On the Costs of Lag-1 Sparing

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The attentional blink (AB) is a dual-target, rapid serial visual presentation (RSVP) deficit thought to represent a failure of perceptual awareness that reflects the dynamics of temporal attention. However, second target (T2) report is typically unimpaired when the targets appear within 150 ms of one another (i.e., lag-1 sparing). In addition, this sparing can be extended if more targets appear sequentially. It is thought that sequential targets are processed in the same attentional window. Here, we investigated the fate of targets processed in these windows and, specifically, the consequence for subsequent targets when an item at lag-1 is reported versus missed. The results demonstrated that target encoding in attentional windows has an all-or-none influence on subsequent item report: When comparing two- and three-target (T1 and T2 not separated by distractors) RSVP streams, there was no difference in AB magnitude for the final target when either T2 or T1 was missed in the three-target condition, but both of these conditions had significantly smaller blinks than those observed when T1 and T2 were accurately reported. A comparison of our results to a computational model of temporal attention demonstrates how structural limitations on the rate of encoding affect perception, even during sparing.

Keywords: temporal attention, capacity limits, attentional blink, lag-1 sparing, computational modeling

A fundamental question in the field of cognitive psychology concerns how the selection and analysis of one stimulus influences that for another (Pashler, 1998). Indeed, in a world that presents individuals with far too much information for it all to be processed up to awareness, one could argue that this question is at the heart of understanding how individuals make sense of their rich sensory experience because perception is far more subjective than veridical.

Key for assessing the consequences of stimulus selection and encoding, or put differently, the capacity limits of attention, is the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992; see also Broadbent & Broadbent, 1987; Weichselgartner & Sperling, 1987). This effect refers to subjects' impaired ability to report the second (T2) of two, to-be-reported items (targets) from among a

rapid serial visual presentation (RSVP; Potter & Levy, 1969) stream of distractors (items to be ignored) if it appears within 200–500 ms of the first target (T1).

The AB has now been observed in hundreds of studies and across a wide variety of conditions (see Dux & Marois, 2009; Martens & Wyble, 2010, for reviews). Targets can be differentiated from distractors based on categorical (e.g., letters among digits) and/or featural (e.g., red letters among black letters) information, and can require either detection (e.g., "Was an X present or absent in the stream?") or identification (e.g., "What was the letter in the stream?"). Similarly, many different types of stimuli are susceptible to this second-target deficit, including letters, digits, shapes, words, pictures, faces, line drawings, and sounds. The AB is also highly robust across subjects. Individuals who were found to exhibit no AB for a task with letter targets and digit distractors displayed an AB of typical magnitude when tested using RSVP streams containing pictures of natural scenes (Martens, Dun, Wyble, & Potter, 2010). This suggests that these subjects had perceptual expertise for a particular stimulus set rather than immunity to the AB. Thus, the AB has been found to be extremely ubiquitous across subjects and across a broad variety of stimulus types. In addition, work on the AB is relevant in a range of theoretical and applied settings. For example, the AB has been hypothesized to draw on central, amodal attention resources and, thus, may reflect a capacity limit that impacts multitasking performance at a number of different levels of information processing, from perception right up to working memory and even decision-making (e.g., Tombu et al., 2011). It has also been proposed that the AB reflects mechanisms involved in general temporal segmentation of information (Wyble, Potter, Bowman, & Nieuwenstein,

2011). Such segmentation would play a key role in allowing the visual system to correctly separate information from distinct visual fixations into distinct memory representations (Kamienkowski, Navajas, & Sigman, 2012). Of import, the AB deficit has also been shown to become more pronounced with age (e.g., Shih, 2009), and magnified in a range of neurological and psychiatric conditions (e.g., see Husain, Shaprio, Martin, & Kennard, 1997, for stroke-induced hemispatial inattention; Cheung, Chen, Chen, Woo, & Yee, 2002; Rokke, Arnell, Koch, & Andrews, 2002, for schizophrenia and depression), suggesting that it may represent a key marker of attentional dysfunction. Indeed, AB magnitude has recently been linked to striatal dopamine function, which is important for general cognitive and behavioral flexibility (Slagter et al., 2012).

At the theoretical level, there is considerable debate whether the AB reflects a bottleneck of perception (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; see Dux & Marois, 2009; Martens & Wyble, 2010, for reviews), an overzealous inhibitory response to an intrusive distractor (Olivers & Meeter, 2008; Raymond et al., 1992; Taatgen, Juvina, Schipper, Borst, & Martens, 2009), or an ostensible limitation that actually improves our ability to encode temporal information (e.g., Wyble, Bowman, & Nieuwenstein, 2009).

A keystone in this theoretical debate is the somewhat paradoxical finding that lag-1 sparing typically goes hand-in-hand with the AB. This effect refers to the consistent finding that no T2 deficit is observed when the targets appear within about 150 ms of one another in an RSVP stream. In fact, this relationship between the AB and lag-1 sparing arguably represents one of the key puzzles in understanding the mechanisms underlying temporal attention and attention function in general, because there is strong evidence that this sparing extends across space at very short stimulus onset aynchronies (Jefferies & Di Lollo, 2009).

Lag-1 sparing has been the subject of considerable investigation, and much is now known about its properties. It typically occurs when there is no task switch/spatial switch/attentional set change between the targets (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999), it is dependent on the time between the target onsets rather than whether a distractor appears between them (Bowman & Wyble, 2007), and the window over which lag-1 sparing is observed is malleable (Akyürek, Toffanin, & Hommel, 2008). A further characteristic of sparing is that it can be somewhat extended over other sequentially presented targets up to the capacity limits of short-term memory (STM) ("spreading of the sparing"; Kawahara, Kumada, & Di Lollo, 2006; Olivers, Van der Stigchel, & Hulleman, 2007; but see Dell'Acqua, Jolicœur, Luria, & Pluchino, 2009; Dux, Asplund, & Marois, 2008, 2009). This latter finding has been arguably the most influential in the last decade of temporal attention research because it has led to considerable rethinking about the mechanisms that underlie the AB phenomenon (Dux & Marois, 2009; Martens & Wyble, 2010).

Traditionally, the AB was thought to reflect resource depletion and, specifically, limitations associated with T1 encoding. For example, Chun and Potter's (1995; Jolicœur & Dell'Acqua, 1998) two-stage model predicts that all RSVP items are rapidly processed at a conceptual level (activate "type" representations) during a preliminary stage of processing (Stage 1), but these initial representations are vulnerable to decay and masking from items that follow in the stream (Potter, 1976, 1993). Based on their predefined features, target items are selected and proceed to the second stage of processing (Stage 2) where they are encoded into working memory and available for conscious report. The AB is assumed to occur at short T1–T2 temporal lags because Stage 2 is capacity limited and, thus, can only process one target at a time. If T2 appears while T1 is undergoing second-stage processing, T2 must wait before it can enter Stage 2 and, consequently, its representation is susceptible to decay and masking (Jolicœur & Dell'Acqua, 1998, have also shown that other operations, like response selection, draw on second-stage resources, and they incorporated this into their short-term consolidation theory).

In support of the two-stage model, it was shown that even a missed T2 can facilitate identification of a third target if the two targets are semantically related (e.g., "A," "a"), suggesting that targets that do not enter STM still show evidence of initial semantic or conceptual processing (Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Peressotti, Pesciarelli, Mulatti, & Dell'Acqua, 2012; Pesciarelli et al., 2007; Shapiro, Driver, Ward, & Sorensen, 1997). Furthermore, several neuroimaging studies have demonstrated that although posterior regions respond to both missed and reported T2s (occipital and temporal areas) parietal and frontal areas are selectively activated for reported items, which is consistent with a two-stage account of target processing (e.g., Kranczioch, Debener, Schwarzbach, Goebel, & Engel, 2005; Marois, Yi, & Chun, 2004).

