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Delay of selective attention during the attentional blink

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ABSTRACT

The attentional blink is the inability to report the second of two targets in an RSVP stream when they are separated by 200–500 ms. Recent evidence shows that this failure results from three dissociable changes to the properties of temporal selective attention. During the attentional blink, selection is suppressed (items are selected less effectively, resulting in greater levels of random guessing), diffused (more letters around the target are selected), and delayed (the items that are selected tend to be later in the RSVP stream relative to the cue) [Vul, E., Nieuwenstein, M., & Kanwisher, N. (2008). Temporal selection is suppressed, delayed, and diffused during the attentional blink. *Psychological Science, 19*(1), 55–61]. Here we assess the properties of the delay in selection and evaluate how the delay contributes to the attentional blink. First, by pre-cueing, we manipulate the delay of selective attention and show that neither delay nor suppression alone is sufficient to account for the failure to report the second target; thus both play a role in the usual attentional blink. Second, we explore the persistence of the delay effect over much longer T1–T2 SOAs and show that the effect remains strong at lags of 1400 ms and appears to subside with a time-constant of roughly 500 ms. Third, we manipulate RSVP rate and find that the "delay" of selection is a delay in time, independent of the number of items.

1. Introduction

Visual selective attention is the mechanism by which people select a subset of their visual stream for detailed perceptual processing and explicit report. For instance, when asked "Which book is on the top shelf?" we must select a subset of visual space (the top shelf), and identify the object present therein—this *spatial* selection is the most commonly studied form of selective attention. Similarly, we may also ask about *temporal* subsets of the visual input, e.g., "Where was the quarterback looking when he was sacked?" To answer this question we have to select a subset of *time* and identify an aspect of the visual scene at that point in time. In both domains, failures of selective attention are diagnostic of underlying mechanisms.

The most documented failure of temporal selective attention is the attentional blink (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992): when two targets appear in close temporal proximity (200–500 ms), observers have difficulty identifying the second target. Although some accounts of the attentional blink have postulated that this failure occurs because of bottlenecks in short-term memory (Chun & Potter, 1995), or because of the central bottleneck responsible for the psychological refractory period (Jolicoeur, Dell'Acqua, & Crebolder, 2000), recent findings suggest that, instead, the attentional blink reflects a failure of visual selective attention (Nieuwenstein, 2006; Nieuwenstein, Chun, ven der Lubbe, & Hodge, 2005; Nieuwenstein & Potter, 2006; Olivers, Van der Stigchel, & Hulleman, 2007; Vul, Nieuwenstein, & Kanwisher, 2008; Olivers, 2007; Raymond et al., 1992).

The failure of temporal selective attention under attentional blink conditions can be evaluated with precision by studying distracter intrusions: when the target is incorrectly reported, what is reported in its place? Several groups found that under single and dual target conditions, selective attention is not perfectly accurate, and temporally proximal items are often reported instead of the target (Botella, Garcia, & Barriopedro, 1992; Reeves & Sperling, 1986; Weichselgartner & Sperling, 1987). Vul et al. (2008) investigated the frequency with which particular serial positions from the RSVP stream are reported (the distribution of reports), and showed that the pattern of these intrusions reveals three independent dimensions along which temporal selection changes due to the attentional blink. These three dimensions may be characterized by summary statistics of the distribution of reports. First, fewer items in the vicinity of the target are selected at all, thus the report distributions will be closer to chance (uniform guessing); this means that selection during the blink is less effective, or "suppressed". Second, the above-chance reports come from a wider range of serial positions around the target; if normally only the two items adjacent to the target are reported above chance, this range may expand to the four nearest items during the attentional blink. That is, selection is rendered temporally less precise, or "diffused". Finally, the entire distribution of selected items, suppressed and diffused though it may be,

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is shifted later in the visual stream, suggesting that selection is rendered systematically inaccurate, “delayed” (see also Chun, 1997; Popple & Levi, 2007) note that this delay is different than the general latency of the attentional gate (Reeves & Sperling, 1986) as it is caused by the interaction of two selection episodes. These three effects may be measured independently and follow different time courses, suggesting that they reflect independent processes (Vul et al., 2008). The delay effect has the slowest time-course of recovery, showing considerable differences between the first and second target even after SOAs of nearly one second. In this paper, we ask three further questions about the delay of temporal selective attention during the attentional blink.

First, is failure to report the second target due to the effect of delay? Several lines of research suggest that delay may be wholly responsible for the attentional blink. Nieuwenstein et al. (2005) and Nieuwenstein (2006) reported that pre-cueing the second target mitigates the attentional blink. Moreover, Popple and Levi (2007) recently showed that although the target is reported less often during the attentional blink, letters within a 7-item window around the target are reported equally often, suggesting that although selection is less accurate (delayed), it is just as effective (not suppressed) during the attentional blink. These findings suggest that the attentional blink may be largely due to delay, in disagreement with the results of Vul et al. (2008), which reported substantial and independent effects of both suppression and delay. In Experiment 1, we measure the contributions of suppression and delay to the attentional blink and show that neither alone is sufficient to account for observers’ inability to report the second target.

Second, we measure the time-course of the delay effect at longer SOAs. Previously, we have shown that the delay in temporal selection lasts up to 833 ms, and extrapolation of the recovery curve suggests that it would not recover to T1 levels for roughly two seconds (Vul et al., 2008). In Experiment 2, we test this prediction by slowing the RSVP stream and measuring delay to SOAs of 1400 ms. We find a significant delay effect at long SOAs, and using these data, we estimate the time-course with which the effect returns to baseline (T1) levels.

