores on the second target were analyzed in a two-way ANOVA with one between-subjects factor (condition: letter–letter, line–letter, letter–line, and line–line) and one within-subjects factor (lag: 100, 200, 300, 500, and 700 msec). The analysis revealed a significant effect of lag [$F(4,240) = 47.87$, $MS_e = 41.36$, $p < .01$], and a significant interaction between lag and condition [$F(12,240) = 10.62$, $MS_e = 41.36$, $p < .01$]. Separate analyses carried out in each of the four conditions yielded significant effects of lag in every case [letter–letter, $F(4,60) = 39.50$, $MS_e =$

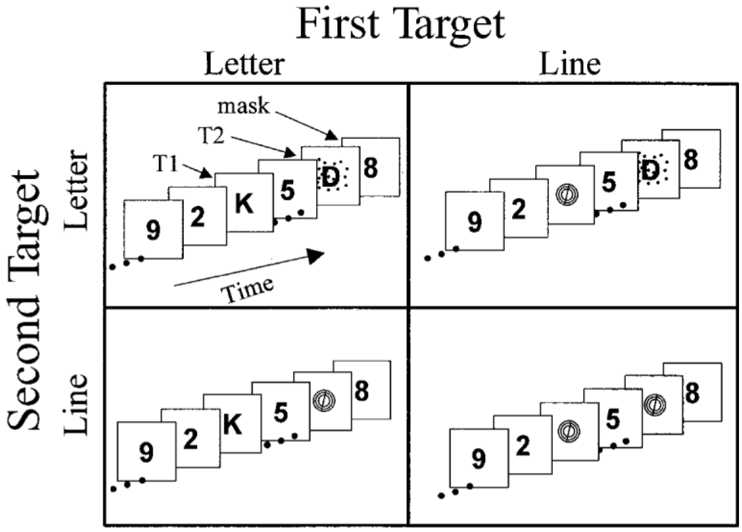

Figure 8. Schematic representation of the sequence of events in each of the four conditions in Experiment 5. T1, first target; T2, second target.

56.39, $p < .01$; line–letter, $F(4,60) = 15.89$, $MS_e = 49.77$, $p < .01$; letter–line, $F(4,60) = 5.24$, $MS_e = 31.05$, $p < .01$; line–line, $F(4,60) = 4.15$, $MS_e = 28.24$, $p < .01$].

An AB deficit was obtained in each of the four conditions in Experiment 5, regardless of task switching, whether or not the second target was an overlearned stimulus. This pattern of results differs sharply from that obtained in Experiment 1 (Figure 2), which comprised the same four conditions as in Experiment 5 except for a trailing mask after the second target. Comparison of Experiments 1 and 5 (Figures 2 and 9) reveals both differences and similarities.

A glimpse into the coding of overlearned stimuli can be gained by comparing Figures 2B and 9B. The results in Figure 2B do not exhibit an AB deficit following a switch from a line to a letter. In accounting for that result, we suggested that an AB did not occur because the second target belonged to a class of overlearned stimuli that are encoded in a form that decays relatively slowly. Because decay is slow, the representation of the second target is still identifiable when processing resources are deployed. In contrast, the corresponding results in Figure 9B reveal a substantial AB deficit. In considering these opposite results, it is well to bear in mind that the conditions that produced the results in Figures 2B and 9B were identical except for a trailing mask in Experiment 5. Considered jointly, these results support two conclusions: First, the representation of the second target decayed relatively slowly (Figure 2B). Second, despite the slow rate of decay, the representation was vulnerable to masking throughout the period for which it remained unattended while the system was busy processing the first target (Figure 9B). More generally, this pattern of results suggests that overlearned stimuli are encoded in a form that, although durable, is vulnerable to masking.

Among the more prominent aspects of the results in Figure 9 is a phenomenon known as *Lag 1 sparing*. This term was introduced by Potter et al. (1998) to denote the often found result that second-target identification is virtually unimpaired at the shortest lag (Lag 1), but drops dramatically at Lags 2 and 3 before recovering at longer lags. This time course gives rise to characteristic U-

