Journal of Experimental Psychology:
Human Perception and Performance
2009, Vol. 35, No. 2, 338–351

0096-1523/09/$12.00 DOI: 10.1037/a0013555

Reevaluating Encoding-Capacity Limitations as a Cause of the Attentional Blink

Roberto Dell'Acqua
University of Padova

Pierre Jolicœur
University of Montreal

Roy Luria and Patrik Pluchino
University of Padova

A number of researchers have emphasized the role of distractors intervening between successive targets as the primary determinant of the attentional blink (AB) phenomenon. They argued that the AB is abolished when 3 or more targets are displayed as temporally contiguous items in rapidly presented serial sequences. In 3 experiments, the authors embedded 1-, 2-, or 3-digit targets among letter distractors in rapidly presented visual sequences. Across the experiments, both the number of targets and the lag between them were manipulated, producing different proportion of trials in which 3 temporally contiguous targets were presented in the test session. Evidence of an AB affecting the targets that followed the first target in these sequences was found in each experiment when the probability of a given target report was conditionalized on a correct response to the preceding targets, thus reinforcing the notion that some form of capacity limitation in the encoding of targets plays a central role in the elicitation and modulation of the AB effect.

Keywords: Attentional blink, lag-1 sparing, multitarget RSVP streams

The term *attentional blink* (AB; Raymond, Shapiro, & Arnell, 1992) refers to a psychological phenomenon that can be observed when two visual targets, usually embedded among distractors, are presented in close temporal succession, in a technique known as rapid serial visual presentation (RSVP). When the temporal interval between the two targets is shorter than about 500 ms, the identification of the first target (T1) is good, whereas the identification of the second target (T2) is often poor. A related phenomenon, termed *lag-1 sparing* (Potter, Chun, Banks, & Muckenhoupt, 1998), refers to the fact that T2 is often preserved from the AB when it is presented within about 100 ms of T1.

Several models proposed in the past share a set of common assumptions about the potential causes of the AB and lag-1 sparing effects (see Dell'Acqua, Jolicœur, Pascali, & Pluchino, 2007, for an overview). One of these assumptions concerns the critical role played by T1 in the generation of these phenomena. Succinctly, the AB is hypothesized to result from a capacity limitation in the encoding of targets into visual short-term memory (VSTM; e.g., Chun & Potter, 1995; Jolicœur, 1998; Jolicœur & Dell'Acqua, 1998; Visser, 2007; Vogel, Luck, & Shapiro, 1998). Processing capacity allocated to T1 cannot be used for T2 during some period of time, leading to a loss of accuracy in reports of T2, if T2 is followed by a trailing mask (Dell'Acqua, Pascali, Jolicœur, & Sessa, 2003; Giesbrecht & Di Lollo, 1998; Jolicœur, 1999; Ptito, Arnell, Jolicœur, & MacLeod, in press). The selection of T1 from distractors is made possible through the activation of an attention filter that reacts promptly to T1 onset, allowing T1 to be selected efficiently for further processing, but reacts sluggishly to T1 offset, allowing the inclusion of T2 in the attention episode triggered by T1 when the two targets are temporally contiguous (e.g., Shapiro, Raymond, & Arnell, 1994; Shih, 2008).

Selection Control and Distractor-Induced "Bouncing" Reactions

A different perspective on the cause of AB and lag-1 sparing phenomena has recently been proposed by Di Lollo, Kawahara, Shahab Ghorashi, and Enns (2005) and by Olivers, van der Stigchel, and Hulleman (2007). In these studies, target identification accuracy for sets of contiguous targets was compared with target identification accuracy for sets in which the sequence of the targets was discontinued by a distractor. The case of interest emerged when as many as three targets were presented. If the targets were contiguous, T3 benefited from a protracted form of sparing effect: T3 report accuracy was as good as T1 report accuracy. The sparing effect was absent, however, if T2 was replaced with a distractor. In that case, T3 report accuracy was substantially worse than T1 report accuracy, suffering from an AB effect. The results of Di Lollo et al. (2005; see also Kawahara, Enns, & Di Lollo, 2006; Kawahara, Kumada, & Di Lollo, 2006) and Olivers et al. (2007) argue against the centrality of capacity limitations in the processing of T1 as the triggering factor of both the AB effect and lag-1 sparing. In contrast, as these authors have argued, the crucial element causing the AB effect appears to be the distractor trailing T1.

Roberto Dell'Acqua, Department of Developmental Psychology and Center for Cognitive Science, University of Padova, Padova, Italy; Pierre Jolicœur, Department of Psychology, University of Montreal, Montreal, Quebec, Canada; Roy Luria and Patrik Pluchino, Center for Cognitive Science, University of Padova.

Correspondence concerning this article should be addressed to Roberto Dell'Acqua, Center for Cognitive Science, Via Venezia 8, Padova 35131, Italy. E-mail: dar@unipd.it

Di Lollo et al. (2005) proposed that the AB is brought about by a temporary loss of control (TLC) over attentional settings required to select targets. According to this proposal, subjects are initially set to filter the incoming information on the basis of the target-defining features. Maintaining this attentional set, however, requires constant monitoring on the part of a central processor that momentarily sways the resources needed to control the input attentional filter toward consolidation mechanisms upon detection of T1. If the TLC occurs when the RSVP stream contains a series of contiguous targets, the loss of control does not hamper the encoding of further targets. In contrast, if the stream contains a discontinued series of targets (e.g., T1–D– . . .), attention settings are exogenously reset in favor of the distractor, at the expenses of successive targets.

Olivers et al. (2007) provided an interpretation of the protracted sparing that is different from the TLC proposal and that has been recently implemented in a computational model called *boost and bounce* (BB) by Olivers and Meeter (in press). Olivers and colleagues proposed that a transient excitatory (boost) attentional response is elicited by T1, which feeds back with a delay of about 100 ms from higher to lower stages of target visual processing (e.g., Lamme & Roelfsema, 2000). When T1 is followed by other targets, the excitatory response allows targets beyond T1 to be encoded in VSTM with no impediments other than those imposed by VSTM capacity. However, when T1 is followed by a distractor, the boosting response, peaking at the time of the distractor presentation (i.e., 100-ms post-T1), is immediately counteracted by a suppressive (bouncing) response that keeps distracting information from accessing VSTM (see also Olivers, 2007).

The Present Study

The scope of the present study was to revisit the issue of protracted sparing in the AB paradigm in light of two considerations. The first consideration concerned the structural organization of the RSVP streams adopted in the Di Lollo et al.'s (2005) and Olivers et al.'s (2007) studies, which were characterized by a particularly compressed temporal distribution of targets embedded in RSVP streams. In these multitarget designs, the lag between successive targets was generally shorter than in standard RSVP designs, given that the targets were always consecutive stimuli, or nearly so (i.e., in most cases, the lag was always 1). As presently formulated, the TLC (Di Lollo et al., 2005) and BB (Olivers & Meeter, in press) accounts of the AB do not make any particular commitments to specific structural conditions leading to the protracted sparing. The tenet of such accounts is that independently of variations in (a) the number of targets (with the proviso to keep it below the VSTM capacity limit) embedded in RSVP streams, (b) the overall length of the RSVP stream in which targets are embedded, and (c) the subjects' knowledge about the number of targets displayed in a particular RSVP stream, the protracted sparing should be found whenever there are no distractors discontinuing the presentation of a set of successive targets. However, all such variations have been shown to exert modulatory effects on the AB and lag-1 sparing phenomena in standard two-target designs. Akyürek, Riddell, Toffanin, and Hommel (2007) have shown variations in reversal errors in report of successive T1 and T2, accompanied by a modulation of the P3 component time-locked to T1 depending on the phenomenological experience subjects had of the rate of presentation of items included in RSVP streams. MacKay and Juola (2007) and Martens and Johnson (2005) observed a reduction of the AB when subjects were cued in advance about the lag separating T1 and T2 in an upcoming RSVP stream. In general, these studies suggest that a certain level of uncertainty about the structural properties of the RSVP streams subjects are exposed to may be detrimental in post-T1 targets processing, and on this empirical evidence, we deemed it appropriate to investigate whether introducing uncertainty in a series of multitarget designs could have analogous modulatory effects on the protracted sparing found in prior multitarget designs.

The second consideration concerned the analysis procedure used in these past studies to determine the presence or absence of the protracted sparing. One traditional procedure used in standard two-target designs is to score accuracy for T2 only for trials in which T1 is reported correctly (i.e., T2 correct conditional on a correct T1, or T2|T1). This ensures that the trials contributing to the estimation of the AB are equated in terms of processing load (i.e., T1 was processed correctly) and in terms of memory load (i.e., VSTM load was 1, given the correct report of T1). We will refer to the practice of conditionalizing accuracy for T2 on a correct performance to T1 as the *within-trial contingency (WTC) principle*. When there are only two targets, it appears as though the application of the WTC principle is not critical (Dell'Acqua et al., 2007; Jolicœur, 1998, 1999). The WTC principle is likely to have more importance in experiments involving more than two targets. The processing load associated with the first two targets (T1 and T2) could have a large impact on the processing of a third target (T3), and differences across trials in which both T1 and T2 are correctly processed—versus trials in which T1, T2, or both are missed—could be substantial.