Third, we ask whether the delay is a function of time or serial position. This question bears on the properties of selective attention more broadly. One possibility is that selective attention operates over discrete objects (Kahneman, Treisman, & Gibbs, 1992), regions (Huang & Pashler, 2007), or events (Chun, 1997). If this were the case, the delay should reflect a tendency to select later serial positions and should have constant magnitude when expressed as a function of serial position. Another possibility is that selective attention may operate continuously over time and space (Reeves & Sperling, 1986; Shih & Sperling, 2002). In this case, delay should have constant magnitude when expressed as a function of time. We test these two possibilities by presenting RSVP streams at 60 ms/item and 120 ms/item. We find that given a specific (temporal) SOA, delay has equal magnitude when measured in units of time and different magnitudes when measured in terms of serial position. These results indicate that ‘delay’ is a delay in time, rather than serial position, suggesting that selective attention operates continuously in time, rather than over discrete events or objects.

2. Experiment 1

First, we investigated the extent to which delay and suppression of selective attention contribute independently to the attentional blink. Earlier work showed that pre-cueing with a second cue almost completely relieved the blink (Nieuwenstein et al., 2005). In their task, subjects had to identify two red digits among gray letters, when the letter preceding the second digit was red (“precued”) the attentional blink was reduced. However, this pre-cuing manipulation adds a second cue (another red object) not just an earlier cue, and this second cue may serve to increase the efficacy of selective attention, relieving suppression, rather than delay. Thus, the improvement may reflect the benefit of an *additional* cue or the benefit of an *earlier* cue. If the benefit observed by Nieuwenstein et al., 2005 was entirely due to an earlier cue, then it would seem that the delay of selective attention is entirely responsible for the deficiency in reporting the second target—this was the conclusion the authors advocated. However, the pre-cueing benefit may also reflect, in part, the presence of a second cue that could relieve suppression. In this case, the observed benefit does not justify the conclusion that delay is wholly responsible for the usual attentional blink. Unlike the previous work on pre-cueing, our cue could be separated from the target both spatially (as it is an annulus surrounding the letters, rather than the color of the letter itself) and temporally, thus allowing us to manipulate its onset in time independently of the onsets of the targets. Thus, we could cue earlier without cueing twice. With this manipulation, we could alter ‘delay’ independently of other effects (e.g., ‘suppression’ or ‘diffusion’), to investigate the extent to which the attentional blink reflects a systematic inaccuracy (delay) in selective attention and to what extent it reflects decreased efficacy (suppression).

2.1. Method

2.1.1. Participants

Nine participants between the ages of 18 and 30 were recruited from the Massachusetts Institute of Technology subject pool and were paid for participation.

2.1.2. Stimuli and design

On each trial, subjects saw an RSVP stream composed of one instance of each of the 26 English letters in a random order. Two annulus cues appeared in the RSVP stream, indicating the first and second target letters (T1 and T2) to the participant. At the end of the trial, subjects were asked to report both targets via a keyboard. Because no letter appeared twice on any trial, we could identify the exact serial position from which the letters reported by the subject originated; thus allowing us to assess the distribution of selection across trials.

We manipulated two parameters of stimulus presentation: the lag between the first and second target (T1–T2 SOA) and the lag between the second cue and the second target (C2–T2 SOA). On each trial the T1–T2 SOA was randomly assigned to be either 4 or 12 items (278 and 840 ms). Trials with a lag of 4 items were well within the attentional blink, while lag 12 trials were outside the typical attentional blink window.

The time between the first cue and the first target was always 49 ms, meaning that the annulus appeared 49 ms before the target. However, we varied the time between the second cue and the second target to be 70, 49, 21, or 0 ms. As illustrated in Fig. 1, a C2–T2 SOA of -70 ms indicates that the cue appeared simultaneously with the letter preceding the second target. A C2–T2 SOA of -49 or -21 ms indicates that the cue appeared in the blank gap between the second target and the preceding letter. Finally, a C2–T2 SOA of 0 ms indicates that the cue appeared simultaneously with the second target. Thus, we could pre-cue the second target without introducing a second cue.

Each letter was presented for 21 ms and was followed by a 49 ms blank, resulting in an RSVP rate of 14.3 items/s. The first (T1) cue appeared for the full duration of the 49 ms blank before the first target. The second (T2) cue appeared for only 21 ms with a randomly chosen onset, as described above. To prevent subjects from anticipating when cues would appear, the onset of the first target was randomly chosen on each trial to be in one of the serial positions 6–10.

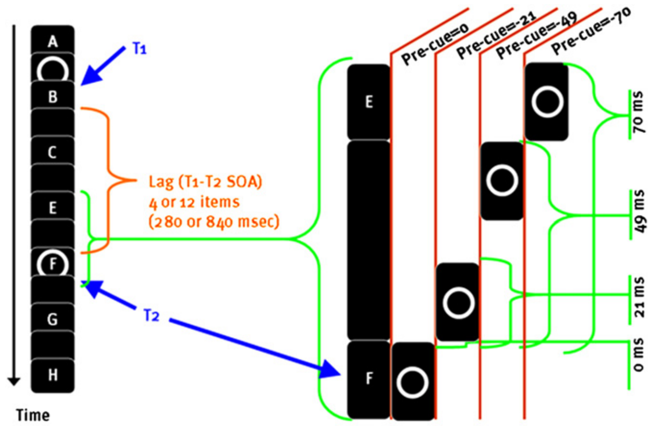

Fig. 1. Experiment 1 design. We manipulated the lag between the first and second target (T1–T2 SOA), as well as the lag between the second *cue* and the second *target* (C2–T2 SOA). Thus, we could manipulate how early attention was cued without disturbing the rest of the stimulus sequence.