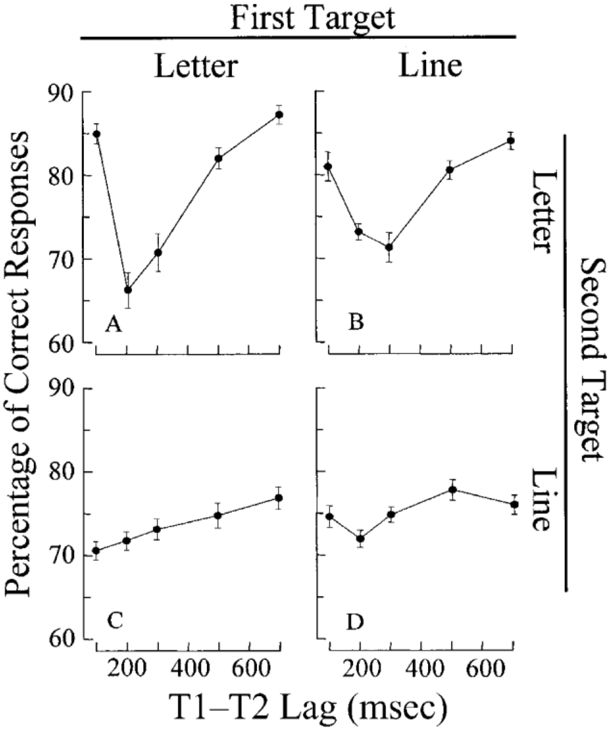

Figure 9. Mean percentages of correct responses to the second target (T2), given correct identification of the first target (T1), in each of the four conditions of Experiment 5. Error bars represent 1 standard error of the mean.

shaped curves (Chun & Potter, 1995; Raymond et al., 1992). In Figure 9, Lag 1 sparing is fully in evidence in panels A and B. In contrast, no evidence of Lag 1 sparing was obtained in either Experiment 1 (Figure 2C) or Experiment 3 (Figures 5B and 5C). The reason for these differences is not immediately apparent. It might be suggested that Lag 1 sparing occurs only when the second target is masked. But this option can be readily dismissed on the evidence in Figure 9C, in which the second target was masked, yet Lag 1 sparing failed to appear. An alternative option is that Lag 1 sparing might occur only when the second target is an overlearned stimulus. This option is supported by the presence of Lag 1 sparing in Figures 9A and 9B and its absence in Figures 2C, 5B, 5C, and 9C. But this evidence is merely suggestive. A definitive answer must await the outcome of experiments designed expressly for this purpose.

GENERAL DISCUSSION

In the present study, we asked whether a task switch between two sequential targets would be sufficient to produce an AB in the absence of a mask after the second target. Experiment 1 yielded an affirmative answer to our question when the switch was from a letter to an oriented line but not when the switch was from a line to a letter. Experiment 2 ruled out the possibility that an AB failed to appear in the line–letter condition because the line task might not have taxed the system's resources. Experiments 3 and 4 confirmed that task switching mediates the AB only when the second target does not belong to a class of overlearned stimuli such as letters or digits. Experiment 5 was a replication of Experiment 1, with the important addition of a mask after the second target. This permitted a direct comparison between task switching and masking as determinants of the AB. In the remainder of this paper, we consider the bearing of these results on our understanding of how the visual system handles rapidly sequential inputs.

Task Switching and the AB

Considered collectively, the results of Experiments 1–4 indicate that task switching can produce an AB even when the second target is not masked, provided that it is not an overlearned stimulus. Why does a task switch yield an AB deficit? In seeking an answer to this question, we need to consider what processing events are inherent in task switching. It has been suggested that task switching involves a reconfiguration of the system in order to handle the new task with maximum efficiency (Meiran, 1996; Monsell, 1996; Visser et al., 1999). Reconfiguration is part of a comprehensive, goal-directed process aimed at tuning the visual system to those attributes and characteristics of incoming stimuli that are likely to prove useful for performing the task at hand. Monsell has referred to this process as *task-set reconfiguration.* In Monsell's view, this is "a process of enabling and disabling connections between processing modules and/or re-tuning the input–output mappings performed by these processes, so that the same type of input can be processed in the different way required by the new task" (Monsell, 1996, p. 135). A similar concept was held by William James (1890/1950), who termed it *ideational preparation* or *adaptation of attention.*

System reconfiguration is likely to have occurred in the present experiments in the conditions involving task switching. Given the order in which the targets are presented, the system needs to be initially configured to optimize performance on the first target, which, therefore, is processed quickly and accurately. The extent to which the system must be reconfigured in readiness for the second target depends on the relationship between the two targets. If the second target belongs to the same category as the first, there is no need for reconfiguration. But if the category of the second target differs from that of the first target, the system will need to be suitably reconfigured if the second target is to be processed efficiently.