One of our concerns about the studies by Di Lollo et al. (2005) and Olivers et al. (2007) arose from noticing that in the analyses of their results, the WTC principle was not applied in the way we have just described. Di Lollo et al. (2005) scored T3 report treating the probabilities of reporting T1, T2, and T3 as independent probabilities. In this case, one possibility was that a portion of trials in which T3 was reported correctly in triplets of contiguous targets were trials in which T1 was missed, T2 was missed, or even both T1 and T2 were missed, leaving significant processing capacity to encode T3. The same argument applies to Olivers et al.'s (2007) work, in which performance with successive targets was conditionalized on T1 correct responses only.[1] A secondary aim of the present work was to test whether a protracted form of sparing for the last of three consecutive targets (T3) could be replicated following a correct application of the WTC principle by conditionalizing the probability for T3—p(T3)—on the correct report of both T1 and T2.

[1] In addition to conditionalizing Tn (when $n > 1$) report accuracy on the basis of T1 report, Olivers et al. (2007) proposed an elegant algorithm for correcting a given target report for the probability of guessing that we did not adopt in any of the present analyses. Note, however, that the application of the WTC principle—as discussed in an earlier section of this article—equates trials in terms of the number of targets correctly reported at the end of each trial. This implies that the probability of guessing a given target across the various conditions that we examined was equivalent.

Experiment 1

One, two, or three digits were embedded in RSVP sequences of letters at unpredictable and independently varying lags. The subjects' task was to report the digits at the end of the trial, without speed pressure. Experiment 1 gave us two opportunities. The first was to monitor the results of a multitarget design in which target report was mutually constrained by a correct response to each target preceding the one monitored in the different conditions implemented in Experiment 1,[2] that is, whether the protracted sparing could be found following the correct application of the WTC principle. The second opportunity was to examine whether the protracted sparing could still be observed, as the TLC and BB accounts would predict, when some form of uncertainty about the number of targets and the lag between them were varied unpredictably from trial to trial.

Method

Subjects. A total of 60 university students (31 females and 29 males; age range, 20–33 years) from the University of Padova participated in the following three experiments (20 subjects each). The subjects were paid or received course credit for their participation. All subjects had normal or corrected-to-normal acuity, and none reported a history of neurological disorders.

Stimuli. The stimuli were 22 letters of the English alphabet (all except the letters B, I, O, and Z) and the digits 2–9. These characters were displayed in light gray (34 cd/m^2) on a uniform black background (6 cd/m^2) on a cathode ray tube computer screen placed at about 70 cm from the subject's eyes. Luminance was measured with a Model LS-100 luminance meter (Konica Minolta, Ramsey, NJ). All characters fit in a square portion of the screen with a side of 0.95°. The RSVP technique was used to display the characters, each of which was displayed for 84 ms at the center of the screen and was immediately replaced by the next item (interstimulus interval [ISI] = 0 ms). We generated each RSVP stream of stimuli by randomly selecting letters without replacement from the list of 22 letters. In three-digit trials, the lag between T1 and T2 and the lag between T2 and T3 were manipulated independently and were varied at three possible levels through the interleaving of 0- (lag = 1), 2- (lag = 3), or 6- (lag = 7) letter distractors between T1 and T2 and between T2 and T3. No digit or letter was ever repeated in a given RSVP stream. The number of letters preceding T1 was varied randomly from two to five across trials. In two-digit trials, T3 was replaced with a letter distractor. In one-digit trials, both T2 and T3 were replaced with letter distractors. Each RSVP stream ended with between two and four distractors following the last target.

Procedure. Each trial began with the presentation of a plus sign at the center of the screen. The trial started with a space bar press, which caused the plus sign to disappear. After a fixed blank interval of 800 ms, the RSVP stream was displayed. A question was displayed 800 ms after the end of the RSVP stream, inviting subjects to report the digit(s) by pressing the corresponding keys on the numeric keypad of the computer keyboard or "0" if no digit was seen. The instructions mentioned explicitly that the order in which the responses were given (when more than one response was made) was not important. Responses were made without speed pressure. Subjects performed seven experimental blocks of 27 trials. One block of 27 practice trials preceded the series of experimental blocks. Streams with one digit, two digits, and three digits were equally likely to be presented within each block of trials.

Results

Analysis. Because of their crucial importance in the present context and for the sake of brevity, this and all subsequent analyses focused only on three-digit trials. Furthermore, unless otherwise stated, the results involving T2 report considered only trials in which T1 was correctly identified, and the results involving T3 considered only trials in which both T1 and T2 were correctly identified, in accordance with the WTC principle. We analyzed the proportion of correct responses to each target in three-digit trials separately using an analysis of variance (ANOVA) in which the T1–T2 lag and the T2–T3 lag were treated as within-subject factors. The order in which subjects indicated the identity of targets was not taken into account.

The proportion of correct responses to T1 was .72, .90, and .90 at the T1–T2 Lags 1, 3, and 7, respectively. The lower proportion of correct responses to T1 at T1–T2 Lag 1 relative to the other two longer lags resulted in a significant effect of T1–T2 lag, $F(2, 38) = 23.1$, $\eta_p^2 = .549$, $p < .001$. No effect of the T2–T3 lag was detected on T1 report accuracy. A summary of the proportion of correct responses to T2 as a function of the T1–T2 lag and as a function of the T2–T3 lag is graphed in Figure 1. The ANOVA indicated a significant effect of T1–T2 lag, $F(2, 38) = 27.4$, $\eta_p^2 = .590$, $p < .001$; a significant effect of T2–T3 lag, $F(2, 38) = 14.3$, $\eta_p^2 = .430$, $p < .001$; and a significant interaction between these factors, $F(4, 76) = 4.3$, $\eta_p^2 = .184$, $p < .005$. As is clearly illustrated in Figure 1, the correct responses to T2 were characterized by a classic U-shaped distribution across T1–T2 lags (i.e., an AB effect), with the exception of the condition of the shortest T2–T3 lag, in which the recovery from the AB at the longest T1–T2 lag was only partial relative to the other two T2–T3 lag conditions.

The proportion of correct responses to T3 as a function of the T1–T2 lag and as a function of the T2–T3 lag is graphed in Figure 2. Overall accuracy for T3 decreased sharply as the lag between T1 and T2 was reduced, $F(2, 38) = 9.4$, $\eta_p^2 = .331$, $p < .001$. The lag between T2 and T3 resulted in a typical AB function for T3 accuracy, $F(2, 38) = 23.5$, $\eta_p^2 = .553$, $p < .001$. The interaction between these factors was not significant, $F(4, 76) = 1.7$, $p > .15$, indicating that we observed generally the same AB function of T2–T3 lag for each T1–T2 lag. An additional set of separate analyses was conducted for T3 report accuracy. In one analysis, T3 report accuracy at the shortest T2–T3 lag was compared across

[2] Two prior attempts at constraining target report probability based on the accurate response to preceding targets in a three-target RSVP design have been made by Chun and Potter (1995) and by Shapiro, Driver, Ward, and Sorensen (1997). Though these attempts were somewhat analogous to the present study, it must be noted that Chun and Potter (1995) examined only p(T2|T1) and p(T3|T2) independently. As far as T3 report is concerned, in the present case, we considered p(T3|T1^T2), which represents a dependent variable that was not computed nor discussed by these authors. Shapiro et al. (1997) analyzed their results following the application of the WTC principle but did not vary systematically the lag between successive targets as we did in the present investigation.

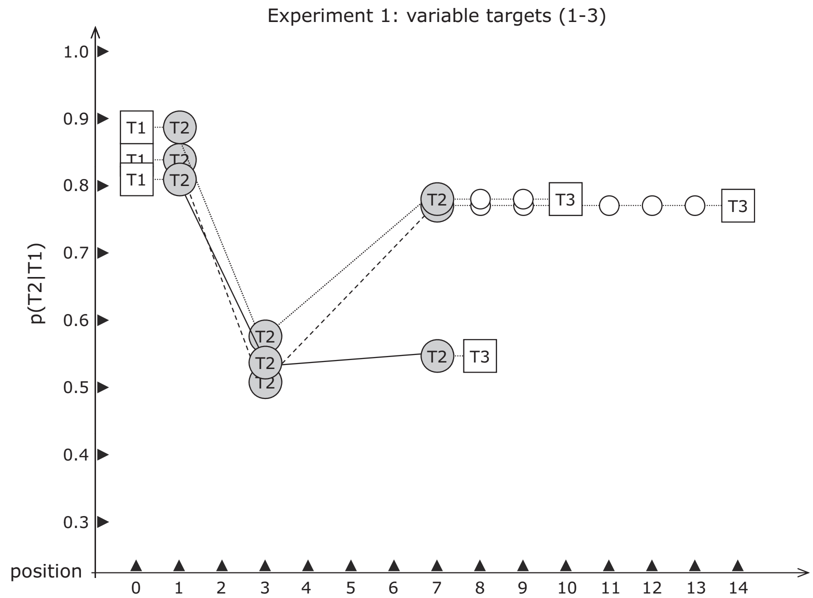

Figure 1. Results of Experiment 1. Gray circles = observed mean proportion (p) of correct responses to Target 2 (T2) contingent on correct response to Target 1 (T1), or p(T2|T1). White squares = positions occupied by T1 and Target 3 (T3; height in graph does not represent accuracy) within rapid serial visual presentation (RSVP) stream generating displayed T2 report distribution functions. White circles = letter distractors. Values on the *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

T1–T2 lags. As is evident in Figure 2, T3 report accuracy increased as T1–T2 lag was increased, $F(2, 38) = 5.8$, $\eta_p^2 = .235$, $p < .007$. In a second analysis, T3 report accuracy at the longest T2–T3 lag was compared across T1–T2 lags. The analysis revealed a significant effect of T1–T2 lag, $F(2, 38) = 3.3$, $\eta_p^2 = .148$, $p < .05$, arising from the higher T3 report accuracy at the longest T1–T2 lag relative to T3 report accuracy at the other two shorter T1–T2 lags, which did not differ significantly, $F < 1$.