In addition to the two-stage (Chun & Potter, 1995) and short-term consolidation (Jolicœur & Dell'Acqua, 1998) bottleneck accounts, multiple other factors, hypothesized to draw on capacity-limited resources, have also been implicated in the AB. For example, Shapiro, Raymond, and Arnell (1994) proposed that the AB arises from a bottleneck in retrieval from STM, such that T2 fails to be reported because it loses the battle for resources, because they are already devoted to T1 and the lag-1 item (based on its temporal proximity). In addition, Dux and Harris (2007; see also Dux & Marois, 2008) argued that a failure of distractor inhibition gives rise to the AB.

All these resource-depletion frameworks assume that lag-1 sparing reflects that T2 enters a temporally "sluggish" attentional gate and, as a result, gets processed along with T1. However, this account was criticized as being internally inconsistent and an "add on" to the notion of capacity limits giving rise to the AB (Di Lollo, Kawahara, Ghorashi, & Enns, 2005). In addition, Di Lollo et al. (2005) further argued that the attentional gate account could not explain the entirety of lag-1 sparing findings observed, particularly spreading of the sparing, which suggested that temporal encoding had a higher capacity and was more efficient than previously thought.

In response to the spreading of the sparing findings from Di Lollo et al. (2005), Kawahara et al. (2006), and Olivers et al. (2007), a number of other mechanisms were proposed to underlie the AB. These accounts predict that the AB results not from the capacity limits of encoding but rather from impaired attentional selection and/or implicit strategic approaches that restrict (either by necessity or unnecessarily) T2 processing at short lags. These include delayed reorienting of attentional resources between targets (e.g., Nieuwenstein, 2006), the strategic suppression of target detection processes while T1 is consolidated into working memory (Taatgen et al., 2009), the inhibition of post-T1 information triggered by the appearance of nontarget information (Olivers &

Meeter, 2008; Raymond et al., 1992), and the postponement of binding a target's conceptual (type) representation with episodic (token) information if another target is already undergoing this process (simultaneous type, serial token [ST^2] models; Bowman & Wyble, 2007; Wyble et al., 2009). In addition, Di Lollo et al. (2005) proposed that the AB deficit occurs because T1 processing triggers a temporary loss of executive control over the input filter used to select targets over distractors. Thus, collectively, these models predict that whatever mechanism gives rise to the AB is only triggered once a sequence or stream of targets ends, because only a single selection operation is triggered by the presentation of the first target under such conditions. This is particularly relevant for the questions and manipulations we address and employ in the present study.

The selection models described above account for sparing under RSVP conditions more naturally than resource depletion theories, because they all predict the AB is triggered by either a distractor or a blank gap (nontarget information) in the RSVP stream following T1. However, the notion that sparing occurs without attentional costs is inaccurate. Indeed, Wyble et al. (2009; see also Akyürek & Hommel, 2005; Chun & Potter, 1995; Wyble et al., 2011) have shown that sparing is associated with a loss of target presentation order information. Dux et al. (2008; see also Dux et al., 2009) have also shown that when attentional resources to T1 are increased under conditions in which three targets are presented sequentially, T1 performance is superior to T3—an AB-like effect. Similarly, Dell'Acqua et al. (2009) observed a similar pattern of results in sequential target report in which T3 performance was conditionalized on T1 and T2 accuracy. Finally, Dell'Acqua, Dux, Wyble, and Jolicœur (2012) found the target report was impaired when T1, T2, and T3 appeared sequentially as opposed to when seven distractors separated the targets from one another. These findings indicate that structural encoding limitations do influence target report in RSVP, and Wyble et al. (2011) predicted that the above results reflect mutual interference between targets that appear in close temporal proximity within the RSVP stream.

Attentional Episodes as an Explanation of Sparing

In the episodic (e)ST^2 model (Wyble et al., 2009; Wyble et al., 2011), it is proposed that the visual system uses *attentional episodes* to provide temporal structure to memory encoding. In this theory, multiple targets presented in close temporal proximity (i.e., no greater than about 150 ms) produce a single window of attention that allows them all to be encoded simultaneously, and the duration of that window is a function of the number of targets presented together. Each target is associated with a distinct *type* representation (a fleeting, abstract identity representation containing information on the featural and conceptual characteristics of a stimulus; Kanwisher, 1987), and when multiple type nodes are activated at the same time, there is interference between them. This interference is weak enough to allow multiple targets to be encoded at once, although, in some cases, the interference pushes a target below the encoding threshold, and it is therefore lost. The evidence for this weak interference is in the data of many AB studies that have shown impairment in T1 performance at lag-1 (e.g., Bowman & Wyble, 2007; Chun & Potter, 1995). This model simulates this small but robust effect as the result of interference between T1 and T2 when they are being encoded together in the

same attentional window or episode. Thus, the model predicts that when there is a sequence of three or more targets, performance typically rises from the first to the second, but decreases thereafter, an effect that is typically found in presentations of three or more sequential RSVP targets (Kawahara et al., 2006; Olivers et al., 2007; Wyble et al., 2011). In the eST^2 model, this drop-off in performance is thought to reflect the accumulation of mutual type interference because more stimuli are entered into the ongoing episode. The model predicts that, given sufficient time, the mutual interference resolves as the targets are encoded, allowing higher levels of performance for subsequent items. In short, the model predicts that there is a combination of attentional and structure limitations (e.g., mutual type interference) that determine performance in RSVP tasks, with interference becoming increasingly stronger when multiple targets are presented sequentially and are encoded within a single attentional episode.

To date, the costs associated with target processing during sparing have only been demonstrated for targets presented within the same attentional window (i.e., when targets are presented sequentially and a single selection operation is required). Currently, we do not know what the consequences are for subsequent targets, appearing in distinct windows (where multiple selection operations are undertaken), when earlier items at lag-1 are reported as opposed to missed. Put differently, does the number of targets encoded within an attentional window affect the depth or duration of the AB for a subsequent item? Herein, we addressed this question by presenting three target RSVP streams, with T2 at lag-1, and manipulating the T2–T3 temporal lag. Crucially, we conditionalized T3 report on whether both T1 and T2 are reported accurately or if just one of these items is consciously perceived. That is, we manipulated encoding demands at lag-1 in the absence of varying selection demands. To preview the results, a reduced AB is observed for T3 in the latter condition, relative to the former, and the profile of this AB also did not differ from the AB found for T2 under typical dual-target conditions. Thus, the encoding of targets in attentional windows has a strong influence on the report of subsequent items that appear in distinct windows. This result suggests a key role of mutual type interference in encoding, and we explored this issue with "modeling experiments." Specifically, we used the eST^2 model, as we previously employed it (Dell'Acqua et al., 2012), to account for capacity limits *within* attentional windows, to explore the contributions of mutual type interference in producing the observed data. For each experiment, two simulations were provided for each condition, one with the same parameters used as in the original eST^2 publication (Dell'Acqua et al., 2012; Wyble et al., 2009) and one with the mutual type interference set to 0.[1]

General Method

Subjects

Eighty students at the University of Padua (49 females) participated in the experiments (20 per experiment) after giving in-

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[1] Note that, in these simulations, there is no noise and each run of the simulation, with the same parameters, produces exactly the same results. Intertrial variability is produced with systematic changes of target strength that varies from one trial to the next in a predetermined fashion, as described in Wyble et al. (2009). Accordingly, there is no sense in which the model provides statistics or error bars, because simulations are strictly deterministic.

formed consent. Their mean age was 24.3 years ($SD = 4.2$), and all subjects had normal or corrected-to-normal visual acuity.