Within this conceptual framework, a general account of the AB can be offered on two assumptions: first, processing of the second target is delayed while the system is being reconfigured following a task switch. This source of delay is assumed to combine with the delay arising from the processing of the first target, to which Duncan, Ward, and Shapiro (1994) referred as *dwell time of attention.* Similar concepts have been proposed in other models of the AB (Chun & Potter, 1995; Jolicœur, 1999). The common theme in these models is that deployment of attention to the second target is delayed while the first target is being processed. The second assumption is that the representation of the second target undergoes progressive decay during the combined delays arising from task switching and first-target processing. A model based on these assumptions is illustrated in Figure 10. Specifically, Figure 10A illustrates the failure to obtain an AB deficit in the absence of a task switch. Figure 10B illustrates the increased likelihood of obtaining an AB deficit following a time-consuming task switch.

We first consider Figure 10A. The diagonal lines indicate the temporal course of decay of the representation of the second target, separately for overlearned and nonoverlearned stimuli. The legibility threshold (segmented horizontal line) denotes the minimum level of clarity (signal-to-noise ratio) necessary for identifying the second target: The target will be perceived accurately provided that its representation has not decayed below the legibility threshold before it is attended. The vertical dotted lines indicate *time of contact* (t_c)—namely, the time at which attentional resources are deployed to the second target. The specific value of t_c is determined by the intertarget lag. Thus, the delay of processing the second target is long when lag is short, reflecting a relatively long dwell time of attention. In Figure 10A, this is illustrated by t_{c1} for a lag of 100 msec. In contrast, when lag is long, the dwell time of attention is correspondingly shorter. Therefore, t_c is located further toward the left on the time axis, indicating shorter processing delays (e.g., t_{c7} for a lag of 700 msec). Of major importance to the present thesis is the fact that all the vertical dotted lines in Figure 10A cross the decay functions at points above the legibility threshold, whether or not the second target is an overlearned stimulus. This means that

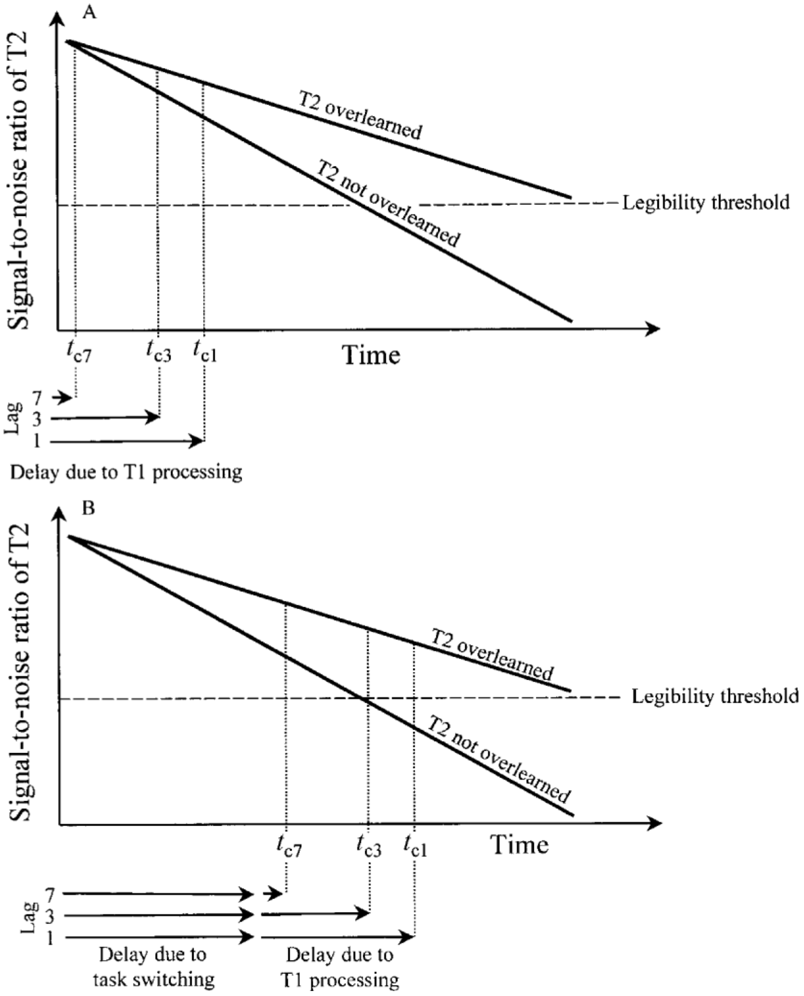

Figure 10. Schematic representation of the interplay between delay of processing and fading trace of the second target as determinants of the accuracy of second-target reporting. The symbol t_c refers to the time at which attention is deployed to the second target: t_{c1}; lag = 100 msec; t_{c3}, lag = 300 msec; t_{c7}, lag = 700 msec. (A) Conditions not involving a task switch between the two targets. (B) Conditions involving a task switch between the two targets. See text for an explanation.