Letters were white on a black background, capitalized, in size 48 Courier font. With our resolution (1024 × 768), monitor (Viewsonic G90f), and viewing distance (roughly 50 cm), letters subtended roughly 2.5 degrees of visual angle. Cues were white annuli with an inner diameter of 2.8 degrees and an outer diameter of 3.2 degrees; thus they appeared as rings around the RSVP letter sequence.

The experiment was programmed in PsychToolbox (Brainard, 1997) on Matlab 7 on a Windows XP computer.

2.2. Procedure

Each participant began the experiment with two practice trials that had a random T1–T2 SOA; the results of these trials were discarded. Following the practice trials, participants completed 5 blocks of 80 trials each.

Each block contained 2 instances of each of the possible 40 permutations of T1 onset (five levels: serial positions 6–10), T1–T2 SOA (two levels: lags of 4 or 12 items) and C2–T2 SOA (four levels: 70, 49, 21, or 0 ms). For instance, in a trial with T1 onset at item 6, a T1–T2 SOA of 4 items, and a C2–T2 SOA of 21 ms, the first cue would appear 49 ms before the 6th item (T1) and the second cue would appear 21 ms before the 10th item (T2) in the sequence. These conditions appeared in a random order within each block.

At the end of each trial subjects were asked to indicate which two letters they thought were cued by the annuli. Subjects reported the letters by pressing the corresponding keys on the keyboard. Duplicate letters were not accepted and subjects were told to report the first letter first and the second letter second (feedback and scoring on each trial reflected this instruction). In addition to the flat rate of $10 for participation, participants were offered bonus cash awards for performance: $0.01 for each letter correctly reported (on average subjects correctly reported about 150 letters across all trials in a given session: a $1.50 bonus). This bonus was provided as an incentive for subjects to try to correctly report the cued letters given particularly difficult conditions.

2.3. Results and discussion

Any letter appeared only once in the RSVP stream, thus allowing us to identify the exact serial position from which any reported letter originated on any given trial. Thus, we could compute the distribution of reported letters as a function of serial position relative to the cue. Fig. 2 shows these report frequencies for the first target (a), second target (b) and the second target when the first target was reported correctly (c). We see a pre-target intrusion pattern around the first target, an effect previously reported under particular conditions (Botella et al., 1992). Two previously reported effects of the attentional blink may be seen in Fig. 2 (Chun, 1997; Popple & Levi, 2007; Vul et al., 2008): compared to T2 reports with a sufficiently long lag (12 items), when the lag is just 4 items, subjects systematically report items from later serial positions in the RSVP stream and subjects report fewer of these items.

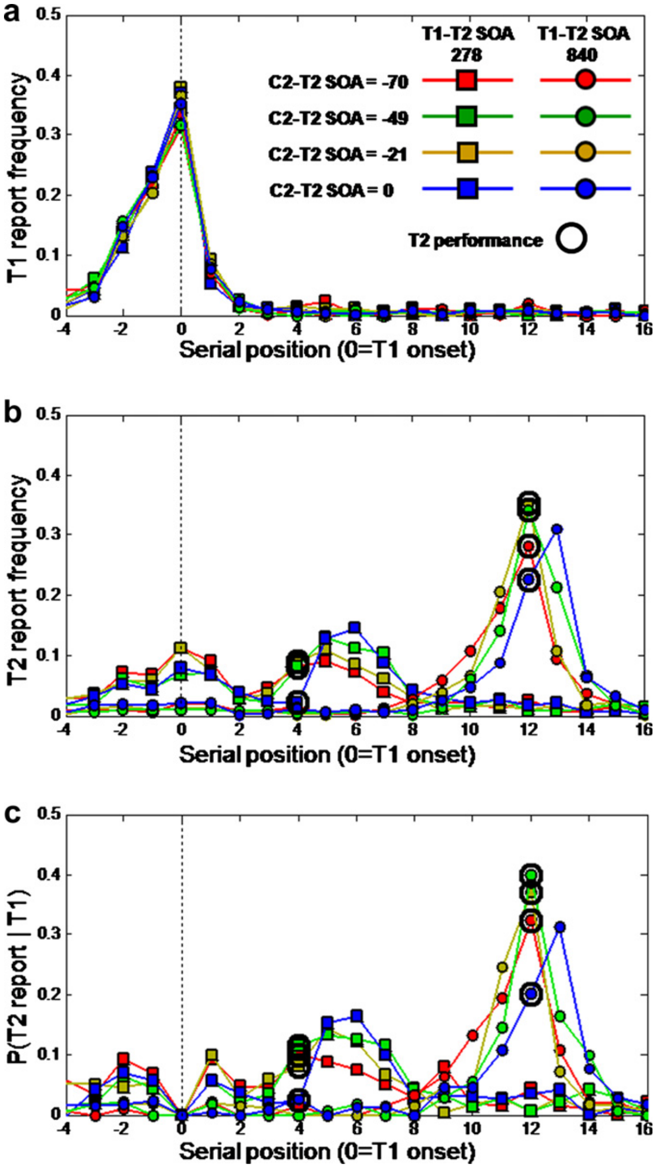

Fig. 2. Experiment 1 results: raw frequencies. For each C2–T2 and T1–T2 SOA condition we show the empirical frequencies (*y*-axis) with which any given serial position (*x*-axis) was reported as the first target (a), the second target (b), and the second target given that the first target was reported correctly (c). The *x*-axis is aligned such that 0 always corresponds to the first target.

These changes to the distribution of reports due to the attentional blink have been called 'delay' and 'suppression' of selective attention and may be quantified via summary statistics of the report histograms (Vul et al., 2008). We calculated the selection statistics for a 7-item window around the target: mean report probability (a measure of suppression; Eq. (1) in Appendix

A), center of mass (a measure of delay; Eq. (2a) in Appendix A), and variance of the center of mass (a measure diffuseness; Eq. (3) in Appendix A).[1] These measures are plotted along with Target 2 accuracy in Fig. 3 as a function of C2–T2 SOA for both T1–T2 SOA conditions.