Stimuli

The stimuli were 22 letters of the English alphabet (excluding B, I, O, and Z) and the Digits 2–9. The stimuli were displayed in light gray (34 cd/m^2) Romantri font against a black (6 cd/m^2) background. Luminance measurements were performed using a Minolta LS-100 chroma meter. Stimuli appeared on a 19-in. CRT monitor, placed at a viewing distance of approximately 60 cm, controlled by an i686 personal computer and MEL software (Psychology Software Tools, Sharpsburg, PA). RSVP streams were composed of distractor digits randomly selected from the available set, plus two or three different target letters (T1, T2, and T3) presented in various positions in the stream (see the Design sections of each experiment). Identical distractor digits in the RSVP stream were always separated by a minimum of three different stimuli. Each stimulus was displayed for 84 ms, and was immediately replaced by the next item (interstimulus interval = 0 ms). The lag between pairs of critical targets (i.e., the T1–T2 lag in the two-target RSVP streams or the T2–T3 lag in three-target RSVP streams) was manipulated by varying the number of distractors between T1 and T2 or between T2 and T3. The number of distractors preceding T1 was varied randomly across trials from six to 11, and for all trials at least three distractors followed the presentation of the last target (i.e., T2 or T3). In Experiments 1–3, the stimuli were scaled to fit in a central, square portion of the monitor measuring $1.0° \times 1.0°$ of visual angle. In Experiment 4, three stimuli (i.e., T1 and the two distractors in the T1 − 1 and T1 + 1 positions) were scaled to fit in a square portion of the monitor, with a side of 2.2° of visual angle.

Procedure

Each trial began with the presentation of a number of horizontally aligned plus signs in the center of the monitor denoting the number of targets that would appear in the forthcoming RSVP stream (i.e., two or three plus signs). Pressing the spacebar resulted in plus signs disappearing and, after a fixed blank interval of 800 ms, the RSVP commenced. A question was displayed 800 ms after the end of the RSVP stream, inviting report of the targets by pressing the corresponding keys on the keyboard. The instructions noted explicitly that target order and speed of response were unimportant. Feedback on an incorrectly reported target was provided at the end of each trial by replacing the plus sign in the position congruent with target order (from left to right, T1, T2, and T3 when present) with a minus sign. Experimental data were collected after exposing subjects to no less than 20 RSVP streams for practice in each condition (see the Design section of each experiment).

Experiment 1

Experiment 1 aimed to investigate the capacity limits of attentional windows across time, specifically, how performance on a target in an RSVP stream is influenced by performance on prior targets that appear in the same attentional episode (lag-1). Subjects completed blocks of two- and three-target RSVP streams, and last target performance was conditionalized on the accuracy of those prior.

Method

A schematic representation of the design of Experiment 1 is presented in Figure 1. RSVP streams contained two (T1 and T2; see Figure 1a) or three (T1, T2, and T3; see Figure 1b) targets. In three-target RSVP streams, T1 and T2 were always consecutive items. The lag between T1 and T2 in two-target RSVP stream and between T2 and T3 in three-target RSVP streams was manipulated by presenting one (lag-2), two (lag-3), three (lag-4), four (lag-5), or seven (lag-8) distractors between these targets. Each subject performed 640 trials, organized into 16 blocks of 40 trials each. Each lag appeared an equal number of times in each block, but their order was pseudorandomized, with the constraint that no more than three consecutive trials could have the same lag. Half of the subjects started with eight blocks of two-target RSVP streams, followed by eight blocks of three-target RSVP streams. The opposite order applied for the other half of the subjects.

Results and Discussion

The key behavioral results of Experiment 1 are displayed in Figure 2a. To assess the influence of lag-1 target load on the AB, an analysis of variance (ANOVA) was performed comparing the mean proportion of T2 correct (given T1 correct) in the two-target RSVP streams, with T3 report in three-target RSVP streams (given the correct report of T1 and T2) as a function of lag. A significant interaction demonstrated that the effect of lag (AB) was more pronounced in three-target than in two-target RSVP streams, $F(4, 76) = 14.5$, $\eta_p^2 = .433$, $p < .001$, demonstrating the lag-1 load influences the AB and, thus, that there are severe capacity limits associated with attention windows. Two additional ANOVAs were carried out to further explore this finding. One compared T3 report in three-target RSVP streams contingent on either pre-T3 target being missed (T1 or T2, not both), with T3 report in three-target RSVP streams contingent on the correct report of both T1 and T2. The other compared T3 (contingent on T1 or T2 report) with T2 report in the two-target RSVP streams contingent on the correct report of T1. The AB effect in three-target RSVP streams was strongly attenuated when either pre-T3 target was missed, $F(4, 76) = 7.9$, $\eta_p^2 = .292$, $p < .001$. However, this AB magnitude did not differ from that observed in the two-target RSVP streams ($F < 1$). This shows that the encoding of targets in an attentional
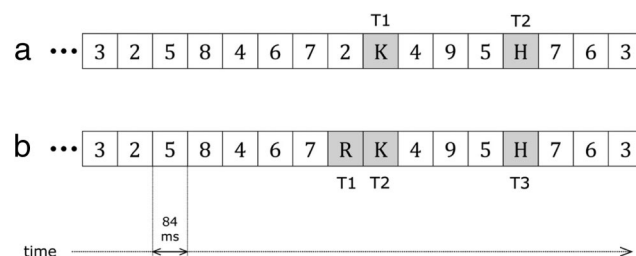

Figure 1. Design of Experiment 1. Two-target rapid serial visual presentation (RSVP) stream in which T2 followed T1 at a varying lag (a). Three-target RSVP stream in which T1 and T2 were always displayed as consecutive items, followed by T3 at a varying lag (b). The shaded background highlights the to-be-reported targets in the different RSVP streams, although no actual change in background color or luminance occurred during the experiment. T = target.
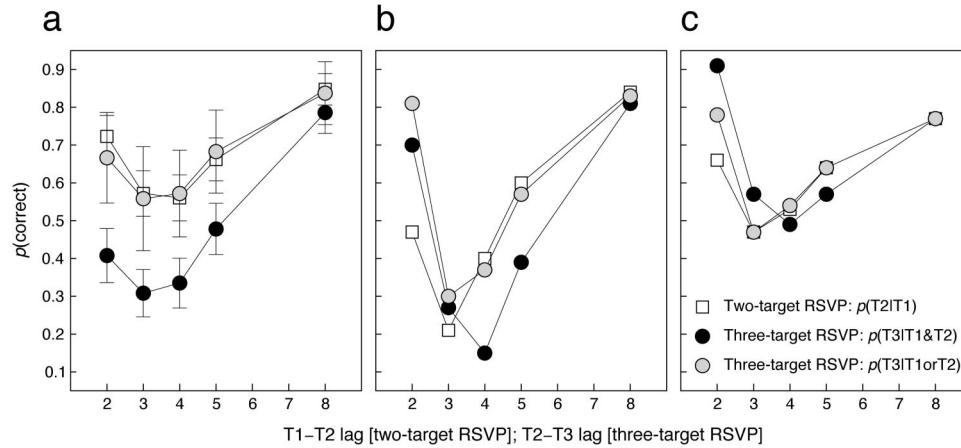
Figure 2. In Experiment 1, the mean proportion of correct responses to the last target in the two- (T2) and three-target rapid serial visual presentation (RSVP) streams (T3), plotted as a function of lag (a). In two-target RSVP streams, p(T2) is conditionalized on the correct report of T1—p(T2|T1). In three-target RSVP streams, p(T3) is conditionalized on the correct report of both T1 and T2—p(T3|T1&T2)—and on the correct report of either T1 or T2—p(T3|T1orT2). eST^2 model stimulations of the data with mutual type interference turned on (b) and off (c) with a stimulus presentation time of 90 ms. T = target. Error bars are ± 1 *SEM*.

window has an all-or-none influence on the report of a subsequent item in a distinct attentional window. Put differently, a missed target at lag-1, within the same attentional window as another target, has the same influence on subsequent target processing, in a distinct window, as does a distractor at lag-1 that does not require report (but would, nonetheless, be processed along with T1 due to its temporal position; e.g., Chua, Goh, & Han, 2001; Chun & Potter, 1995; Maki et al., 1997; Raymond et al., 1992). Were there an influence of a missed target at lag-1, one would expect differences in the T2–T3 AB magnitude between dual-target trials and three-target trials in which either T1 or T2 is missed. However, the ABs in these conditions did not differ, but were significantly reduced relative to the results observed for T3 when both targets in a preceding attentional window were reported.