Protracted sparing and the WTC principle. We compared T1 report accuracy and T3 report accuracy (mean proportion correct, represented by "p") when T1, T2, and T3 were contiguous targets. A summary of the results is shown in Figure 3 (leftmost graph). First, we compared p(T1) and p(T3), treating them as independent probabilities, that is, without applying the WTC principle (dotted line). The results of the ANOVA indicated no difference between p(T1) and p(T3), $F < 1$. In two further analyses, we compared p(T1) with p(T3|T1) and compared p(T3|T1) with p(T3|T1^T2). According to accounts based on the notion of capacity limitations (e.g., Chun & Potter, 2005; Jolicœur & Dell'Acqua, 1998), considering trials in which only T1 was reported correctly (i.e., disregarding the success in T2 report) or in which both T1 and T2 were reported correctly should produce a differential impact on the AB effect on T3. If the AB for T3 is modulated by the load imposed on mechanisms engaged to consolidate pre-T3 targets, then a larger AB for T3 should be found when trials are conditionalized on just T1 report (T3|T1) compared with accuracy not conditionalized on correct T1, and an even larger AB for T3 should be found when trials are conditionalized on both correct T1 and T2 responses (T3|T1^T2). This is because consolidation mechanisms would be taxed to a lesser extent when processing just one pre-T3 target (i.e., just T1) than when processing two pre-T3 targets (i.e., T1 and T2). These results are also summarized in Figure 3 (dashed lines and solid lines). The new ANOVAs showed that p(T3|T1) was significantly worse than p(T1), $F(1, 19) = 4.8$, $\eta_p^2 = .203$, $p < .04$, and p(T3|T1^T2) was significantly worse than p(T3|T1), $F(1, 19) = 5.3$, $\eta_p^2 = .219$, $p < .04$.

Discussion

Consider first the results from trials in which T1, T2, and T3 were contiguous targets. Protracted sparing in this condition—that is, no significant difference between accuracy for T1 and T3—was observed only when the WTC principle was not applied. In contrast, when the WTC principle was applied, accuracy for T3 was significantly lower than for T1. It should be noted that the AB for T3 increased as a function of the number of pre-T3 targets correctly reported (whether just T1, or both T1 and T2), a result that cannot be explained by either the TLC or the BB account. The two accounts are strongly predicated on protracted sparing of post-T1 targets when a set of targets is not discontinued by distractors. In striking contrast, the results of Experiment 1 raise the possibility that either a reduced level of uncertainty about the temporal or structural distribution of targets in the RSVP streams used in prior multitarget studies (Di Lollo et al, 2005; Olivers et al., 2007) or an incorrect application of the WTC principle may have been responsible for previous reports of protracted sparing.

Experiment 2

The results in Experiment 1 cannot be used to distinguish among the possible causes of the failure to find protracted sparing for T3 when the

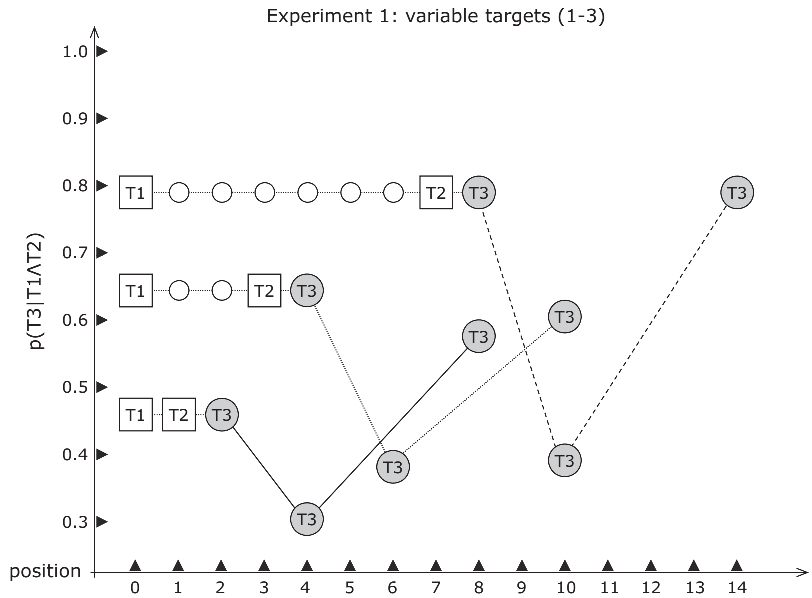

Figure 2. Results of Experiment 1. Gray circles = observed mean proportion (p) of correct responses to Target 3 (T3) contingent on correct responses to Target 1 (T1) and Target 2 (T2), or p(T3|T1ˆT2). White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T2 (height in the graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

WTC principle was applied. Although it appears reasonable to suspect that some form of uncertainty on the part of subjects may have contributed to altering the protracted sparing, the results do not make clear whether the uncertainty was generated by variations in the number of targets in the RSVP streams or by the variations of the lags between targets, given that these factors were confounded in Experiment 1.

The aim of Experiment 2 was to isolate one of the factors potentially responsible for the failure to observe the protracted sparing for T3. We systematically manipulated and controlled for the impact of variations in the number of targets on protracted sparing predicted by the TLC and BB models. Experiment 2 included two conditions. One condition, *one/two/three targets*,

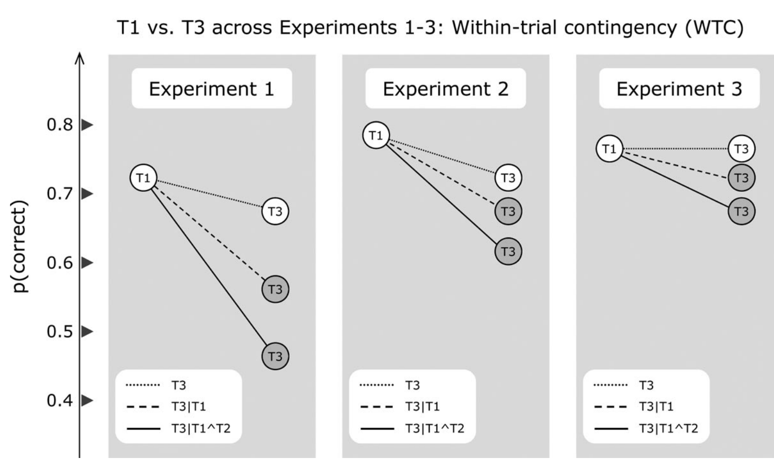

Figure 3. Results of Experiments 1–3. Observed mean proportion (p) of correct responses to Target 1 (T1) and Target 3 (T3; Target 2 = T2; see labels inside white boxes) in three-digit trials in which targets were temporally contiguous. Results are shown as function of type of algorithm subtended in application of within-trial contingency (WTC) principle. Dotted lines = T1–T3 report functions generated in trials in which WTC principle was not applied (unconditional T3). Dashed lines = T1–T3 report functions generated in trials in which WTC principle was applied only partially (T3|T1). Solid lines = T1–T3 report functions generated in trials in which WTC principle was applied fully (T3|T1ˆT2). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

was a replication of Experiment 1, in which the number of targets in the RSVP streams was varied unpredictably. The other condition, *always three targets,* contained only trials with three targets. This manipulation was performed with a within-subjects design, which allowed us to determine whether the always-three-targets condition would replicate the protracted sparing for T3 found in prior work (e.g., Di Lollo et al., 2005; Kawahara et al., 2006; Olivers et al., 2007), while also allowing us to see whether the patterns of results from the one/two/three-targets condition would replicate those found in Experiment 1.

Method

The stimuli and the algorithm for the generation of the RSVP streams were identical to those used in Experiment 1. Subjects performed seven experimental blocks of 27 trials in which they were informed through written instructions that the number of target digits varied unpredictably in the RSVP streams. In each of these one/two/three-targets blocks, streams with one digit, two digits, or three digits were equally likely to be presented. A question was displayed 800 ms after the end of the RSVP stream, inviting subjects to report the digit or digits they saw by pressing the corresponding keys on the numeric keypad of the computer keyboard or "0" if no digit was seen. In the always-three-targets condition, subjects also performed seven experimental blocks of 27 trials in which they were informed through written instructions that each RSVP stream always contained three digits. A question was displayed 800 ms after the end of the RSVP stream, inviting subjects to report the digits by pressing the corresponding keys on the numeric keypad of the computer keyboard. Subjects in these trial blocks were instructed always to enter three digits as responses and to guess if necessary. The instructions mentioned explicitly that the order in which the responses were given was not important. Responses were made without speed pressure. One block of 27 practice trials preceded each series of experimental blocks in a given condition. The order in which the two series of trial blocks (one/two/three targets vs. always three targets) were performed was counterbalanced across subjects.