Several predicted differences may be observed between a T2 within the blink (T1–T2 SOA of 4 items) and a T2 outside of the blink (T1–T2 SOA of 12 items). Target accuracy is greater for T2 at the long SOA than the short SOA (Fig. 3d; for all C2–T2 SOA conditions, $t(8) > 6.4$, $p < .01$). Mean probability of report is greater for a T2 outside of the blink, reflecting suppression (Fig. 3a; for all C2–T2 SOA conditions, $t(8) > 3.9$, $p < .01$). The variance of the center of mass is greater for a blinked T2, reflecting diffusion (Fig. 3c; for all C2–T2 SOA conditions, $t(8) > 4.9$, $p < .01$). Finally, the center of mass is greater for a T2 within the blink, reflecting delay (Fig. 3b; C2–T2 = −70: $t(8) = 1.46$, $p < .1$; C2–T2 = −49: $t(8) = 3.13$, $p < .01$; C2–T2 = −21: $t(8) = 2.5$, $p < .05$; C2–T2 = 0: $t(8) = 1.53$, $p < .1$). These effects have been reported before (Chun, 1997; Vul et al., 2008). Our present question is to what extent delay and suppression for blinked T2 account for the decrement in accuracy.

We now turn to our pre-cueing manipulation: varying C2–T2 SOA. When the second target is cued earlier, delay is reduced, as evidenced by the positive slope of the center of mass of reports as a function of C2–T2 SOA (Fig. 3b). However, suppression does not change systematically as C2–T2 SOA varies (Fig. 3a). Thus our pre-cueing manipulation had the predicted effect and successfully teased apart suppression from delay, indicating that we can manipulate delay independently of suppression.

A T2 within the blink with a C2–T2 SOA of 70 ms has the same (or smaller) amount of delay (center of mass: −0.03) as a T2 outside of the blink with a C2–T2 SOA of 21 ms (center of mass: 0.14); the same is true of a T2 within the blink with a C2–T2 SOA of 49 ms (center of mass: 0.28) and a T2 outside of the blink with a C2–T2 SOA of 0 ms (center of mass: 0.40). Thus, delay is equated in these two pairs (or at least, the T2 outside of a blink has a greater, less accurate, center of mass). However, in both pairs, T2 report accuracy is significantly greater for a T2 outside of the blink than a T2 within the blink (pair 1: $t(8) = 6.96$, $p < .01$; pair 2: $t(8) = 4.97$, $p < .01$). Because in these conditions delay is equivalent (even biased against the longer SOA) and performance still reflects the typical advantage of a longer SOA seen in the attentional blink, this pattern indicates that delay alone is not sufficient to account for the usual attentional blink performance deficit.

Can suppression alone account for the attentional blink? We asked this question by comparing suppression and target 2 accuracy for the T2 within a blink at a C2–T2 SOA of 0 ms. In this condition, the average probability of reporting an item in a window around T2 is substantially higher than chance (.07 compared to .04; Fig. 5a; $t(8) = 3.4$, $p < .01$), indicating that subjects reliably report items around the target. However, target 2 accuracy is significantly *below* chance (.022 compared to .04; Fig. 5d; $t(8) = 2.53$, $p < .05$). This pattern indicates that although subjects can reliably report letters around T2 (subjects are more likely than chance to report letters within a window around the target), they *reliably* report the *wrong* letters: the letters after T2 rather than T2 itself. These results indicate that suppression alone does not account for the T2 performance deficit during the attentional blink and that the delay of selective attention further reduces T2 performance.

These results show that suppression and delay are independent, in that delay may be manipulated without manipulating suppression. Furthermore, neither delay nor suppression alone is sufficient to account for the performance decrement during the attentional blink, indicating that in classically reported attentional blink tasks, both delay and suppression contribute to the performance hit seen at SOAs within the blink.