An additional issue to address is whether target-order swaps at lag-1 influenced performance in the three-target RSVP streams. Previous work has demonstrated that, under sequential target presentation conditions, there are often occurrences of target-order report reversals (i.e., T2 being reported in the place of T1 and vice versa; Akyürek & Hommel, 2005; Akyürek et al., 2008; Akyürek et al., 2012; Bowman & Wyble, 2007; Wyble et al., 2009; Wyble et al., 2011). It has been argued that such order reversals can reflect integration of the T1 and T2 stimuli into a single representation (Akyürek et al., 2012). Thus, in three-target trials in which both T1 and T2 were reported correctly, we could be averaging across trials with (swaps in report) and without (no swaps in report) lag-1 integration, and these conditions could have distinct effects on T3 performance. To assess this, we examined three-target trials conditional on both T1 and T2 report as a function of lag and report order of T1 and T2 (correct order vs. swap). There was no consistent effect of target report order at lag-1 on overall T3 accuracy ($F < 1$), however, there was a significant interaction, $F(4, 76) = 4.91$, $\eta_p^2 = .21$, $p < .005$. Follow-up t tests, corrected using a false discovery rate (FDR; Benjamini & Hochberg, 1995) approach, found a significant difference at lag-4 with no-swap trials having superior T3 performance

relative to swap trials, $t(1,19) = 5.7$, $p < .01$. But, no such difference in T3 accuracy was found at lag-2 and 3, where the AB is maximal, nor at lag-5 and 7, where the AB deficit dissipates (ts < 1). Given this inconsistent effect across lag, it appears that whether or not there was integration at lag-1 between the T1 and T2 stimuli did not have a meaningful influence on the pattern of results observed.

Figure 2 shows the qualitative simulations produced by eST^2 when mutual type interference (see Figure 2b) was implemented in the model, and when mutual type interference was not implemented in the model (see Figure 2c). These simulations use the same parameters as were present in the original Wyble et al. (2009) formulation of the model, apart from deactivating mutual type interference for the simulation in Figure 2c. This model correctly simulates that the AB is larger when T1 and T2 are both encoded than when either of them is missed. Without type interference, the AB is of similar depth in the two analyses.

An important consideration for the above conclusion is whether T3 report was different when it was conditionalized on which pre-T3 target was correctly reported (see Figure 3). Data from two subjects were discarded from this analysis because of one or more empty cells.[2] There was a main effect of lag, $F(4, 68) = 13.0$, $\eta_p^2 = .466$, $p < .001$, but no effect of which pre-T3 target was correctly reported (T1 vs. T2; $F < 1$). However, there was a significant interaction between these variables, $F(4, 68) = 3.8$, $\eta_p^2 = .190$, $p < .01$.

Visual inspection of Figure 3a makes the nature of this interaction clear. The AB effect triggered by T1 (white diamonds in Figure 3) was devoid of sparing effects at lag-2, and the AB recovered earlier in this condition than the T2 conditionalized trials, which were also characterized by sparing at lag-2. These

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[2] The data set of Experiment 1 resulting from the exclusion of the two subjects with empty cells was submitted to the same set of analyses outlined in this section, with no observable quantitative and/or statistical deviations from the results obtained considering the entire data set.
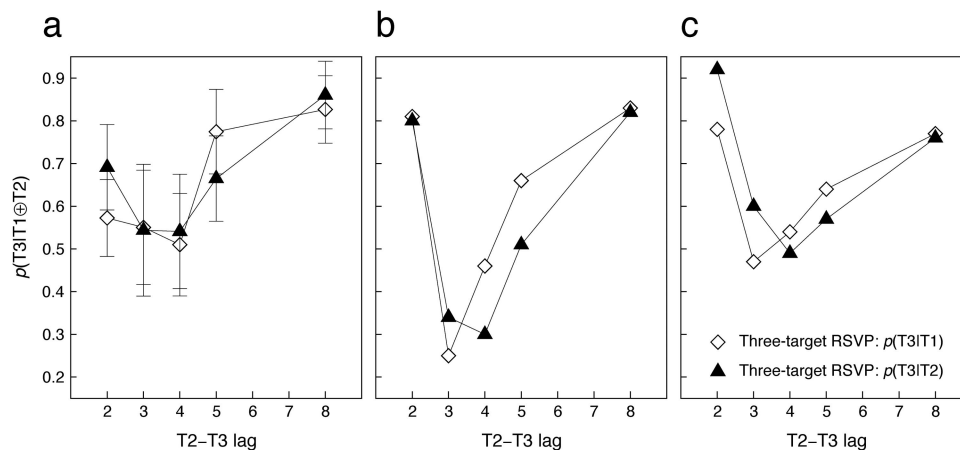
Figure 3. In Experiment 1, the mean proportion of correct responses to T3 in three-target rapid serial visual presentation streams when either T1 or T2 was missed, plotted as a function of whether T1—p(T3|T1)—or T2—p(T3|T2) was the correctly reported pre-T3 target. eST^2 model stimulations of the data with mutual type interference turned on (b) and off (c). T = target. Bars are ± 1 *SEM*.

observations were supported statistically by a series of FDR-corrected (Benjamini & Hochberg, 1995), one-way ANOVAs. T3 report contingent on the correct report of T1 did not differ between lag-2 and lag-3 ($F < 1$), whereas the difference between these lags was significant for T3 report contingent on the correct report of T2, $F(1, 17) = 11.1$, $\eta_p^2 = .410$, $p < .01$. A significant difference in T3 report determined by which pre-T3 target was correctly reported was also detected at lag-5, $F(1, 17) = 4.8$, $\eta_p^2 = .231$, $p < .05$. Furthermore, whereas T3 report contingent on the correct report of T1 did not differ between lag-5 and lag-8, $F(1, 17) = 1.1$, $\eta_p^2 < .100$, $p > .30$, a significant difference between these lags was found for T3 report contingent on the correct report of T2, $F(1, 17) = 24.6$, $\eta_p^2 = .606$, $p < .001$. Of import, a larger AB was observed for T3 when it was conditional on report of *both* T1 and T2 than when it was conditionalized on either target being reported, $F(4, 68) = 2.9$, $\eta_p^2 = .155$, $p < .03$, or T2, $F(4, 68) = 5.6$, $\eta_p^2 = .260$, $p < .001$. Thus, our conclusions from the main analysis hold.

Figures 3b and 3c suggest that eST^2 reproduces these results with or without mutual type interference. What these simulations suggest is that the difference in the duration of the AB, depending on whether T1 or T2 was reported, can be explained by attentional effects alone. In the model, a single target will produce an AB that ends when target encoding is completed. Because T2 appears nearly 100 ms after T1, it is to be expected that its encoding would last considerably longer, and thus so would the AB.

Other results of interest related to the report of the pre-T2 and -T3 targets are summarized in Table 1. An ANOVA carried out on the mean proportion of correct responses to T1 in two- and three-target RSVP streams as a function of lag revealed that T1 report was superior for two-target relative to three-target RSVP streams, $F(1, 19) = 63.7$, $\eta_p^2 = .770$, $p < .001$, and T1 report varied across lags, $F(4, 76) = 7.4$, $\eta_p^2 = .279$, $p < .001$.

