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Revisiting the spread of sparing in the attentional blink

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Abstract The *attentional blink* (AB) refers to a deficit in reporting the second of two targets (T_2) in a rapid serial visual presentation (RSVP) stream when this target is presented less than 500 ms after the onset of the first target (T_1). It is under debate whether the AB originates from a limitation of cognitive resources or from an attentional suppression process triggered by a distractor or by target discontinuity. In this study, we placed a distractor (D_{inter}) or an extra target (T_{inter}) between T_1 and T_2 while at the same time manipulating the time interval between D_{inter} (or T_{inter}) and T_2 (0, 200, or 500 ms). The level of attentional enhancement induced by the detection of T_1 was also manipulated by adding external noise to T_1. The results showed that, as compared to the dual-target condition, T_2 performance was better in the consecutive-target condition, when T_2 was close in time to T_{inter} (i.e., the spread of sparing), but was worse with a longer interval between T_2 and the preceding item. Adding external noise to T_1 improved T_2 performance when T_2 was close in time to the preceding item, irrespective of whether this item was D_{inter} or T_{inter}. These findings present difficulties for the existing models of the AB, although the overall pattern observed is generally more consistent with the episodic simultaneous-type, serial-token (eSTST) model than with conventional resource accounts or distractor-based attentional selection accounts of the AB.

Keywords Attentional blink · RSVP · Spread of sparing

When observers search for two targets in a rapid serial visual presentation (RSVP) stream, they usually have no difficulty reporting the first target (T_1). But if the second target (T_2) appears after T_1 onset with a stimulus onset asynchrony (SOA) of 200 to 500 ms, the T_2 report accuracy drops dramatically relative to the performance at longer SOAs (e.g., longer than 500 ms). This phenomenon is known as the *attentional blink* (AB; Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992).

Aimed at understanding the underlying mechanism of AB, several theorists have postulated that the AB originates from a capacity limitation of central processing resources, such as those for working memory consolidation (Jolicœur & Dell'Acqua, 1998; Jolicœur, Tombu, Oriet, & Stevanovski, 2002). According to these resource accounts, mental resources that are limited in capacity are required for working memory. The detection of a potential target triggers the opening of an attentional gate, allowing the perceptual representation of the target to enter the memory-encoding stage and initiate consolidation. The closing of this gate is sluggish, allowing the directly succeeding item to also enter the memory-encoding stage due to its temporal proximity to the target. Thus, if this $T_1 + 1$ item is a distractor (i.e., distractor at lag 1), the processing of this distractor interferes with T_1 consolidation, resulting in an extension of the time course of memory encoding for T_1. Given the limitation of central processing resources, the transfer of all subsequently presented items to the memory-encoding stage may fail, due to depletion of the central resource by T_1 processing, rendering the representations of these items vulnerable to decay or interruption. If this loss of representation occurs on T_2, an effect of AB (i.e., a deficit of T_2 report) is observed.

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Resource accounts of the AB are supported by several lines of research. For example, an unreported T_2 is nonetheless processed at a relatively high level—for example, the semantic level—indicating that the bottleneck of identifying a second target during the AB is not located at the perceptual processing stage (Chua, Goh, & Hon, 2001; Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Shapiro, Driver, Ward, & Sorensen, 1997). Increasing the difficulty of encoding T_1 into working memory by increasing memory load leads to more severe AB on T_2, indicating that T_2 performance varies as a function of the resource requirement of T_1 processing (Akyürek, Hommel, & Jolicœur, 2007; Akyürek, Leszczyński, & Schubö, 2010; Jolicœur & Dell'Acqua, 1998; Ouimet & Jolicœur, 2007; Scalf, Dux, & Marois, 2011). On the other hand, if the distractor directly following T_1, which provides backward masking to T_1 and prolongs T_1 processing, is replaced by a brief blank, the report of T_2 shows no (Chun & Potter, 1995; Raymond et al., 1992; Seiffert & Di Lollo, 1997) or little (Nieuwenstein, Potter, & Theeuwes, 2009; Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009) performance deficit.

A well-known phenomenon in the study of the AB, *lag 1 sparing*, can also be interpreted in the framework of resource accounts. If T_2 is presented immediately after T_1, the report of T_2 does not suffer from a performance deficit (Potter, Chun, Banks, & Muckenhoupt, 1998). According to the resource accounts, T_2 is either included in the attentional gate opened by T_1 and can experience consolidation together with T_1, or T_1's perceptual representation enters into working memory without competition for resources from a distractor, and hence does not delay T_2 processing.

However, a new finding, called the *spread of sparing*, provides difficulties for the resource account. No AB effect is observed on T_2 if the distractors between T_1 and T_2 in the RSVP stream are replaced with other targets. That is, the sparing effect on T_2 in the lag 1 sparing phenomenon also spreads to later lags if more targets are presented continuously (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Kawahara, Kumada, & Di Lollo, 2006; Nieuwenstein & Potter, 2006; Olivers, van der Stigchel, & Hulleman, 2007). It is difficult for the resource account to interpret this spread of sparing, since the resource account predicts that the depletion of resources would become more severe as the number of targets increases, and a more severe report deficit should be observed on the targets presented after lag 1.

Aimed at interpreting both the AB effect and the spread-of-sparing phenomenon, another group of accounts of the AB focuses on attentional selection processes, rather than resource limitation (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers & Meeter, 2008; Taatgen, Juvina, Schipper, Borst, & Martens, 2009; Wyble, Bowman, & Nieuwenstein, 2009). An early version of the selection accounts, called the *interference theory*, postulates that the distractor at the $T_1 + 1$ position, due to its temporal proximity to T_1 and the sluggish attentional window opened by T_1, elicits an attentional inhibition process that interferes with T_1 identification and, more importantly, suppresses the processing of subsequent inputs (Raymond et al., 1992). If T_2 is presented during this suppression period, it would be difficult for T_2 to be processed at the conscious level, resulting in the AB effect.