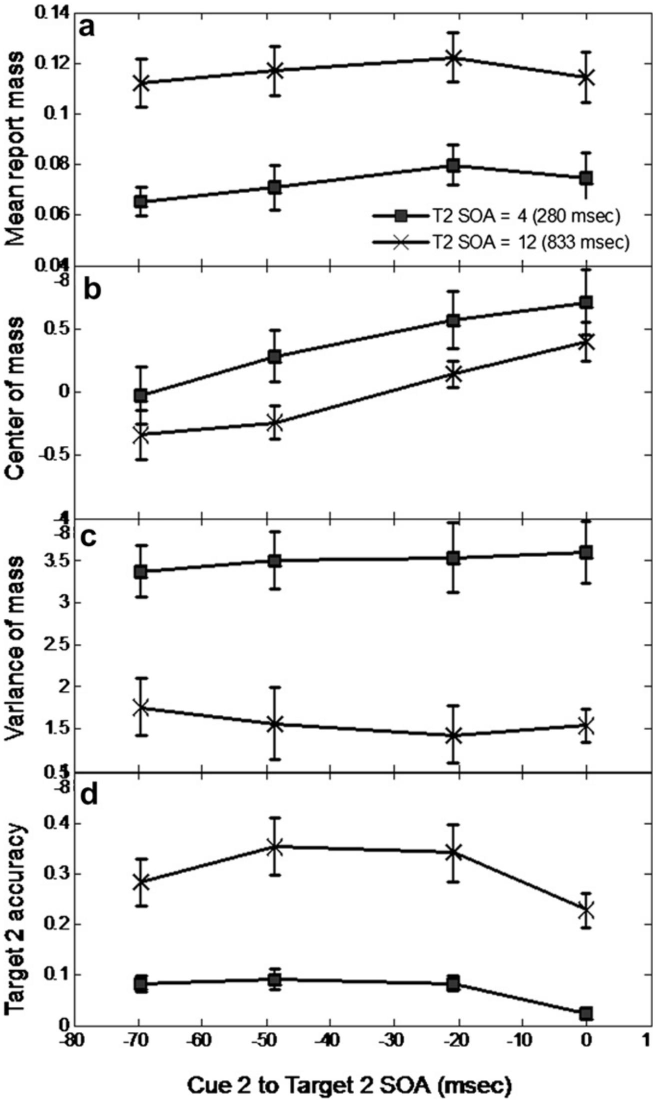

Fig. 3. For each C2–T2 SOA (*x*-axis) and T1–T2 SOA (280 ms: solid line; 833 ms: dashed line) we show (a) the mean probability of reporting an item in a 7-item window around the target (a measure of 'suppression'); (b) center of mass (in items) of the reported serial position in that target window (a measure of 'delay'); (c) variance of the center of mass (a measure of 'diffusion'); and (d) target 2 report accuracy. See text for discussion.

3. Experiment 2

Previous research has shown that delay lasts substantially longer than suppression: up to 833 ms (Vul et al., 2008). In Experiment 2, we estimated how long the delay of T2 persists. We slowed our RSVP stream to allow SOAs up to 1400 ms and estimated the rate at which the delay of selective attention for T2 returned to T1 levels.

3.1. Method

3.1.1. Participants

Seventeen participants between the ages of 18 and 30 were recruited from the same Massachusetts Institute of Technology subject pool and were paid for participation.

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[1] Formulae for these computations in the Appendix are reprinted from Vul et al. (2008).

3.1.2. Stimuli and design

As in Experiment 1, subjects saw an RSVP stream on every trial (although presented at a slower rate—10 items/s). We manipulated the T1–T2 SOA to be either 2, 4, 6, 8, 10, 12, or 14 items (200–1400 ms).

Letters were presented for 33 ms each and followed by a 67 ms blank (an RSVP rate of 10 items/s). The cue-target SOA was always 67, meaning that the cue appeared in the blank period before the target letter.

3.2. Procedure

The procedure was identical to that of Experiment 1, including bonus cash rewards for performance. However, the number of trials for each participant was changed to 5 blocks of 70 trials each.

3.3. Results and discussion

Just as in Experiment 1, because any letter appeared only once, we could compute the frequency with which any serial position was reported, relative to the onset of the cue. In this experiment, we were specifically interested in the persistence of the delay effect. Again, we computed the magnitude of the delay as the center of mass (Eq. (2a) in Appendix A) for each SOA. These results are shown in Fig. 4.

The distribution of target 2 reports is significantly delayed when T1–T2 lag is greater than 2 items (200 ms). This is true at all lags greater than 2 items (all $t(16) > 1.75$, $p < .05$).[2] This means that the delay effect lasts at least 1400 ms.

From our data, we can also compute the rate at which the T2 delay effect returns to T1 levels. Since relative center of mass may be altered by the timing of the annulus cue, we define delay as the difference in center of mass between 'normal' (T1) selection and selection for T2. We fit an exponential decay function to our observed delay, defining the observed delay to be equal to the maximum delay (D) at 364 ms (an estimate from Vul et al., 2008, as well as the marginal mean fit to our current data), and then decays as the SOA (in ms) increases, with a time-constant of tau:

$$Delay = D\exp(-(t-364)/\tau)$$

From the function fit we estimated the time-constant (tau) with which delay returns to T1 levels. This value is 586 ms (±78, SD). The peak delay (D) corresponds to a shift of the center of mass by slightly less than 1 item (0.76 ± 0.06 SD), roughly 75 ms[3] ($R^2 = 0.93$). From these numbers one can predict the magnitude of delay at particular SOAs or the SOA required to achieve a particular delay: for instance, to obtain a delay effect at 10% of maximum, the T1–T2 lag required is roughly 1.7 s. From our results here and those of Vul et al. (2008), the delay effect declines with increasing SOA, suggesting a transient effect. However, because we do not observe *any* SOA at which the center of mass of target 2 reports is equal to that of target 1, it is possible that the 'delay' effect never returns to baseline. Such a possibility may be consistent with a fixed cost for storing target 1 in short-term memory, which precludes 'normal' operation of selective attention. Whether the delay ever returns to baseline (target 1 levels) will be an important question for future research to characterize this aspect of the attentional blink.

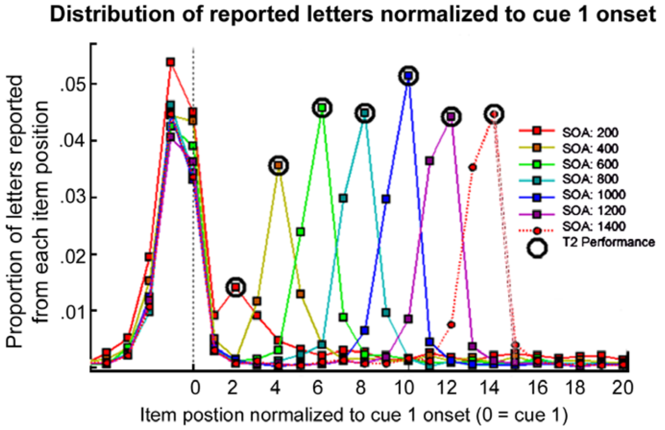

Fig. 4. Experiment 2 results: raw data. As in Fig. 2 we plot the empirical frequency (y-axis) with which a particular serial position (x-axis normalized to T1 onset = 0) is reported as a function of T1–T2 SOA. The black circles indicate the positions corresponding to the second target (T2 accuracy). The dashed line indicates the T1 position.