Results

Analysis. In a first set of analyses, we examined results from trials with three digits using an ANOVA model that considered one/two/three-targets versus always-three-targets blocks as a within-subjects variable. The ANOVA on the proportion of correct responses to T1 revealed a main effect of the T1–T2 lag, $F(2, 38) = 24.2$, $\eta_p^2 = .560$, $p < .001$, which was the reflection of the lower T1 report accuracy at the shortest T1–T2 lag (.79) relative to the other two longer lags (.89 and .89, at T1–T2 Lags 3 and 7, respectively). No other main effect or interaction was significant in this analysis (all Fs < 1), and in particular there was no interaction with type of block.

The proportion of correct responses to T2 is shown in Figure 4 as a function of the T1–T2 lag and as a function of the T2–T3 lag. The ANOVA carried out on the proportion of correct responses to T2 revealed a main effect of the T1–T2 lag, $F(2, 38) = 52.5$, $\eta_p^2 = .734$, $p < .001$; a main effect of the T2–T3 lag, $F(2, 38) = 46.0$, $\eta_p^2 = .708$, $p < .001$; and a significant interaction between these two factors, $F(4, 76) = 10.1$, $\eta_p^2 = .348$, $p < .001$. The source of the interaction is evident in Figure 4, in which a pattern

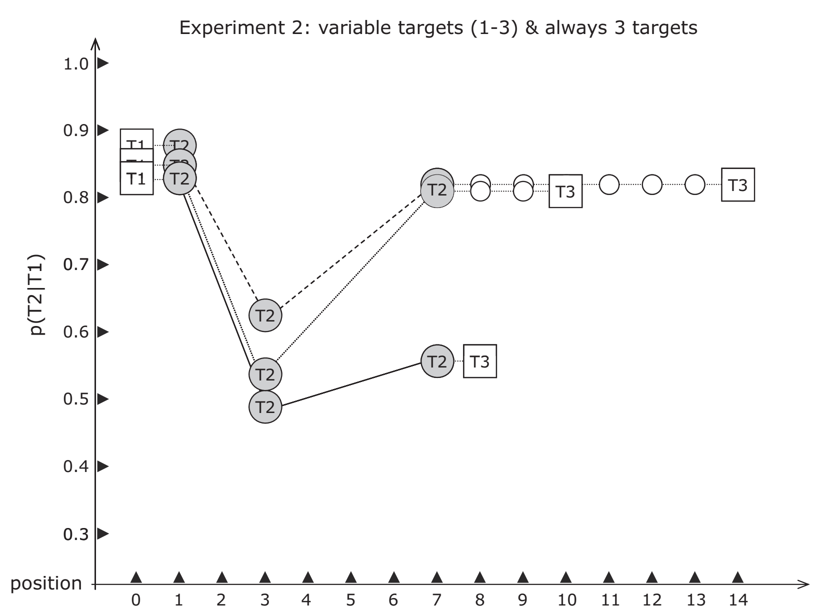

Figure 4. Results of Experiment 2. Gray circles = observed mean proportion (p) of correct responses to Target 2 (T2) contingent on correct response to Target 1 (T1), or p(T2|T1). Results were produced by collapsing data from conditions in which target number was variable (between one and three) and in which number of targets was fixed (always three). White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T3 (height in graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

of results closely resembling the results obtained in Experiment 1 can be observed. The classic U-shaped AB pattern was evident in all conditions. However, whereas the recovery from the AB was full for T2 followed by T3 presented at T2–T3 Lags 3 and 7, the recovery from the AB was only partial for T2 when the T2–T3 lag was 1. The analysis indicated a main effect of target number, $F(1, 19) = 34.2$, $\eta_p^2 = .643$, $p < .001$, reflecting an overall higher proportion of correct responses to T2 in the always-three-targets condition (.77) relative to the one/two/three-targets condition (.67). No other interaction was significant in this analysis (all $Fs < 1$).

The mean proportion of correct responses to T3 for trials with a correct report of both T1 and T2 is shown in Figures 5 and 6 for each combination of T1–T2 and T2–T3 lags. Figure 5 shows the results from one/two/three-targets blocks, and Figure 6 shows the results from always-three-targets blocks. The ANOVA revealed a main effect of T1–T2 lag, $F(2, 38) = 4.4$, $\eta_p^2 = .189$, $p < .02$; a main effect of the T2–T3 lag, $F(2, 38) = 40.0$, $\eta_p^2 = .678$, $p < .001$; and a significant interaction between these two factors, $F(4, 76) = 4.0$, $\eta_p^2 = .175$, $p < .005$. Accuracy for T3 was higher on average (.70) in always-three-targets blocks than in one/two/three-targets blocks (.52), $F(1, 19) = 43.8$, $\eta_p^2 = .697$, $p < .001$. No other factor or interaction was significant in this analysis (all $Fs < 1$).

Additional analyses were conducted on T3 report accuracy. In one analysis, T3 accuracy at the shortest T2–T3 lag was compared across T1–T2 lags. As is evident in both Figures 5 and 6, T3 report accuracy at T2–T3 Lag 1 increased as T1–T2 lag increased, $F(2, 38) = 7.4$, $\eta_p^2 = .281$, $p < .002$. In a second analysis, T3 report accuracy at the longest T2–T3 lag was compared across T1–T2 lags. The analysis indicated that the effect of T1–T2 lag on T3 report was not significant ($F < 1$).

Protracted sparing and the WTC principle. As in Experiment 1, T1 report accuracy and T3 report accuracy were compared when T1, T2, and T3 were contiguous targets. A summary of the results is shown in Figure 3 (center panel). The ANOVA comparing accuracy for T1 and T3 when the WTC principle was not applied revealed a nonsignificant difference, $F(1, 19) = 2.0$, $\eta_p^2 = .106$, $p > .15$; that is, there was a (statistical) protracted sparing for T3 (dotted line), although clearly the mean suggests a lower accuracy for T3. In two separate analyses, we compared p(T1) with p(T3|T1) and p(T3|T1) with p(T3|T1ˆT2) using a design identical to that used in Experiment 1. These results are also summarized in Figure 3 (dashed lines and solid lines). The new ANOVAs showed that p(T3|T1) was significantly worse than p(T1), $F(1, 19) = 8.1$, $\eta_p^2 = .298$, $p < .02$), and that p(T3|T1ˆT2) was significantly worse than p(T3|T1), $F(1, 19) = 14.8$, $\eta_p^2 = .439$, $p < .01$.

Discussion

As in Experiment 1, the most important findings were those when T1, T2, and T3 were contiguous targets (without intervening distractors). Following the application of the WTC principle, both in the condition of uncertainty about the number of targets (one/two/three-target blocks) and in the condition in which subjects were consistently presented with three targets (always-three-targets blocks), there was a marked difference in the probability of a correct response, p(T1) and p(T3), with p(T3) significantly worse than p(T1) in both types of blocks, the more so as the number of pre-T3 targets reported correctly was included in the conditional probability calculation. Although p(T1) was numerically greater than p(T3) even when p(T3) was not conditionalized on correct pre-T3 targets, the difference was not statistically significant,

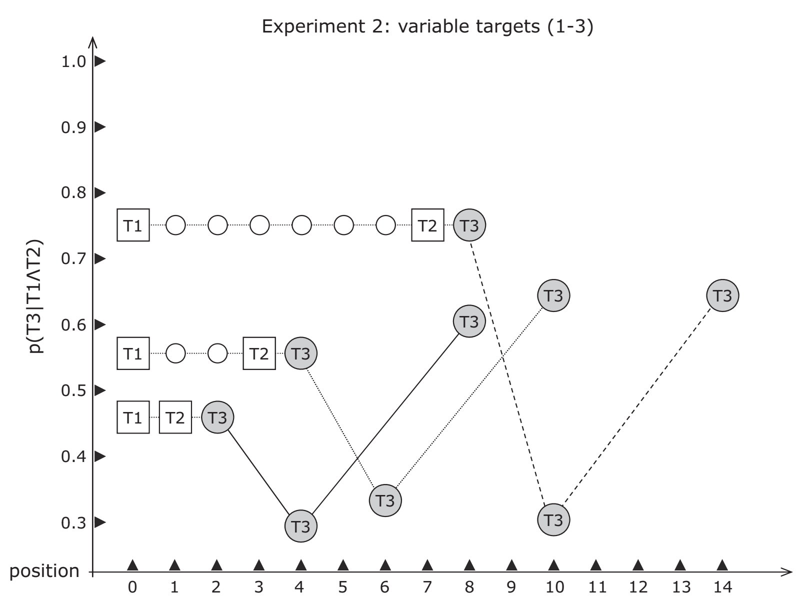

Figure 5. Results of Experiment 2 (variable-targets condition). Gray circles = observed mean proportion (p) of correct responses to Target 3 (T3) contingent on correct responses to Target 1 (T1) and Target 2 (T2), or p(T3|T1ˆT2). White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T2 (height in graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