attention is deployed while the representation is still legible and, therefore, that the second target will be perceived accurately at all lags with no evidence of an AB deficit. This corresponds to the results obtained in all the no-switch conditions in Experiments 1, 3, and 4 (Figures 2A, 2D, 5A, 5D, 7A, and 7D).

Figure 10B illustrates the same events as Figure 10A except that the procedure involves a task switch between the two targets. The system reconfiguration associated with task switching introduces an additional processing delay that causes all values of t_c to be located further toward the right on the time axis. An important thing to notice in Figure 10B is the distinction between the *overlearned* and *not-overlearned* decay functions. Notably, some of the vertical dotted lines cross the not-overlearned decay function at points below the legibility threshold. For example, t_{c1} intersects the not-overlearned decay line at a point well below threshold. This means that the probability of identifying a not-overlearned second target correctly at a lag of 100 msec is relatively low. In contrast, t_{c7} intersects the not-overlearned decay function at a point above the legibility threshold, indicating that the probability of a correct response at a lag of 700 msec is relatively high. In brief, the probability of correctly identifying a not-overlearned second target is low at Lag 1 and high at Lag 7. This is the classical AB pattern, corresponding to the results obtained in the switch conditions of Experiments 1 and 3 involving not-overlearned second targets (Figures 2C, 5B, and 5C).

The picture is substantially different for overlearned targets. All the vertical dotted lines in Figure 10B cross the overlearned decay function at points above the legibility threshold. This means that attention can be deployed to an overlearned second target while its representation is still legible. Thus, the probability of correctly identifying an overlearned second target is relatively high at all lags, even when the procedure involves task switching. This corresponds to the absence of AB deficits in the switch conditions in Experiments 1 and 4 when the second target was an overlearned stimulus (Figures 2B, 7B, and 7C).

A final point needs to be made regarding the relationship between the AB and stimuli below the legibility threshold. An AB is produced when the probability of a stimulus' falling below the legibility threshold varies as a function of lag. As is illustrated in Figure 10A, this occurs when the stimulus representation decays during a lag-related delay of processing. However, this is not the case when the target is made illegible by the addition of noise dots, as was done in the dynamic adjustment procedure used in the present experiments. Namely, on any given trial in which the random configuration of the noise dots renders the target illegible, an error will be recorded at the particular lag tested on that trial. This will reduce accuracy of identification evenly across all lags and will, therefore, not produce the lag-dependent deficit that is the signature of the AB.

The Role of Masking

The results of Experiment 5, in which the second target was backward masked, differed markedly from those of the preceding experiments, which investigated the effects of task switching on the AB without masking of the second target. In a nutshell, task switching alone produced an AB only if the second target was not an overlearned stimulus; in contrast, masking invariably produced an AB, regardless of switching or overlearning, thus replicating the standard finding in the AB literature (Brehaut et al., 1999; Chun & Potter, 1995; Jolicœur, 1999; Raymond et al., 1992).

This pattern of results strongly suggests that there are at least two mechanisms capable of producing an AB deficit. One is decay of the representation of the second target over processing delays mediated by such events as task switching, as is illustrated in Figure 10B. The other is backward masking of the second target, a factor ubiquitous in the AB literature. We have proposed elsewhere that masking produces an AB deficit through a process called *object substitution* (Di Lollo et al., 2000; Enns & Di Lollo, 1997).

In object substitution, the representation of the mask is said to replace that of the target if the mask arrives while the target is unattended. These are precisely the conditions that arise in conventional AB studies. It is generally agreed that the second target remains unattended while processing resources are devoted to the first target (Chun & Potter, 1995; Duncan et al., 1994; Giesbrecht & Di Lollo, 1998; Jolicœur, 1999; Shapiro, Raymond, & Arnell, 1994). Therefore, if a trailing stimulus is presented during this period of inattention, the second target will be masked and an AB deficit will occur.