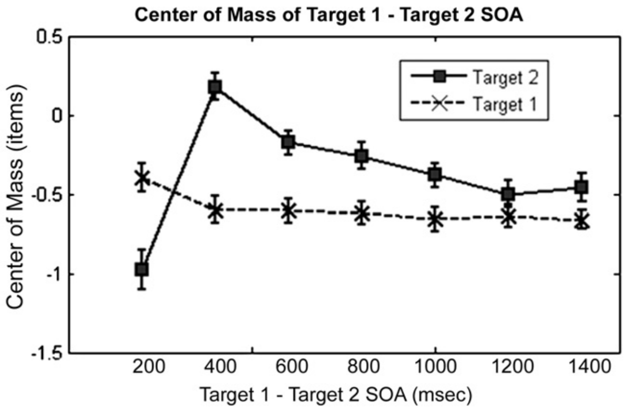

Fig. 5. Experiment 2 results: center of mass (y-axis, in items) as a function of T1–T2 SOA (x-axis, in ms) up to 1400 ms. At SOAs greater than 400 ms, center of mass for T2 reports is significantly delayed relative to the center of mass for T1 reports, and this delay effect appears to decay in magnitude with a time-constant greater than 500 ms.

Whether the delay effect we observe is transient or persistent, the effect remains at 25% peak magnitude at an SOA of 1400 ms, long after the usual measure of the attentional blink (target 2 accuracy) has recovered to target 1 levels (Fig. 5). This finding indicates that the commonly reported, brief (500 ms) inability to report the second target, is just one, relatively short-lived, change to the properties of temporal selective attention change arising from the interaction of two proximal selection episodes. It is interesting to note that most attentional blink research considers a second target presented at an SOA of 900 ms to be 'outside' of the blink; however, in this experiment we show that at that SOA, selective attention does not yet operate 'normally', that is, identically to its operation during the first target.

4. Experiment 3

So far we have been investigating delay (change to the center of mass of reports) as a function of serial position. However, it is important to ascertain whether selective attention is delayed in serial position or in time. One possibility, suggested by serial processing models of the attentional blink, is that temporal selective attention operates over symbolic representations—individual items (Chun & Potter, 1995). However, another camp suggests that selective attention is a continuous dynamic process—effectively a gate in time (Reeves & Sperling, 1986; Shih & Sperling, 2002).

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[2] The lowest t-value of 1.75 was observed for a lag of 12 items, at a lag of 14-items the difference in center of mass between T1 and T2 was more significant $t(16) = 2.66$, $p < .01$.

[3] Parameter estimates correspond to marginal means and standard deviation.

Wyble and Bowman (2005) and Bowman and Wyble (2007) showed that the attentional blink itself is a function of time, not serial position: when the RSVP stream is sped up to 20 items/s (50 ms/item), subjects benefit from "lag 2 sparing", indicating that the sparing classically observed for the lag 1 item (at the commonly used speed of 100 ms/item) transfers to the lag 2 item if that one follows 100 ms after the first target. This result indicates that the *interaction* between two selection episodes is time (not serial position) dependent. However, these data do not speak to how selection itself operates: given a particular interval between two selection episodes, does the observed *delay* reflect a delay in time of a continuous selection window, or a delay due to slower processing of discrete items? In Experiment 3 we test these two alternative accounts by asking whether the "delay" effect reflects a delay in time or a delay in serial position. If the delay effect reflects a slowed response of a continuous selection 'gate', then delay should be constant in time rather than serial position. If attentional selection is a symbolic process requiring the binding of cues to targets, then the delay may reflect greater mis-binding of contiguous letters, resulting in a delay effect that would be constant in serial position, not time.

Circumstantial evidence suggests that the delay does reflect a delay in time: Vul et al. (2008) reported greater rates of post-target intrusion than Chun (1997), at a higher RSVP rate. However, this hypothesis has not been directly tested. To tease apart these two possibilities, we measured delay in RSVP streams with different rates to ascertain whether the magnitude of delay is constant in units of time or constant in units of items.

4.1. Method

4.1.1. Participants

Nine participants between the ages of 18 and 30 were recruited from the same Massachusetts Institute of Technology subject pool and were paid for participation.

4.1.2. Stimuli and design

As in the previous experiments, subjects saw an RSVP stream of all 26 English letters, of which two were cued with white annuli surrounding the letter stream. In this experiment, we manipulated T1–T2 stimulus onset asynchrony to be either 360 or 960 ms. As we saw in Experiment 2, at an SOA of about 360 ms we should see the peak delay effect, and we should see a substantially decreased delay effect with an SOA of 960 ms.

Crucially, we manipulated the RSVP rate in this experiment. On fast trials, the RSVP rate was 16.7 items/s (each letter was presented for 20 ms, with a 40 ms blank interval between letters). On slow trials, the RSVP rate was 8.3 items/s (each letter was presented for 40 ms, with an 80 ms blank interval between letters). This means that for fast trials, the 360 ms SOA was a lag of 6 items, while the same temporal SOA was only a 3-item lag on the slow trials. By manipulating the RSVP rate we could assess whether 'delay' reflects a delay in time or in serial position.

Other stimulus parameters and experimental conditions were identical to the second experiment.

4.2. Procedure

The procedure was identical to that of Experiment 1, including bonus cash rewards for performance. However, the number of trials for each participant was changed to 4 blocks of 100 trials each.

4.3. Results and discussion

As in the previous two experiments, we computed the frequency with which any given serial position was reported. Fig. 5 shows these histograms of reports for each SOA and RSVP rate combination. Of course, performance is worse with a faster RSVP stream; however, interestingly, the temporal spread of the histograms of reports for targets at a short (within the blink) SOA appear to be roughly similar across the two RSVP rate conditions.