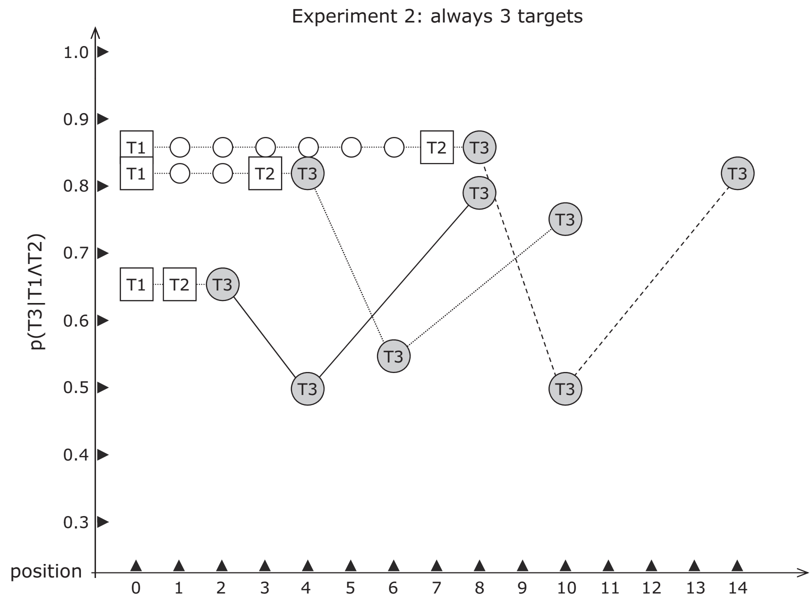

Figure 6. Results of Experiment 2 (always-three-targets condition). Gray circles = observed mean proportion (p) of correct responses to Target 3 (T3) contingent on correct responses to Target 1 (T1) and Target 2 (T2), or p(T3|T1^T2). White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T2 (height in graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

replicating previous failures to find a deficit in p(T3) when the WTC principle was not applied.

Experiment 3

One tentative conclusion that may be derived from the results of Experiment 2 is that the protracted sparing may be sensitive to unpredictable variations in the number of targets, as it was not found following a correct application of the WTC principle. In Experiment 3, all trials contained three digits. Unlike the procedure in Experiment 2, however, we manipulated the temporal distribution of targets embedded in the RSVP streams. In the *variable-lags* condition, the lags between target pairs were varied as in the three-digit trials of Experiments 1 and 2. In the *contiguous-targets* condition, the three targets were presented without any intervening distractors, reproducing exactly the conditions of prior multitarget designs in which forms of protracted sparing were observed (e.g., Di Lollo et al., 2005; Olivers et al., 2007).

In addition, the design of Experiment 3 allowed us to test encoding-capacity limitation versus simple memory load, which we could not perform in Experiments 1 and 2; these earlier experiments had too few three-target trials due to the inclusion of one-target and two-target trials. Recall that when T1, T2, and T3 were consecutive targets and targets report was scored following the application of the WTC principle, T1 report was consistently superior to T3 report. One account of these results is that targets competed for capacity-limited encoding mechanisms. However, another possibility is that such performance decrements reflected effects of memory load due to the need to maintain representations of earlier targets in memory at the time of presentation of later targets (e.g., Jolicœur & Dell'Acqua, 1998; Logan, 1978). Indeed, Jolicœur and Dell'Acqua (1998) found evidence consistent with the view that memory load effects due to maintenance of representations in memory, though smaller than load effects at encoding, were effective in modulating reaction times to an auditory stimulus presented after the to-be-encoded visual information. According to Jolicœur and Dell'Acqua (1998), one way to differentiate between encoding effects and maintenance effects is to show an interaction of load and lag; this argument is based on the theory that effects at long lags, presumably after encoding is complete, reflect mainly maintenance costs, whereas effects at short lags reflect mainly encoding costs.

We sought to differentiate between encoding and maintenance costs in Experiment 3 by examining lag effects relative to the presentation of T1 and by contrasting results from trials in which T1 was correctly reported with trials in which T1 was missed. The key empirical question was whether T3 report accuracy would be affected to a different extent by the success or failure to report T1 at a short T1–T2 lag compared with a long T1–T2 lag. If T3 report were only affected by variations in memory load induced by maintaining one target versus two targets (i.e., just T2, or T1 and T2), a null effect of the T1–T2 lag would be expected under these conditions.

Method

The stimuli and the algorithm for the generation of the RSVP streams were identical to those used in Experiment 1 and Experiment 2, except where noted in the following. All trials contained three targets. There were seven experimental blocks of 27 variable-lags trials in which the number of letter distractors separating the three target digits varied unpredictably in the RSVP streams. There were also seven experimental blocks of 27 contiguous-targets trials in which the three targets in each RSVP were always presented contiguously, and subjects were informed of this arrangement prior to testing through written instructions. A question was displayed 800 ms after the end of the RSVP stream, inviting subjects to report the digits by pressing the corresponding keys on the numeric keypad of the computer keyboard; trials were conducted without speed pressure. Subjects were instructed always to enter three digits as responses and to guess if necessary. The instructions mentioned explicitly that the order in which the responses were given was not important. One block of 27 practice trials preceded each series of experimental blocks in a given condition. The order in which the two sets of blocks were performed was counterbalanced across subjects.

Results

A first set of separate ANOVAs concentrated on the proportion of correct responses to each target in the variable-lags condition. In these analyses, T1–T2 lag and the T2–T3 lag were considered as within-subject factors. The ANOVA on the proportion of correct responses to T1 revealed a main effect of the T1–T2 lag, $F(2, 38) = 11.2$, $\eta_p^2 = .372$, $p < .001$, which reflected the lower T1 report accuracy at the shortest T1–T2 lag (.78) relative to the other two longer lags (.88 and .87, at T1–T2 Lags 3 and 7, respectively). No other main effect or interaction was significant in this analysis (all *Fs* < 1).

The proportion of correct responses to T2 is shown in Figure 7 as a function of the T1–T2 lag and as a function of the T2–T3 lag. The ANOVA carried out on the proportion of correct responses to T2 revealed a main effect of T1–T2 lag, $F(2, 38) = 59.4$, $\eta_p^2 = .758$, $p < .001$); a main effect of the T2–T3 lag, $F(2, 38) = 5.3$, $\eta_p^2 = .219$, $p < .01$; and a significant interaction between these two factors, $F(4, 76) = 2.7$, $\eta_p^2 = .125$, $p < .04$. The source of the interaction is evident in Figure 7, in which a pattern of results closely resembling the results obtained in Experiments 1 and 2 can be observed. Again, whereas the recovery from the AB was full for T2 followed by T3 presented at T2–T3 Lags 3 and 7, the recovery from the AB was only partial for T2 when the T2–T3 lag was 1.

The proportion of correct responses to T3 in the variable-lags condition (light gray circles) and in the contiguous-targets condition (dark gray circle) is shown in Figure 8. We compared the proportion of correct responses to T3 in the variable-lags condition with the proportion of correct responses to T3 in the contiguous-targets condition, after isolating trials in the variable-lags condition in which the both T1–T2 lag and the T2–T3 lag were both equal to 1 (i.e., when T1, T2, and T3 were contiguous). As can be seen in Figure 8, there was no difference between these two proportions ($F < 1$).

For results from the variable-lags blocks, the ANOVA of T3 report accuracy revealed a main effect of T1–T2 lag, $F(2, 38) = 9.9$, $\eta_p^2 = .342$, $p < .001$; a main effect of the T2–T3 lag, $F(2, 38) = 34.0$, $\eta_p^2 = .642$, $p < .001$; and a significant interaction

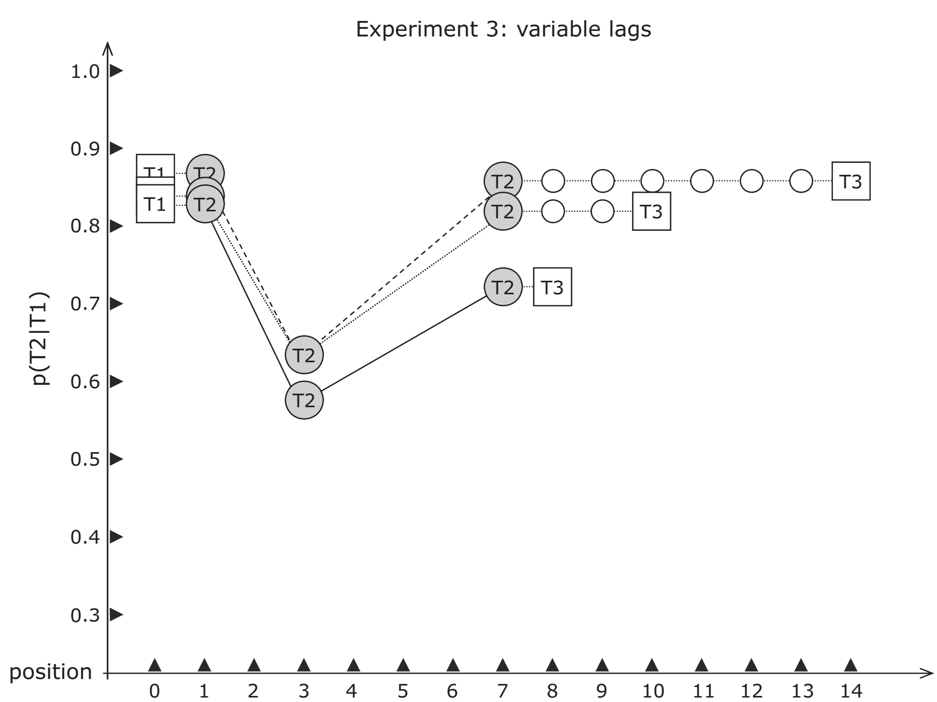

Figure 7. Results of Experiment 3 (variable-lags condition). Gray circles = observed mean proportion (p) of correct responses to Target 2 (T2) contingent on a correct response to Target 1 (T1), or p(T2|T1). White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T3 (height in graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

between these two factors, $F(4, 76) = 2.5$, $\eta_p^2 = .117$, $p < .05$. T3 report accuracy at the shortest T2–T3 lag was compared across T1–T2 lags. As is evident in Figure 8, T3 report accuracy increased as T1–T2 lag was increased, $F(2, 38) = 8.0$, $\eta_p^2 = .296$, $p < .002$. T3 report accuracy at the longest T2–T3 lag did not differ across T1–T2 lags ($F < 1$).