Table 1 suggests that lag effects could be due to the slightly superior T1 report at lag-3 relative to the other lags. When the data from lag-3 were temporarily excluded from consideration, T1 report still differed between two- and three-target RSVP streams,

$F(1, 19) = 62.3$, $\eta_p^2 = .777$, $p < .001$, but lag effects were no longer significant, $F(3, 57) = 2.2$, $\eta_p^2 < .110$, $p > .1$. A separate ANOVA was carried out on T1 report in three-target RSVP streams as a function of T2 report (correctly reported vs. missed). This analysis did not reveal any significant effects ($F_{max} = 1.1$, $\eta_{p\,max}^2 = .068$, $p_{min} > .3$).

Experiment 2

Experiment 1 demonstrated the capacity limits associated lag-1 sparing, namely, that subsequent target performance is significantly influenced by whether targets prior to it, appearing at lag-1, are reported on not. Lag-1 sparing is typically found when stimuli appear sequentially, however, it can also be observed for spatially separate RSVP streams if the focus of attention is diffused to cover the portion of space where targets appear simultaneously (lag-0; e.g., Potter, Staub, & O'Connor, 2002). Here, we tested whether the findings from Experiment 1 would extend to conditions in which sparing is observed across space.

Method

Figure 4 displays a schematic representation of the design of Experiment 2. RSVP streams always contained three potential

Table 1
Mean Proportion T1 and T2 Correct in Experiment 1 as a Function of Lag and Rapid Serial Visual Presentation Stream Condition

Lag		2	3	4	5	7
Two-target	p(T1)	.920	.948	.934	.930	.934
Three-target	p(T1)	.769	.827	.770	.781	.798
Three-target	p(T2|T1 missed)	.742	.822	.822	.856	.845
Three-target	p(T2|T1 correct)	.770	.828	.773	.781	.802

Note. Lag refers to T1–T2 lag in two-target rapid serial visual presentation (RSVP) streams and to T2–T3 lag in three-target RSVP streams (see Figure 1). T = target.
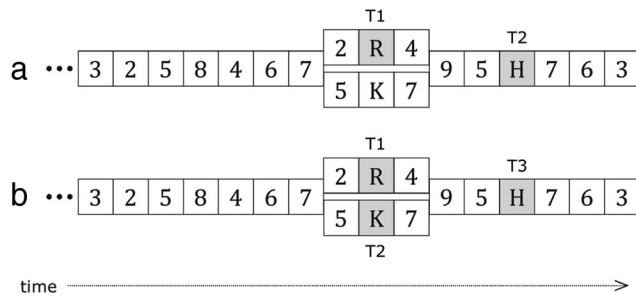
Figure 4. Design of Experiment 2: two-target rapid serial visual presentation (RSVP) stream (a) and three-target RSVP stream (b). Both types of RSVP streams always contained three potential targets (T1, T2, and T3). T1 and T2 were always simultaneously displayed above or below fixation, followed by T3 displayed centrally at a varying lag. In two-target RSVP streams, subjects had to report only one target (T1) from the two-target array displayed at a prespecified position, and then T3. In three-target RSVP streams, subjects had to report both simultaneous targets (T1 and T2), and then T3. The shaded background used in the figure highlights the to-be-reported targets in the different RSVP streams, although no actual change in background color or luminance occurred during the experiment. T = target.

target letters, the first two appeared simultaneously above and below fixation, with a center-to-center distance of 1.1°. Pairs of digit distractors preceded and followed the targets at the same positions. In two-target RSVP trials (see Figure 4a), half of the subjects were instructed to report the target above fixation (T1) and then the following target presented at fixation (T2); the other subjects were instructed to report the target below fixation (T1) and the following target presented at fixation (T2). In three-target RSVP streams (see Figure 4b), subjects were instructed to report all three targets, the two eccentric targets (T1 and T2) and the following target presented at fixation (T3). In both two- and three-target RSVP streams, the lag between the pair of eccentric

targets and the following target displayed at fixation was manipulated by interleaving a pair of simultaneous distractors trailing the targets, plus two (lag-3), three (lag-4), four (lag-5), six (lag-7), or nine (lag-10) distractors at fixation. Each subject performed 600 trials, organized in 20 blocks of 30 trials each. Half of the subjects started with 10 blocks of two-target RSVP streams, followed by 10 blocks of three-target RSVP streams. The opposite order applied for the other half of subjects.

Results and Discussion

The most relevant behavioral results of Experiment 2 are displayed in Figure 5a. Again, the AB effect was more pronounced in three-target than in two-target RSVP streams, $F(4, 76) = 7.8$, $\eta_p^2 = .292$, $p < .01$, and, as was the case in Experiment 1, the AB effect in three-target RSVP streams was strongly attenuated when either pre-T3 target was missed, $F(4, 76) = 4.5$, $\eta_p^2 = .192$, $p < .001$. Indeed, the AB magnitude in three-target RSVP streams when either pre-T3 target was missed did not differ from the AB magnitude observed in two-target RSVP streams, $F(4, 76) = 1.6$, $\eta_p^2 < .1$, $p > .2$, and this was independent of which pre-T3 target (T1 vs. T2) was correctly reported ($F < 1$). The simulations from the eST^2 model are reported in Figures 5b (mutual type interference included) and 5c (mutual type interference not included). As in Experiment 1, the deeper AB obtained when both T1 and T2 are encoded is contingent on mutual type interference within the model.

T1 results are summarized in Table 2. On average, T1 report was superior in two- relative to three-target RSVP streams, $F(1, 19) = 9.9$, $\eta_p^2 = .343$, $p < .01$, and T1 report varied across lags, $F(4, 76) = 6.4$, $\eta_p^2 = .252$, $p < .001$. The lag effect could reflect the small drop in T1 performance at lag-10 relative to the other lags. When the data from lag-10 were temporarily excluded from consideration, T1 report still differed between two- and three-target RSVP streams, $F(1, 19) = 11.5$, $\eta_p^2 = .378$, $p < .001$, but lag effect was no longer present, $F(3, 57) = 2.6$, $\eta_p^2 < .1$, $p > .1$.
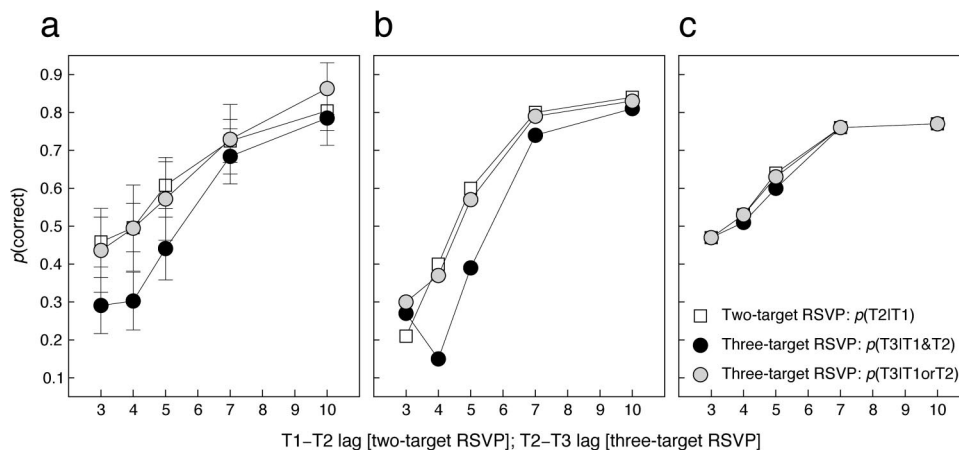

Figure 5. In Experiment 2, the mean proportion last target accuracy in the two- and three-target rapid serial visual presentation (RSVP) streams, plotted as a function of lag (a). In two-target RSVP streams, $p(T2)$ is conditionalized on the correct report of T1—$p(T2|T1)$. In three-target RSVP streams, $p(T3)$ is conditionalized on the correct report of both T1 and T2—$p(T3|T1\&T2)$—and on the correct report of either T1 or T2—$p(T3|T1orT2)$. eST^2 model stimulations of the data with mutual type interference turned on (b) and off (c). T = target. Bars are ± 1 *SEM*.