From these report frequencies, we computed the center of mass of reports for each condition. To assess whether 'delay' is a delay in time or serial position, we computed the center of mass in items (the same method employed in the previous two experiments; Eq. (2a) in Appendix A) and we also computed the center of mass in time, wherein each letter is tabulated not by its serial relation to the cue but by its temporal distance (in milliseconds) from the cue (Eq. (2b) in Appendix A). These calculations allow us to assess whether the center of mass changes constantly in serial position or constantly in time when the RSVP rate doubles.

In Fig. 6, we compare the change in the center of mass as measured by serial position (a) to the delay effect as measured in time (b). Center of mass, as measured by serial position is very different

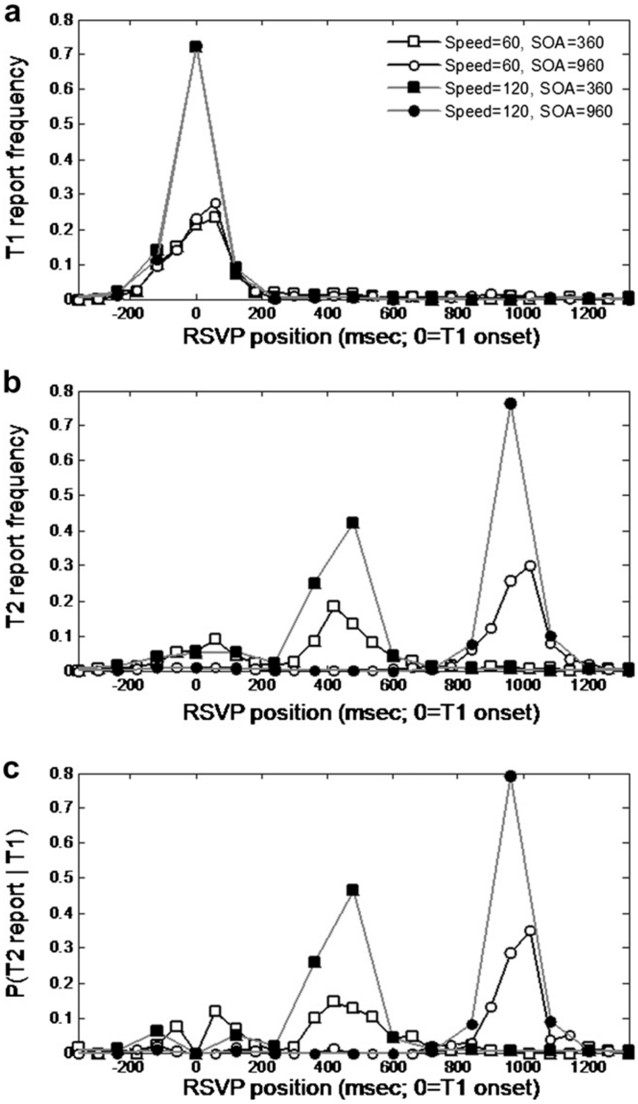

Fig. 6. Experiment 3 results: raw data. As in Fig. 2 we plot the raw empirical frequencies with which any given item was reported in Experiment 3 for each RSVP rate (60 or 120 ms/item) and T1–T2 SOA (360 or 960 ms) condition. The *x*-axis corresponds to the onset time of different items in the RSVP stream aligned such that 0 ms corresponds to the T1 item. The *y*-axis is frequency of report. (a) T1 report frequencies, (b) T2, and (c) T2 given that T1 was reported correctly.

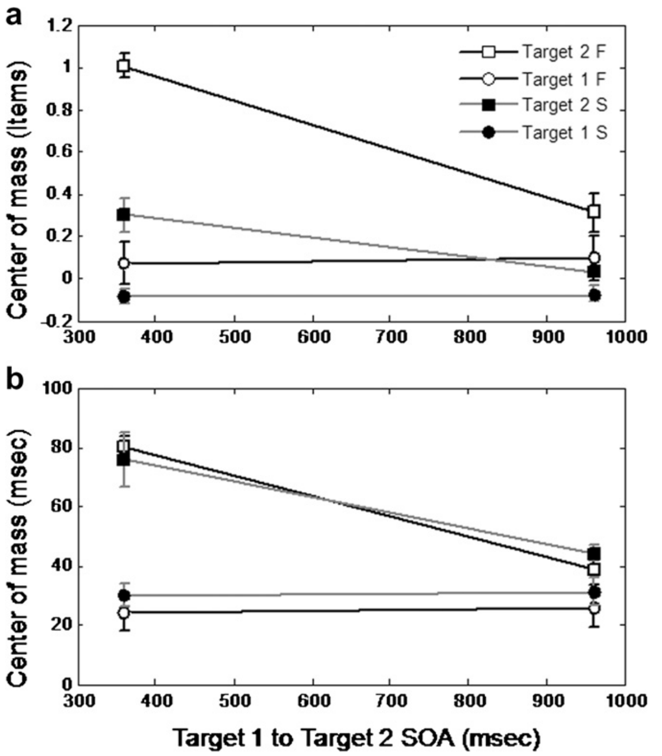

Fig. 7. Experiment 3 results: center of mass. Here we plot the center of mass (y-axis) as a function of T1–T2 SOA (x-axis, in ms) for the fast (F, 60 ms/item) and slow (S, 120 ms/item) RSVP rates. Crucially, in panel (a) we display the center of mass in terms of serial position (items), and in panel (b) we show the center of mass in terms of time (ms). The 'delay' is identical in the two presentation rate conditions as a function of time, but very different as a function of serial position.

in the two RSVP rate conditions for the blinked (360 ms SOA) T2 ($t(8) = 10.7$, $p < .01$; 60 ms/item, center of mass = 1; 120 ms/item, center of mass = .3). The same is true of the 960 ms SOA: $t(8) = 4.9$, $p < .01$ (60 ms/item, center of mass = .3; 120 ms/item, center of mass = .04). Thus, as a function of serial position, the delay of the center of mass changes dramatically when the RSVP rate is doubled (Fig. 7).