Testing effects of memory load versus encoding-capacity limitation. We conducted an ANOVA on T3 report accuracy including only trials in which T2 was correctly reported and considering T1 report accuracy (correct vs. incorrect) and T1–T2 lag as within-subject factors. The analysis was conducted on the data collapsed across T2–T3 lag levels and temporarily excluded from consideration the data at the intermediate T1–T2 lag. The data from 1 subject had to be eliminated to avoid empty cells. A summary of the results is shown in Figure 9. The ANOVA revealed a main effect of T1 accuracy, $F(1, 18) = 48.0$, $\eta_p^2 = .727$, $p < .001$, reflecting a generally higher T3 report accuracy when T1 was missed relative to when T1 was correctly reported, and a significant interaction between T1 accuracy and T1–T2 lag, $F(1, 18) = 5.5$, $\eta_p^2 = .232$, $p < .04$. The interaction reflected a larger effect difference in T3 accuracy for T1 report success versus failure at short T1–T2 lag than at long T1–T2 lag.

Protracted sparing and WTC principle. As in Experiments 1 and 2, we compared T1 report accuracy and T3 report accuracy when T1, T2, and T3 were contiguous targets. A summary of the results is reported in Figure 3 (rightmost panel). The ANOVA comparing p(T1) and p(T3) when the WTC principle was not applied showed a null difference between these two probabilities ($F < 1$), that is, an apparent protracted sparing for T3 (Figure 3, dotted line). In two separate analyses, we compared p(T1) with p(T3|T1) and p(T3|T1) with p(T3|T1ˆT2) using a design identical to that used in Experiments 1 and 2. These results are also summarized in Figure 3 (dashed lines and solid lines, respectively). The new ANOVAs showed that p(T3|T1) was significantly worse than p(T1), $F(1, 19) = 4.5$, $\eta_p^2 = .205$, $p < .05$, and that p(T3|T1ˆT2) was significantly worse than p(T3|T1), $F(1, 19) = 11.3$, $\eta_p^2 = .374$, $p < .01$.

To ascertain whether the order in which subjects performed the different contiguous-targets and variable-lags conditions of Experiment 3 had any effects in modulating the probability to report T1 and T3, we conducted an ANOVA on the data filtered according to the WTC principle that considered target (T1 vs. T3) and condition order (contiguous-targets condition first vs. variable-lags condition first) as within-subject factors. The ANOVA revealed a main effect of target, $F(1, 18) = 12.5$, $\eta_p^2 = .410$, $p < .003$, and a trend of subjects to perform generally worse in contiguous-targets blocks if they started with variable-lags blocks, $F(1, 18) = 3.3$, $\eta_p^2 = .154$, $p < .09$, rather than vice versa. The interaction between condition order and target, however, was not significant ($F < 1$).

Combined analysis of p(T1) vs. p(T3) across Experiments 1–3. We performed an ANOVA considering Experiment (1 vs. 2 vs. 3) as a between-subject factor and target (T1 vs. T3) and WTC principle (applied vs. not applied) as within-subjects factors. The ANOVA revealed a main effect of the WTC principle, $F(1, 57) = 39.5$, $\eta_p^2 = .409$, $p < .001$, indicating a lower general level of target report accuracy when the WTC principle was applied (.67) relative to when the WTC principle was not applied (.74) and a

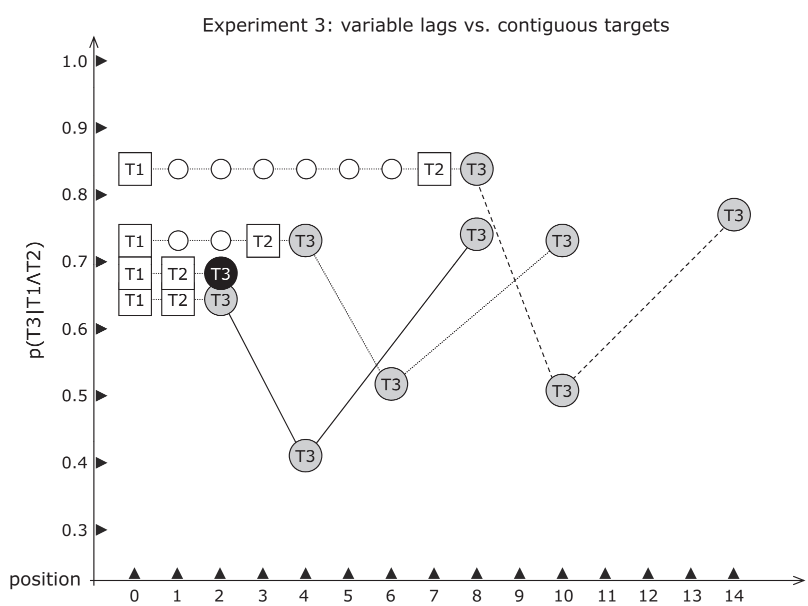

Figure 8. Results of Experiment 3. Light gray circles = observed mean proportion (p) of correct responses to Target 3 (T3) contingent on correct responses to Target 1 (T1) and Target 2 (T2), or p(T3|T1ˆT2), in variable-lags condition. Dark gray circle = mean proportion of correct responses to T3 in contiguous-targets condition. White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T2 (height in graph does not represent accuracy). White circles = letter distractors. Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

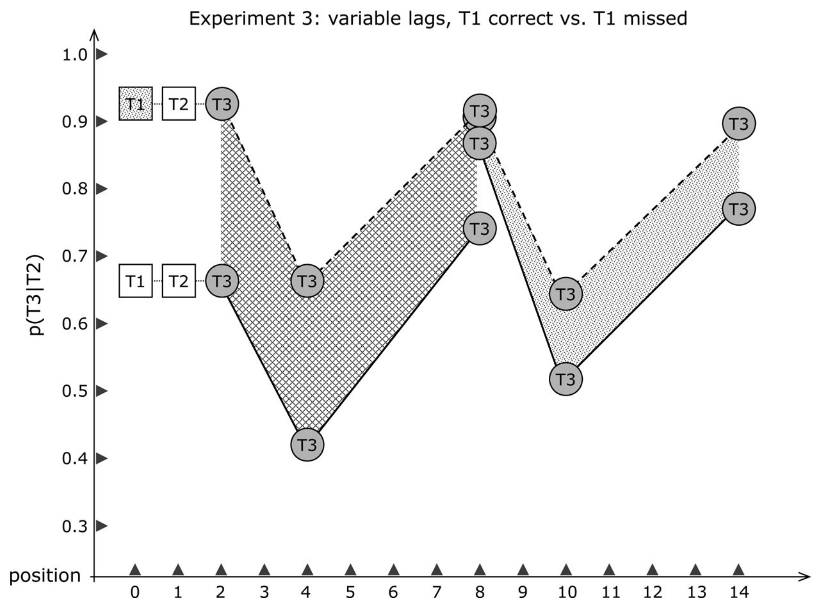

Figure 9. Results of Experiment 3. Gray circles = observed mean proportion (p) of correct responses to Target 3 (T3) contingent on correct response to Target 2 (T2), or p(T3|T2). Results are plotted as function of Target 1 (T1) response accuracy. White squares = rapid serial visual presentation (RSVP) stream positions occupied by T1 and T2 (height in graph does not represent accuracy). White square with blurred background filling = incorrect response to T1. Dashed lines = T3 report functions generated in trials in which T1 had been missed. Solid lines = T3 report functions generated in trials in which T1 had been reported correctly. Shaded areas between dashed and solid lines = impact of missing or correctly reporting T1 on T3 report accuracy as a function of the T2–T3 lag. Note that rightmost T3 functions differ from leftmost T3 functions in number of distractors intervening between T1 and T2 (i.e., left functions: T1–T2 1ag = 1; right functions: T1–T2 lag = 7. Results for T1–T2 lag = 3 were omitted to avoid crowding graph with results not considered strictly relevant.) Values on *x*-axis = positions occupied by targets in RSVP streams relative to T1 (plotted in position 0). Number of distractors preceding T1 and following T3 (not displayed in graph) was varied randomly from trial to trial.

main effect of target (T1 vs. T3, .76 vs. .65), $F(1, 57) = 13.6$, $\eta_p^2 = .192$, $p < .001$. The WTC principle factor interacted significantly with experiment, $F(2, 57) = 3.4$, $\eta_p^2 = .107$, $p < .04$, and with target, $F(1, 57) = 39.4$, $\eta_p^2 = .409$, $p < .001$. There was also a significant three-way interaction among experiment, WTC principle, and target, $F(1, 57) = 3.4$, $\eta_p^2 = .107$, $p < .04$. Figure 3 suggests that a potential source of this interaction was the reduction in the impact of the WTC principle in Experiment 3 with respect to Experiment 1 and Experiment 2. An ANOVA in which data from Experiment 3 was temporarily excluded again showed a main effect of the application of the WTC principle, $F(1, 38) = 25.9$, $\eta_p^2 = .406$, $p < .001$, and a main effect of target (T1 vs. T3, .76 vs. .62), $F(1, 38) = 10.8$, $\eta_p^2 = .222$, $p < .003$. The WTC principle interacted with target, $F(1, 38) = 25.9$, $\eta_p^2 = .406$, $p < .001$. There was, however, no main effect of experiment ($F < 1$) and no three-way interaction among the factors considered in the analysis, $F(1, 38) = 2.7$, $p > .2$. A further separate analysis was conducted on contiguous trials without the application of the WTC principle, with experiment (between-subject) and target (within-subject) as factors. The analysis detected no significant effects for these factors or interaction (highest $F = 2$, lowest $p = .12$).