Table 2

Mean Proportion T1 and T2 Correct in Experiment 2 as a Function of Lag and Rapid Serial Visual Presentation Stream Condition

Lag		3	4	5	7	10
Two-target	p(T1)	.895	.904	.899	.884	.860
Three-target	p(T1)	.786	.816	.799	.795	.773
Three-target	p(T2|T1 missed)	.847	.757	.773	.741	.763
Three-target	p(T2|T1 correct)	.780	.745	.761	.719	.745

Note. Values reported in the last two rows of the table were calculated after removing data from one subject because of an empty cell. The data set of Experiment 2 resulting from the exclusion of the subject with an empty cell was submitted to the same set of analyses outlined in this section, with no observable quantitative and/or statistical deviations from the results obtained considering the entire data set. T = target.

Collectively, the results mirror those of Experiment 1, with the AB strongly influenced by what occurred at lag-1. The present experiment demonstrates that the results of Experiment 1 were not an artifact of the sequential presentation of T1 and T2. Two targets presented simultaneously exhibited exactly the same characteristics with regard to the link between encoding of one or two targets and encoding of a following third target.

Experiment 3

In Experiment 3, we aimed to replicate the findings of the first two experiments when two- and three-target RSVP streams were randomly intermixed to assess the generality of our results and to rule out any strategic differences between blocks of trials. We employed the spatial configuration of Experiment 2; however, in two-target trials, T1 could appear either below or above fixation with the other location always containing "O"—a stimulus that was neither a member of the target nor a distractor set.

Method

The temporal and spatial structure of RSVP streams in Experiment 3 was identical to that of Experiment 2, except in two important aspects. In two-target RSVP streams, rather than displaying two simultaneous potential targets, only one target (T1) could be displayed above or below fixation with equal probability. In addition, no indication was given to subjects regarding the position of T1 in these streams, as two- and three-target RSVP streams were pseudorandomly intermixed within each block of trials. When only one target was displayed eccentrically, T1 was always accompanied by the letter "O" in the opposite spatial position, that is, by a character that was included in neither the target nor the distractor set. Subjects were instructed to report all targets they saw at the end of each RSVP stream. Each subject performed 600 trials, organized in 15 blocks of 40 trials each. The same feedback as in Experiments 1 and 2 on target(s) report was provided to subjects at the end of each trial. However, unlike Experiments 1 and 2, a single plus sign was displayed at fixation prior to the beginning of each RSVP stream.

Results and Discussion

A summary of the key results of Experiment 3 appears in Figure 6. Consistent with the first two experiments, the AB was more
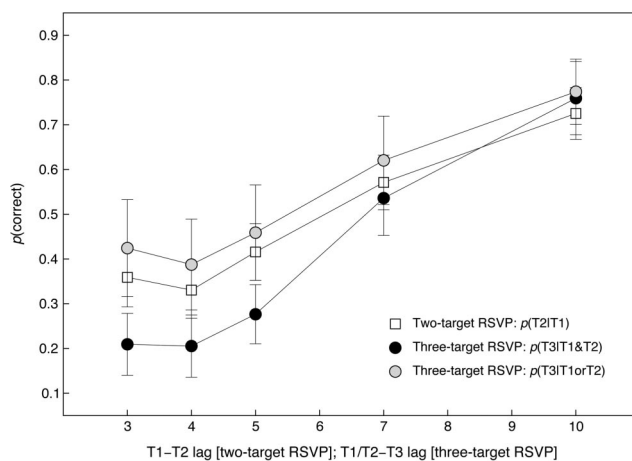

Figure 6. In Experiment 3, the mean proportion last target accuracy in the two- and three-target rapid serial visual presentation (RSVP) streams, plotted as a function of lag. In two-target RSVP streams, p(T2) is conditionalized on the correct report of T1—p(T2|T1). In three-target RSVP streams, p(T3) is conditionalized on the correct report of both T1 and T2—p(T3|T1&T2)—and on the correct report of either T1 or T2—p(T3|T1orT2). T = target. Bars are ± 1 *SEM*.

pronounced in three-target than in two-target RSVP streams, $F(4, 76) = 10.2$, $\eta_p^2 = .349$, $p < .001$, and the AB magnitude in the three-target RSVP streams was strongly attenuated when either pre-T3 target was missed, $F(4, 76) = 8.8$, $\eta_p^2 = .317$, $p < .001$. On average, T3 report contingent on either pre-T3 target being missed in three-target RSVP streams was slightly superior to T2 report in two-target RSVP streams, $F(1, 19) = 8.3$, $\eta_p^2 = .304$, $p < .001$. However, the ABs in these latter two conditions did not differ, and this did not depend on which pre-T3 target (T1 vs. T2) in three-target RSVP streams was correctly reported ($F < 1$).

T1 results are summarized in Table 3. T1 report was superior in two-target trials relative to the three-target RSVP trials, $F(1, 1) = 35.4$, $\eta_p^2 = .651$, $p < .01$, and T1 report varied across lags, $F(4, 76) = 3.8$, $\eta_p^2 = .167$, $p < .01$.

Table 3 suggests that lag effects could be due to the small drop in T1 report at lag-10 relative to the other lags. When the data from lag-10 were temporarily excluded from consideration, T1 report still differed between two- and three-target RSVP streams, $F(1, 19) = 32.5$, $\eta_p^2 = .631$, $p < .001$, but the effect of lag effect was no longer significant, $F(3, 57) = 2.0$, $\eta_p^2 < .1$, $p > .2$.

The key results of Experiment 3 replicate those of the earlier experiments, confirming the costs associated with sparing across

Table 3

Mean Proportion T1 and T2 Correct in Experiment 3 as a Function of Lag and Rapid Serial Visual Presentation Stream Condition

Lag		3	4	5	7	10
Two-target	p(T1)	.805	.814	.830	.807	.782
Three-target	p(T1)	.752	.738	.752	.728	.725
Three-target	p(T2|T1 missed)	.798	.839	.818	.818	.854
Three-target	p(T2|T1 correct)	.716	.716	.709	.715	.687

Note. T = target.

Table 4
Mean Proportion T1 and T2 Correct in Experiment 4 as a Function of Lag and Rapid Serial Visual Presentation Stream Condition

Lag		3	4	5	7	10
Two-target	p(T1)	.934	.955	.943	.950	.932
Three-target	p(T1)	.759	.768	.727	.744	.674
Three-target	p(T2|T1 missed)	.842	.856	.834	.815	.804
Three-target	p(T2|T1 correct)	.743	.702	.712	.714	.685

Note. T = target.

both space and time. Crucially, the results from this experiment rule out that strategic differences across blocks gave rise to the two- versus three-target results found in Experiments 1 and 2. Thus, we can be more confident in our conclusions about the capacity limits of attentional windows.

In this and the following experiment, eST^2 was not applied, because this model does not contain a component that simulates strategic differences between conditions that are blocked versus pseudorandomly intermixed. Thus, no differences between Experiment 2 and present experiment's simulated results would be obtained.

Experiment 4

As a final control, we sought to equate the extent to which attention was dispersed in our spatial two- and three-target RSVP streams to ensure that the previous differences observed were not due to the influence of spatial attentional focus. To do this, in the two-target trials, we increased the size of the target, and the item directly before and after it, so that it was approximately the same size as the two simultaneously presented targets in the three-target trials.