However, when we compute the center of mass as a function of time, rather than serial position, a 360 ms T1–T2 SOA produces identical delays for the two RSVP rates: 60 ms/item center of mass = 80.5 ms; 120 ms/item, center of mass = 76 ms; $t(8) < 1$; 90% confidence intervals on the difference: -6 to 15 ms. The same is true of the 960 ms SOA: 60 ms/item center of mass = 38.9 ms; 120 ms/item, center of mass = 44.4 ms; $t(8) = -1.3$; 90% confidence intervals on the difference: -12 to 1 ms. Thus, when the delay is computed as a function of time, rather than serial position, we see that the magnitude of delay is identical regardless of RSVP rate.

Thus, we dissociated time and serial position and found that the delay effect must reflect an increased latency of selective attention in time rather than a delay in serial position. This result suggests that temporal selective attention operates continuously in time, rather than over discrete, differentiated serial positions or symbols.

5. Discussion

We explored the contribution of delay in temporal selective attention to the attentional blink. In Experiment 1, we showed that neither a systematic inaccuracy (delay) nor a systematic inefficacy (suppression) of selective attention alone is sufficient to account for the attentional blink. In Experiment 2, we measured the time-course of the delay effect and found that the latency of temporal selective attention returns to T1 levels with a time-constant of roughly 500 ms, indicating that it takes roughly 3 seconds for the effect to diminish to 1% of its peak magnitude. In Experiment 3, we determined that the delay effect reflects a delay of selective attention in time, rather than serial position. This finding suggests that selective attention is a continuous process in time, rather than a symbolic process that operates over discrete objects or serial positions.

The findings of Experiment 1 appear to be in conflict with other recent reports. First, Nieuwenstein et al., 2005 reported that precueing relieves the attentional blink completely. However, in those experiments, the pre-cue was an additional, preceding cue; thus cueing earlier meant cueing twice. In our experiment we controlled the relative onset of the cue to the target, and thus showed that although an earlier cue may mitigate the 'delay' effect, it does not eliminate the attentional blink. The discrepancy between our first experiment and those of Nieuwenstein et al. may be attributable to an effect like 'spreading the sparing' (Olivers et al., 2007): a second, earlier cue serves to relieve suppression and thus the real cue that follows is more effective. Second, Popple and Levi (2007) also came to a conclusion that differs from ours. They found that although the second target may be missed during the attentional blink, nearby items are reported just as often, indicating that selection is just as efficient during the blink as outside the blink, but it is less accurate. The difference in RSVP rates between our studies may account for this discrepancy: our RSVP rate was quite fast (14.3 items/s), while the range of RSVP rates used by Popple and Levi was slower (6 to 10 items/s). Perhaps the difference in results for different RSVP rates indicates that the documented 'suppression' effect (Vul et al., 2008) is an effect of greater forward and backward masking during the attentional blink, thus making higher RSVP rates more susceptible to suppression. Circumstantial evidence for such a claim comes from the increased susceptibility of T2 accuracy to backwards masking (Kawahaa, Di Lollo, & Enns, 2001).

In sum, we find that a systematic delay in selective attention contributes to the attentional blink but is not sufficient to account for the full effect. More importantly, this delay reveals fundamental properties of selective visual attention. First, for an attentional defect, the delay lasts an unusually long time (decaying from a peak at an SOA of 350 ms with a time-constant of roughly 600 ms). Second, since we have shown that this effect is constant in time regardless of the number of intervening items, the delay isolates a purely analog (rather than object-based) component of selective attention. Finally, a 'delay' of temporal selective attention reveals a fundamental non-linearity in how attention operates. Attention is not merely a selection function (attentional gate) that is convolved with the presented cues, but instead, the selection function changes its temporal profile due to the presence of other, proximal selection episodes. Future research might productively investigate modifications to linear-systems accounts of selective attention that can align such models with our evidence of a persistent non-linear interaction in the system.

Appendix A. Equations used

A is the total mass of reports (efficacy of selection, our measure of suppression.)

C is the center of mass (latency of selection, our measure of delay).

V is the variance of the center of mass (precision of selection, our measure of diffusion).

ks and ke are the lower and upper bounds of the window used to compute these measures, expressed in serial position of the item (relative to the cue position). We used $ks = -3$ and $ke = 3$ (0 is the correct target).

n is the total number of items in the selection window (in our case, 7).

P_i is the probability (empirical frequency) of reporting an item from serial position i (relative to the target position, 0).

L_i is the latency in milliseconds (relative to the onset of the cue) of serial position i.

Eq. (1): Average probability of report (measure of efficacy, suppression)

$$A = \frac{\sum_{i=ks}^{ke} P_i}{n} \tag{1}$$

Eq. (2a): Center of mass (measure of latency, delay, in items)

$$C = \frac{\sum_{i=ks}^{ke} P_i * i}{A * n} \tag{2a}$$

Eq. (2b): Center of mass (measure of latency, delay, in ms)

$$C_{ms} = \frac{\sum_{i=ks}^{ke} P_i * L_i}{A * n} \tag{2b}$$

Eq. (3): Variance of the center of mass (measure of precision, diffusion)

$$V = \frac{\sum_{i=ks}^{ke} P_i * (i - C)^2}{A * n} \tag{3}$$

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