Discussion

There were three key findings in Experiment 3. The first was that T3 report accuracy in trials in which the three targets were always temporally contiguous did not differ from T3 report accuracy in trials in which the T1–T2 lag and the T2–T3 lag were varied unpredictably and were both equal to 1. In other words, in terms of T3 report accuracy, it made no difference whether subjects were expecting contiguous targets or not under conditions in which the three targets were contiguous. In Experiment 2, we had ruled out uncertainty about the number of targets as having a crucial role in the failure to replicate the protracted sparing involving T3 documented in prior studies; the present findings strongly suggest that uncertainty about the temporal distribution of targets in the RSVP streams cannot be a potential factor responsible for such failure.

The second crucial finding was related to the role of VSTM load in modulating T3 report accuracy in an analysis contingent on the correct report of T2 comparing trials in which T1 was missed with trials in which T1 was correctly reported. T3 report accuracy was indeed lower when T1 was reported correctly, but most important, this effect was larger at short T1–T3 lags than at long T1–T3 lags, suggesting that at least part of the effect was a reflection of encoding-capacity limitations rather than of memory maintenance costs (Jolicœur & Dell'Acqua, 1998).

The third finding emerged from the combined analysis of Experiments 1–3 considering the impact of the application of the WTC principle in the comparison between p(T1) and p(T3). The analysis revealed a reduced impact of the WTC principle when three targets were invariably presented in the RSVP streams relative to the impact observed in Experiments 1 and 2, and this suggests that a reduced level of uncertainty on the part of subjects about the structural properties of the RSVP streams may actually have had a beneficial effect on T3 report accuracy in these circumstances. The analysis, however, also indicated a residual AB on T3 when the WTC principle was applied, both partially and in full form. This finding is all the more important if one considers that Experiment 3 was designed to replicate closely the conditions described by Di Lollo et al. (2005) and Olivers et al. (2007).

General Discussion

Summary and Comparison

Across the present experiments, we manipulated the level of uncertainty along two dimensions—the target–target lag and the number of targets—and analyzed the most critical results (i.e., those from trials with three contiguous targets, with and without the application of the WTC principle). When T3 accuracy was not conditionalized on correct report of T1 and T2, p(T3) was not significantly different from p(T1). As can be seen in Figure 3, we found this in all three experiments, thereby replicating a key pattern of results reported by Di Lollo et al. (2005) and Olivers et al. (2007). In each of the present experiments, however, p(T3), when scored in accordance with the WTC principle, always reflected an AB; that is, p(T3) report was consistently worse than p(T1). A crucial finding was related to whether only T1 was taken into account for conditionalizing T3 report (T3|T1) or whether both T1 and T2 were taken into account (T3|T1^T2). When both pre-T3 targets were taken into account, T3 report suffered from an AB that was more pronounced relative to the condition in which only T1 was taken into account.

This pattern of results was conceptually replicated in all three experiments, albeit with quantitative variations that are informative vis-à-vis the relative weight of subjects' knowledge about the structural properties of the RSVP streams in processing multiple targets. The results of Experiment 3, in particular, when compared with the results of Experiments 1 and 2, provide a suggestion that reducing the level of uncertainty allowed a more efficient processing of contiguous sequential targets, a finding that is consistent with prior work (briefly reviewed in the introduction of this article) suggesting that subjects' advance knowledge about the structural or temporal organization of RSVP paradigms often results in beneficial effects on post-T1 targets processing. Despite the quantitative variations mentioned, however, it is clear that the present findings represent a serious challenge for both the TLC and BB models, as presently formulated, under several aspects. First, neither of these models at present reflects the possibility that when targets are immediately successive items embedded in RSVP streams, post-T1 targets processing may be influenced by a subjectively controlled dynamic adjustment of the accessibility of VSTM by multiple targets. That was made manifest across Experiments 1–3 through the systematic manipulation of a subset of temporal or structural parameters (i.e., the number of targets and the target–target lag) used in the generation of the RSVP streams. Second and also important, although for different reasons, it is hard to see how the TLC and BB accounts could explain the residual AB effect on T3 found in Experiment 3, that is, under conditions that replicated exactly the general structure of the paradigms used in studies showing the protracted sparing. According to the TLC account, p(T1) and p(T3) should be equivalent because no loss of control over attentional selection mechanisms and no reset in favor of distracting information are hypothesized to occur in the absence of distractors. With no intervening distractors, equivalent results would be predicted by the BB account, according to which successful access to VSTM by multiple targets is granted by an uninterrupted sequence of target-locked boosts of activation. On the other hand, these findings highlight the importance of the application of the WTC principle in the examination of results in multitarget RSVP designs and provide direct support for a tenet of capacity limitation accounts: A decrease in correct report of T3 should be expected as capacity is devoted to encoding other targets, and this decrease should be larger when there are more competing targets, as was found again in the present work (e.g., Jolicœur & Dell'Acqua, 1998; see also the section *An Explanatory Framework*, which follows).

A comment is in order concerning a further empirical case apparently against capacity limitations as the prime cause of the AB effect that was reported by Nieuwenstein and Potter (2006). The experiment in that study that is directly comparable to the present experiments is their Experiment 2, in which monochromatic targets could be selected on the basis of their alphanumeric class (and not color, as used in other experiments reported by Nieuwenstein & Potter, 2006). Subjects were exposed to sequences of six letters, and the task was either to report as many of them at the end of *whole-report* trials or to start encoding the letters in the RSVP stream after detecting a specific letter that was shown to subjects prior to the beginning of each *partial-report* trial. A whole-report superiority effect was observed for targets occupying a given position in the RSVP steam relative to the same target in the partial-report condition, when the probability of reporting a given target was estimated according to the WTC principle. It must be noted that the whole-report versus partial-report comparison is confounded with a task switch, which is known to exacerbate, under particular conditions, the AB effect (Enns, Visser, Kawahara, & Di Lollo, 2001; Peterson & Juola, 2000; Potter et al. 1998; Visser, Bischof, & Di Lollo, 1999). Contrary to the whole-report condition, in which subjects had simply to identify and encode as many letters as possible from each RSVP stream (no task switch), in the partial-report condition, subjects had first to detect the cued letter (i.e., T1) and then start to identify and encode as many letters as possible among those trailing T1 (task switch). Therefore, one possible explanation for the worse performance in partial report relative to whole report is that the switch from an attentional set that had been adjusted to *detect* T1 to an attentional set that had been adjusted to *identify* the letters immediately following T1 could have reduced accuracy in the partial-report condition relative to the whole-report condition. A task switch was implicated in none of the present experiments.

An Explanatory Framework

The present findings seem to be more easily accounted for by capacity limitations models on the basis of two explanatory principles. One principle is that the processing of targets encoded for later report proceeds in two stages: an initial high-capacity identification stage followed by a lower capacity memory-encoding stage. This idea is instantiated in the two-stage model of Chun and Potter (1995) and the central interference theory proposed by

Jolicœur (1998). According to this type of model, all alphanumeric characters composing a RSVP sequence are processed up to the level of individual character identities (Dux & Coltheart, 2005) at an early stage (Stage 1) but only T1 and T2 are selected for access to a later stage of processing (Stage 2) that consolidates T1 and T2 into durable memory representations that are stored in VSTM (see Duncan, 1980). The metaphor of an attentional gate is normally invoked in these models to explain how the system isolates T1 and T2 for further processing. The identification or categorization of T1 causes the gate to open, and this is hypothesized to be a rapid sequence of events; in contrast, the closing of the gate is hypothesized to be more sluggish (Shih, 2000, 2008). If T2 immediately follows T1, T2 is selected for processing in Stage 2 before the gate can close, and T1 and T2 are processed in Stage 2 at the same time. Jolicœur and Dell'Acqua (1998) referred to this encoding process as *short-term consolidation*. Given that short-term consolidation is a capacity-limited process, some competition between T1 and T2 ensues, such that some of the gain in performance for T2 occurs at a cost to performance for T1. The second principle is instantiated in the model proposed by Jolicœur and Dell'Acqua (1998), which incorporates basically the same assumptions concerning the different stages implicated in target consolidation, with the important addition that the time devoted to target consolidation increases as the quantity of information to be encoded into VSTM increases. The principle suggests that, all else being equal, the short-term consolidation of two alphanumeric characters takes longer than the short-term consolidation of a single alphanumeric character (see also Jolicœur, 1999; Jolicœur, Tombu, Oriet, & Stevanovski, 2002; Ouimet & Jolicœur, 2006).