In this event, an AB deficit occurs because it is the mask, not the second target, that eventually gains access to later processing stages. Studies in which the nature of the errors made when the second target is misidentified has been examined confirm this prediction (Chun, 1997; Isaak, Shapiro, & Martin, 1999). The most common misidentification of the second target arises from the reporting of the next item instead, suggesting that the trailing item in the RSVP stream replaces the second target, while the latter is unattended.

Classification and Terminology

We have argued that there are at least two ways in which an AB deficit can arise. One is through object substitution, which occurs when a mask arrives while the second target is unattended. The other is through excessive decay of the second target's representation during a period of inattention, a period that is significantly increased by task switching. This leads to a question of classification and terminology: Do the deficits obtained with the two procedures belong to the same class of events? Or are the procedures sufficiently different from one another to justify different terms and classifications for the ensuing deficits? For example, should the term AB be reserved for the deficit that occurs when the second target is masked, and another term such as *dual-target deficit* be used when the second target is not masked and the procedure involves a task switch?

To be useful, a differential classification must employ clear criteria for distinguishing the two types of procedures and the related deficits. In the absence of such criteria, a differential classification would be premature. We believe this to be the case for the two procedures outlined above, because both share a single critical factor—namely, a temporal delay between the onset of the second target and the time at which attention can be deployed to it. On the assumption that the delayed representation is vulnerable to masking, a second-target deficit will arise either if a mask is presented during the delay or if the delay is sufficiently long to cause the target's representation to decay beyond recognition. In this scheme, the delay caused by the requirement to process the first target and the delay caused by a task switch are seen as functionally equivalent ways of mediating the AB. Therefore, task switching is not, in itself, an essential factor, but is merely one way of increasing the all-important delay, during which the target's representation can be masked or can continue to decay.

Procedures other than task switching, such as increasing the time required to process the first target (see, e.g., Visser & Bischof, 2000) can be used to increase the delay and produce an AB in the absence of a trailing mask. In this scheme, an AB deficit can be obtained without a task switch, provided either that the second target is backward masked or that a long delay is generated by some other means so that the representation decays beyond recognition by the time attention is deployed. We believe the general term *attentional blink* to be appropriate in this case, because, in both instances, the second-target deficit is mediated by a brief period of inattention. It is perhaps worth noting that the present unitary conception of the second-target deficit is akin to the general notion of a central bottleneck proposed by Jolicœur and Dell'Acqua (1998, 1999) and differs in some details from the account of Potter et al.

(1998), who regarded the AB as a kind of interference distinct from task switching. Clearly, more evidence is needed to resolve all the questions that surround the nature and even, perhaps, the number of processing bottlenecks that contribute to the AB.

Concluding Remarks

Several issues arising from the present work need to be explored further. An initial step in that direction was taken in Experiment 5, which, when compared with Experiment 1, revealed a number of issues as yet unresolved.

One such issue is lag 1 sparing, which was in evidence only when the second target was a letter that was backward masked (Figures 9A and 9B). We noted in the Discussion section of Experiment 5 that an account of the presence of lag 1 sparing in Figures 9A and 9B, and its absence from Figures 9C and 9D (as well as from all instances of AB deficits obtained with task switching alone), is unlikely to be resolved without further study. A second issue is illustrated in Figure 9: The magnitude of the AB deficit appeared to be greater when the second target was a letter (Figures 9A and 9B) than when it was an oriented line (Figures 9C and 9D). It is possible that the trailing digit might have made for a more effective mask when the second target was a letter than when it was a line; in that case, a new masking configuration might yield a different outcome. Or it could be that, under masking conditions, overlearned stimuli yield greater AB deficits than do not-overlearned stimuli. Additional evidence will be required for this issue to be resolved.

Finally, the present distinction between overlearned and not-overlearned stimuli is clearly in need of elaboration. There is no question that the AB deficit produced by the class of stimuli exemplified by letters and digits differs markedly from that produced by the class of stimuli exemplified by lines and boxes. The need now is to identify the critical attributes that separate the two classes of stimuli from one another. In our earlier discussion, we distinguished between the two classes on the basis of overlearning and used that attribute as a denotative term. But, as has been mentioned above, the two classes of stimuli differ along other dimensions, including meaningfulness and complexity. An examination of such distinguishing characteristics could yield findings whose importance would go beyond the immediate confines of the AB: It may reveal how different classes of stimuli are encoded within the visual system and how this affects the course of events in visual information processing.

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