Method

A schematic representation of the design of Experiment 4 is displayed in Figure 7. In two-target RSVP streams (see Figure 7a), the size of T1 and temporally surrounding distractors was magnified so to cover an area equivalent to that occupied by the eccentric stimuli displayed in three-target RSVP streams (see Figure 7b). Two- and three-target RSVP streams were intermixed at random within each block of trials. Subjects were instructed to report all targets they saw at the end of each RSVP stream. Each subject performed 600 trials, organized in 15 blocks of 40 trials each. Response feedback and fixation marker were the same as in Experiment 3.

Results and Discussion

A summary of the key results of Experiment 4 is shown in Figure 8. The same pattern to that found in Experiments 1–3 was observed. The AB effect was more pronounced in three- than in two-target RSVP streams, $F(4, 76) = 15.9$, $\eta_p^2 = .455$, $p < .001$, and the AB effect in three-target RSVP streams was strongly attenuated when either pre-T3 target was missed, $F(4, 76) = 5.7$, $\eta_p^2 = .230$, $p < .001$. On average, T2 report in two-target RSVP streams was slightly superior to T3 report contingent on either
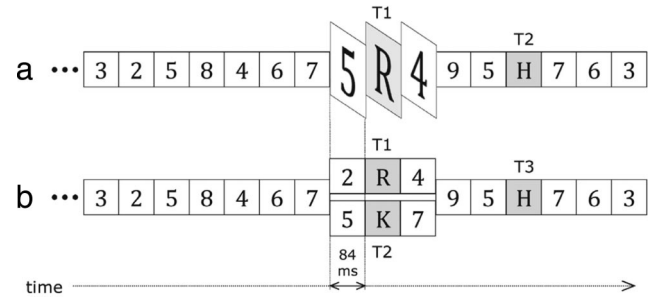

Figure 7. Design of Experiment 4. Two-target rapid serial visual presentation (RSVP) stream in which the size of T1, as well as that of the distractors in the T1 − 1 and T1 + 1 positions, was increased to cover the same area as that occupied by two simultaneous targets displayed above or below fixation in the three-target trials (a). T2 followed T1 at a varying lag. Three-target RSVP streams in which T1 and T2 were simultaneously displayed above or below fixation, followed by T3 displayed at a varying lag (b). The shaded background used in the figure highlights the to-be-reported targets in the different RSVP streams, although no actual change in background color or luminance occurred during the experiment. T = target.

pre-T3 target being missed in three-target RSVP streams, $F(1, 19) = 27.5$, $\eta_p^2 = .592$, $p < .001$. However, the ABs in these two conditions did not differ significantly, and this did not depend on which pre-T3 target (T1 vs. T2) was correctly reported ($F < 1$).

T1 results are summarized in Table 4. Again, T1 report was superior in two- relative to three-target RSVP streams, $F(1, 19) = 118.4$, $\eta_p^2 = .862$, $p < .001$, and varied across lag, $F(4, 76) = 10.2$, $\eta_p^2 = .349$, $p < .01$. The analysis also indicated that lag effects differed between two- and three-target RSVP streams, $F(4, 76) = 7.5$, $\eta_p^2 = .282$, $p < .001$.

Based on analogous results in the present set of experiments, the data were reanalyzed following the temporary exclusion of the
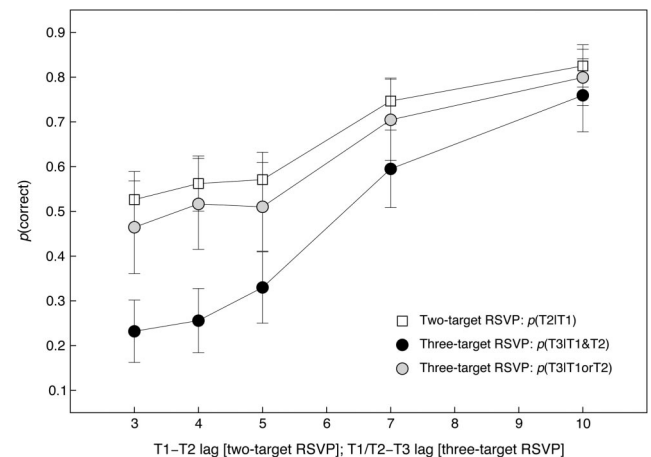

Figure 8. In Experiment 4, the mean proportion last target correct in the two- and three-target rapid serial visual presentation (RSVP) streams, plotted as a function of lag. In two-target RSVP streams, p(T2) is conditionalized on the correct report of T1—p(T2\|T1). In three-target RSVP streams, p(T3) is conditionalized on the correct report of both T1 and T2—p(T3\|T1&T2)—and on the correct report of either T1 or T2—p(T3\|T1orT2). T = target. Bars are ± 1 *SEM*.

values at lag-10. In this analysis, T1 report still differed between two- and three-target RSVP streams, $F(1, 19) = 103.8$, $\eta_p^2 = .845$, $p < .001$, and marginally across lags, $F(3, 57) = 2.6$, $\eta_p^2 = .130$, $p < .06$.

An identical pattern of results was observed here relative to the earlier experiments. Thus, it appears as if sparing is not without its capacity limits, and the differences found between performance on two- and three-target RSVP conditions are consistent across space and time and do not reflect differences in strategy or, as the current experiment demonstrates, the spatial dispersion of attention.

General Discussion

We investigated the extent to which failures of perception during attentional episodes influence encoding in subsequent episodes. To do this, we presented subjects with three-target RSVP streams, in which T1 and T2 appeared sequentially or simultaneously (and consequently in the same attentional window) and T3 was separated from T2 by varying lags. We then assessed the AB observed for this final target as a function of whether both T1 and T2, or just one of these items, was accurately reported. The magnitude of the AB for T3 was strongly influenced by the number of targets reported from the T1–T2 episode, not the number of targets presented. There was a much larger AB observed for T3, when both T1 and T2 were reported, as opposed to only one of these stimuli was correctly identified.

Of import, this effect was observed independently of whether it was T1 or T2 that was missed and, surprisingly, the AB observed for T3 under these conditions did not differ from that obtained under dual-target RSVP conditions when lag was manipulated between T1–T2. In addition, an identical pattern of results was observed whether T1 and T2 were presented simultaneously at two locations or sequentially at one location. We were also able to demonstrate that the present results also do not reflect strategic effects because blocking two- and three-target RSVP streams did not alter the observed pattern.

Collectively, the empirical results suggest that it is the amount of information encoded within one attentional episode that drives the AB magnitude in a subsequent episode. Of note, it appears that processing of either target presented at lag-1, or indeed during simultaneous presentation (lag-0), has an all-or-none effect on subsequent target encoding. When a target item is missed, there is no difference in performance relative to when a distractor is presented in its place, even though, in both cases, the target and distractor would be processed in an attentional window along with another target. Previously, we had shown (Dell'Acqua et al., 2012) that sequential target presentation in RSVP, nevertheless, was influenced by structural limitations, because performance under these conditions was inferior to that when the targets were each separated by seven distractors. Here, we provide an important extension to these results by showing that the load at lag-1 or lag-0 influences subsequent target performance. Put differently, sparing comes at a cost, because it impairs identity encoding in following attentional windows.

The relevance of this result lies in understanding what role is played by structural limitations in the encoding of information into working memory and, specifically, during sparing. The present results suggest that the number of encoded targets within an attentional episode determines the depth of the ensuing AB, and

this is consistent with a role of structural encoding limitations in determining performance.