The two principles outlined are sufficient to explain the present findings. An AB is triggered every time a stimulus that needs to be consolidated in VSTM is encountered. The AB is manifest unless a target (T2) trailing the one critical for the AB generation (i.e., T1) is presented within 100–120 ms of T1. In that case, T1 and the trailing target, T2, are integrated into a single postperceptual processing batch that undergoes consolidation, with the consequent (sometimes partial) sparing of T2. This explains the two consecutive U-shaped AB effects characterizing the performance of T2 and the performance of T3 when we manipulated the T1–T2 lag and the T2–T3 lag independently in three-digit trials. Consolidating a batch consisting of two integrated targets (e.g., T1 and T2) takes longer than consolidating a batch consisting of a single target. Manipulating the probability that T1 and T2 would be integrated into a single to-be-consolidated batch should have a modulatory consequence for T3 report performance. A similar prediction would be made on the basis of the overall amount of attention resources required for the processing of T1 in three-target trials. With the increase of the T1–T2 lag, the probability that T1 and T2 would enter the same consolidation batch decreases. Conversely, following an increment in attention resources needed for T1 processing, less attention resources should be left for processing post-T1 targets, especially when targets are temporally contiguous. This, on the one hand, explains why in three-digit trials on which T3 was the item immediately following T2, T3 report accuracy improved as the T1–T2 lag was increased. On the other hand, the prediction that increasing the attention demands for T1 processing would alter the availability of resources for T3 processing in three-target trials has just been empirically confirmed by Dux, Asplund, and Marois (in press) and by Dux and Harris (2007). These studies showed that in a design closely resembling that used by Di Lollo et al. (2005), T3 report was consistently suppressed relative to T1 report when T1 was associated with a marked color difference with respect to distractors and when T1 was rotated by 90° with respect to distractors. A particularly marked color difference associated with an abrupt onset, as well as the recognition of an object displayed in a noncanonical position, had already been shown to demand more attention with respect to less salient changes marking a difference between targets and distractors or canonically positioned objects (e.g., Maki & Mebane, 2006; Serences et al., 2005; Van Selst & Jolicœur, 1994).

Finally, in Experiment 3, we examined accuracy of report for T3 depending on whether T1 was reported correctly or incorrectly. At long T1–T2 lags, a U-shaped decrement in T3 report dependent upon a correct report of both T1 and T2 was found, and these effects were larger than when T2 was correctly reported but T1 was missed. We had assumed that such divergence could constitute evidence of differential VSTM load, reflected in T3 report, in the two types of trials. When the lag between T1 and T2 was decreased, as predicted by capacity models, the VSTM load effect on T3 report increased in magnitude. As suggested previously, decreasing the lag between T1 and T2 increases the probability that consolidation mechanisms will be busy with T1 at the time of presentation of T3. The ensuing costs in terms of consolidation time, which are assumed to be diminished if T1 is missed and not subjected to short-term consolidation, add to VSTM load costs, supporting further the arguments for a central role of capacity limitations of short-term consolidation in the AB phenomenon (Jolicœur & Dell'Acqua, 1998). The present results and analyses suggest that the explicit exclusion of encoding-capacity limitations embodied in the TLC and BB models prevent these models from providing a complete account of important aspects of the AB phenomenon.

References

Akyürek, E. G., Riddell, P. M., Toffanin, P., & Hommel, B. (2007). Adaptive control of event integration: Evidence from event-related potentials. *Psychophysiology, 44,* 383–391.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 109–127.

Dell'Acqua, R., Pascali, A., Jolicœur, P., & Sessa, P. (2003). Four-dot masking produces the attentional blink. *Vision Research, 43,* 1907–1913.

Dell'Acqua, R., Jolicœur, P., Pascali, A., & Pluchino, P. (2007). Short-term consolidation of individual identities leads to lag-1 sparing. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 593–609.

Di Lollo, V., Kawahara, J., Shahab Ghorashi, S. M., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research, 69,* 191–200.

Duncan, J. (1980). The demonstration of capacity limits. *Cognitive Psychology, 12,* 75–96.

Dux, P. E., Asplund, C. L., & Marois, R. (in press). An attentional blink for sequentially presented targets: Evidence in favor of resource depletion accounts. *Psychonomic Bulletin & Review*.

Dux, P. E., & Coltheart, V. (2005). The meaning of the mask matters: Evidence of conceptual interference in the attentional blink. *Psychological Science, 16,* 775–779.

Dux, P. E., & Harris, I. M. (2007). Viewpoint costs occur during consolidation: Evidence from the attentional blink. *Cognition, 104,* 47–58.

Enns, J. T., Visser, T. A., Kawahara, J., & Di Lollo, V. (2001). Visual masking and task-switching in the attentional blink. In K. L. Shapiro (Ed.), *The limits of attention* (pp. 65–81). New York: Oxford University Press.

Giesbrecht, B. L., & Di Lollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1454–1466.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded $Task_1$ decisions. *Memory & Cognition, 26,* 1014–1032.

Jolicœur, P. (1999). Dual-task interference and visual encoding. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 596–616.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36,* 138–202.

Jolicœur, P., Tombu, M., Oriet, C., & Stevanovski, B. (2002). From perception to action: Making the connection. In W. Prinz and B. Hommel (Eds.), *Attention and performance: Vol. XIX. Common mechanisms in perception and action* (pp. 558–586). Oxford, UK: Oxford University Press.

Kawahara, J., Enns, J. T., & Di Lollo, V. (2006). The attentional blink is not a unitary phenomenon. *Psychological Research, 70,* 405–413.

Kawahara, J., Kumada, T., & Di Lollo, V. (2006). The attentional blink is governed by a temporary loss of control. *Psychonomic Bulletin & Review, 13,* 886–890.

Lamme, V. A. F., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neuroscience, 23,* 571–579.

Logan, G. D. (1978). Attention in character-classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General, 107,* 32–63.

MacKay, A., & Juola, J. F. (2007). Are spatial and temporal attention independent? *Perception & Psychophysics, 69,* 972–979.

Maki, W. S., & Mebane, M. W. (2006). Attentional capture triggers an attentional blink. *Psychonomic Bulletin & Review, 13,* 125–131.

Martens, S., & Johnson, A. (2005). Timing attention: Cueing target onset interval attenuates the attentional blink. *Memory & Cognition, 33,* 234–240.

Nieuwenstein, M. R., & Potter, M. C. (2006). Temporal limits of selection and memory encoding: A comparison of whole versus partial report in rapid serial visual presentation. *Psychological Science, 17,* 471–475.

Olivers, C. N. L. (2007). The time course of attention: It is better than we thought. *Current Directions in Psychological Science, 16,* 11–15.

Olivers, C. N. L., & Meeter, M. (in press). A boost and bounce theory of temporal attention. *Psychological Review*.

Olivers, C. N. L., van der Stigchel, S., & Hulleman, J. (2007). Spreading the sparing: Against a limited capacity account of the attentional blink. *Psychological Research, 71,* 126–139.

Ouimet, C., & Jolicœur, P. (2006). Beyond $Task_1$ difficulty: The duration of T1 encoding modulates the attentional blink. *Visual Cognition, 15,* 290–304.

Peterson, M. S., & Juola, J. F. (2000). Evidence for distinct attentional bottlenecks in attention switching and attentional blink tasks. *Journal of General Psychology, 127,* 6–26.

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 979–992.

Ptito, A., Arnell, K., & Jolicœur, P., & MacLeod, J. (in press). Intramodal and crossmodal processing delays in the attentional blink paradigm revealed by event-related potentials. *Psychophysiology*.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860.

Serences, J. T., Shomstein, S., Leber, A. B., Golay, X., Egeth, H. E., & Yantis, S. (2005). Coordination of voluntary and stimulus-driven attentional control in human cortex. *Psychological Science, 16,* 114–122.

Shapiro, K. L., Driver, J., Ward, R., & Sorensen, R. E. (1997). Priming from the attentional blink: A failure to extract visual tokens but not visual types. *Psychological Science, 8,* 95–100.

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 357–371.

Shih, S. (2000). Recall of two visual targets embedded in RSVP streams of distractors depends on their temporal and spatial relationship. *Perception & Psychophysics, 62,* 1348–1355.

Shih, S. (2008). The attention cascade model and the attentional blink. *Cognitive Psychology, 56,* 210–236.

Van Selst, M., & Jolicœur, P. (1994). Can mental rotation occur before the dual-task bottleneck? *Journal of Experimental Psychology: Human Perception and Performance, 20,* 905–921.

Visser, T. A. W. (2007). Masking T_1 difficulty: Processing time and the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 285–297.

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin, 125,* 458–469.

Vogel, E. K., Luck, S. J., & Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1656–1674.

Received October 9, 2007
Revision received July 15, 2008
Accepted July 20, 2008 ■