To explore this point further, we employed the eST^2 model of temporal attention (Wyble et al., 2009; Wyble et al., 2011) to examine the mechanisms that underlie our results. This framework postulates that both mutual type interference, within attention windows, and the suppression of attentional enhancement contribute to the size of the AB. For Experiments 1 and 2, wherein the former T1 and T2 appeared sequentially and in the latter simultaneously, we used the model to explore the contribution of mutual type interference to the deeper AB on trials in which both targets were reported. These "modeling experiments" where definitive in their outcomes: mutual type interference between the two targets being encoded together is essential for replicating the deeper AB on trials in which both targets were reported, relative to trials in which either T1 or T2 was reported. Without mutual type interference, the success or failure of encoding played no role in determining the depth of the AB (see Figure 9 for representative simulations from the eST^2 model). These traces illustrate the

a. T1 and T2 encoded
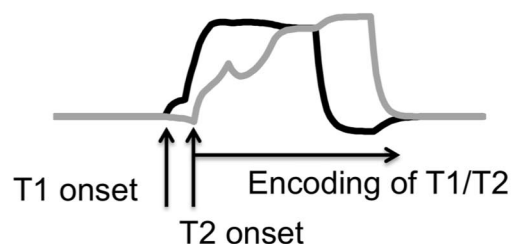
b. Only T1 encoded

c. T1 and T2 encoded

Figure 9. Activation traces for T1- and T2-type nodes presented at lag-1 in simulations from the eST^2 model. Each trace represents the activity of a type during encoding into memory. The magnitude of the AB produced by the encoding of T1 and T2 is related to the duration of encoding, with longer durations producing a deeper blinks. These traces illustrate why the AB is deeper on trials in which both targets are encoded (a) as opposed to when one of the targets is not encoded (b). Also, when type interference is artificially deactivated (c), T1 and T2 are encoded with the same duration as when a single target is encoded. T = target.

relative duration of encoding when T1 and T2 are both encoded (see Figure 9a), when only T1 is encoded (see Figure 9b), and when both targets are encoded but mutual type activity is artificially deactivated (see Figure 9c). It is clear that even though the model can encode T1 and T2 simultaneously, the type interference causes some of the T2 encoding to occur after T1 encoding. Of import, it must be noted that this is not data fitting (see also footnote 1), because the parameters of the eST^2 model were not altered compared to its original description (Wyble et al., 2009) or our previous investigations (Dell'Acqua et al., 2012). Put simply, the present simulations reflect predictions inherent to the theory and demonstrate that both attentional selection and capacity limitations influence the temporal profile of performance in these tasks. More specifically, interference between targets prolongs the duration of encoding both targets during lag-1 sparing and this, in turn, causes a deeper AB for a following third target.

Dell'Acqua et al. (2012) tested the ability of several other prominent AB models to simulate their finding of impaired report for three sequential targets relative to those each separated by seven distractors. Along with the eST^2 model, the threaded cognition model (Taatgen et al., 2009) simulated the results, for despite being an account that predicts the AB only reflects strategic attentional processing, it actually has a structural limit because the application of a strategic rule takes slightly longer than 100 ms (the standard RSVP rate), impairing three-target report. Oliver and Meeter's (2008) boost and bounce theory explicitly excludes capacity limitations in the ability to encode multiple targets in rapid sequence (apart from a limit on the number of working memory slots), and suggests that the AB is entirely the result of a mechanism intended to keep distractors out of working memory. This model could not simulate the results of Dell'Acqua et al. (2012). We do not simulate these models here because the threaded cognition model's rule application timing is hard wired into the broader class of ACT-R ("adaptive control of thought—rational"; Anderson, 2007) frameworks on which it is based and, thus, is difficult to turn on and off as we did with the eST^2 model (Wyble et al., 2009; Wyble et al., 2011). In regard to the boost and bounce model, this theory does not simulate single trials and, consequently, one cannot not apply conditional analyses, which are crucial for the current study.

Attractor Dynamics Produce Highly Nonlinear Activity

One of the most surprising aspects of the data is that depth of the AB produced by the successful encoding of T1 or T2, but not both, was almost exactly equivalent to the AB evoked by a single target. Instead, one might have expected that a failed encoding of either target would have produced at least some interference, such that p(T3|T1orT2) would have shown an AB that was smaller than p(T3|T1&T2) but also larger than the AB calculated by p(T2|T1).

The eST^2 model suggests that we can understand this counterintuitive finding as evidence of attractor dynamics at the time of encoding, which produce a highly nonlinear relationship between the initial activation of a type representation and the amount of encoding activity it produces. In the model, encoding is the result of a recurrent excitatory circuit between a type node and the binding pool (which is the substrate for working memory storage in the model). There is a threshold for initiating this attractor state,

and a type node that fails to hit this level of activation will produce much less activity than a type node that crosses this threshold (see Figure 10). Because the mutual type interference is essentially computed as the integral of the amount of type activity shown in Figure 10, a failed encoding produces virtually no type interference relative to a successful encoding. Note that these traces illustrate T2 at different levels of strength, but the dynamics work similarly for T1 as well. Like T2, a first target stimulus, which is just short of the threshold to initiate encoding, will fail to enter the attractor state and will, consequently, produce dramatically less interference for the T2.

On the Representational Status of Missed Targets in the AB

The present results suggest a fundamental distinction between targets missed because of the AB and targets missed at lag-1. On top of a general failure to engage consolidation (or binding) mechanisms, we argued that missed targets at lag-1 suffer from mutual type interference, implying that activation of the corresponding type representations is attenuated for such targets. This hypothesis is supported by simulations from the eST^2 model, which illustrate the influence of mutual type interference on the T2 activation trace in Figure 10. Note that T2 activity is negative prior to T2 onset, which is due to the suppression from T1 encoding. This suppression might help to reconcile the flood of studies that have shown priming from missed targets during the AB, some of them overviewed in the Introduction, with the nil impact of lag-1 missed targets on T3 report repeatedly found in the present series of experiments. Whereas an AB-induced failure to engage consolidation or binding mechanisms does not prevent full activation and persistence of a type representation from a missed target during the AB (Maki et al., 1997; Shapiro et al., 1997), lag-1-missed targets' conceptual representation may be effectively suppressed.

Conclusion

The goal of the current work was to better understand the dynamics of attentional windows and, to do this, we employed
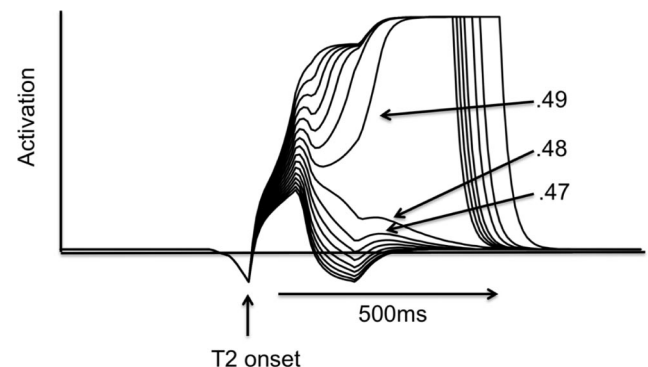

Figure 10. Activation traces for a T2-type node, presented at lag-1 (T1 not shown) in simulations from the eST^2 model. Each trace represents the activity of the type node for a different level of the input strength, from .40–.55 in steps of .01. The attractor dynamics involved in encoding cause a highly nonlinear amount of activation in the T2 neurons such that a small increment in input strength produces a dramatic increase in activity that is coincident with successful encoding. T = target.

sparing where two targets are encoded readily when presented in close temporal and spatial proximity. This was accomplished by examining the impact of encoding these targets on a subsequent third target in a variety of conditions. Collectively, our results clarified that the encoding of two targets at lag-1 (or lag-0) comes at a cost for encoding subsequent information. In the terms of attentional episodes, the more information that is successfully encoded during an episode, the longer the consequent AB. Comparison with simulations from the eST^2 model provided evidence that this additional cost is primarily caused by structural limitations in the encoding of multiple type nodes at the same time.

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