Another version of the selection accounts, called the *boost-and-bounce theory* (Olivers & Meeter, 2008), further details the distractor interference mechanism. According to this theory, the detection of target-like features opens an attentional gate, allowing the target representation to enter into working memory. The onset of a target will trigger a top-down attentional enhancement effect (a *boost*) and benefit the processing of subsequent items presented within several hundreds of milliseconds (Nakayama & Mackeben, 1989). In contrast, detection of distractor features would close this attentional gate and trigger an inhibitory process, impairing the processing of subsequent items. Importantly, given that the $T_1 + 1$ distractor is processed along with T_1 because of its temporal proximity to T_1, it initially receives a boost of attentional enhancement; this boost, however, would then induce a stronger inhibitory process that lasts for an extended period of time (a *bounce*).

In the same vein, the *threaded cognition model* (Taatgen et al., 2009) assumes that the detection of a distractor that immediately follows a target will activate a control rule that prevents the processing of further input and protects the consolidation of the current target. This control process lasts until target consolidation is finished. Thus, the T_2 that appears after a distractor and during the T_1 consolidation period will be blocked from high-level processing, leading to an AB effect.

The interference theory, the boost-and-bounce theory, and the threaded cognition model all focus on the interference process elicited by distractors immediately following the target; thus, these accounts can be labeled *distractor-based selection accounts* (Lagroix, Spalek, Wyble, Jannati, & Di Lollo, 2012). The distractor-based selection accounts can conveniently interpret the spread of sparing, given the absence of interference on T_2 processing from distractors. Similarly, these accounts can also accommodate the finding that the AB seems to be removed when the distractors between T_1 and T_2 are replaced by a blank time interval (Raymond et al., 1992). However, other studies have shown that, with a more sensitive T_2 task, an AB is still observable when no intertarget distractor is presented (Lagroix et al. 2012; Nieuwenstein, Potter, & Theeuwes, 2009; Nieuwenstein, Van der Burg, et al., 2009). The latter finding could still be accommodated by distractor-based selection accounts, if these accounts assume that a blank interval preceding T_2 would cause a weak interruption to attentional engagement and a deficit in T_2 report (e.g., in the boost-and-bounce theory; Olivers & Meeter, 2008; see also Lagroix et al., 2012).

Another model, called the *episodic simultaneous-type, serial-token model* (i.e., eSTST), attempts to interpret the spread of sparing, the basic AB effects, and the AB effects in the condition when an intertarget distractor is absent (Wyble et al., 2009). The eSTST model assumes that some mechanisms parse visual input into temporal packets (episodes) as they are encoded into memory. In searching through a sequence of stimuli, a target will initiate an attentional episode that lasts for about 200 ms. The encoding of this target would activate a competition to regulate attention: an *excitatory* process that is induced by the visual input and sustains attention during the encoding of the target, and an *inhibitory* process that is caused by ongoing memory encoding of the target. For the target, the excitatory process dominates the competition and enhances attention, lasting for about 200 ms (Nakayama & Mackeben, 1989). If the following (lag 1) item is a distractor or a blank, it would provide sufficient time for attention to be suppressed, assuming that each item is presented for 100 ms. This would produce an AB for a subsequent target (T_2). However, if the lag 1 item is a target (T_2), the suppression elicited from T_1 is counteracted by the amplified excitation from T_2, and the attentional gate is held open, leading to lag 1 sparing. The same procedure can be applied to all succeeding targets, and the spread of sparing is then observed.

Although the eSTST model postulates a form of resource limitation by assuming that targets may interfere with each other in perceptual processing and/or in memory encoding, this interference is assumed to be weak and only to function within an episode: It is not the dominant factor in the attentional dynamics that results in the AB, and thus does not cause a major portion of the attentional blink (Wyble, Potter, Bowman, & Nieuwenstein, 2011). However, this interference could be more severe when the number of targets within a single episode increases (i.e., when T_1's memory load is elevated), leading to prolonged T_1 memory encoding, which produces stronger suppression of attention for a longer duration. This may explain why the AB is more severe in the high than in the low T_1-memory-load situation (Akyürek et al., 2007; Akyürek et al., 2010; Jolicœur & Dell'Acqua, 1998; Ouimet & Jolicœur, 2007; Scalf et al., 2011).

Note that the interference between targets may also occur at the semantic level. Taylor and Hamm (1997) found that the T_2 report deficit is more severe when T_1 and T_2 belong to the same category (e.g., both targets are letters) than when T_1 and T_2 belong to different categories (e.g., T_1 is a number when T_2 is a letter). The authors therefore put forward a semantic interference account to interpret the findings. This idea of semantic interference could help to understand the asymmetry of the AB effect between the left and right visual fields, in which the T_2 report deficit during the AB is more severe when both targets are presented in the right visual field than when they are in the left visual field (Holländer, Corballis, & Hamm, 2005; Holländer, Hausmann, Hamm, & Corballis, 2005; Verleger, Śmigasiewicz, & Möller, 2011). Since the left hemisphere is superior in language processing, targets presented to the left hemisphere through the right visual field may cause more semantic interference than targets presented to the right hemisphere (Holländer, Corballis, & Hamm, 2005).

In summary, although the AB has been investigated for a relatively long time, we still do not have a unified understanding of its underlying mechanisms. By revisiting the spread of sparing, in the present study we aimed to provide new evidence for discriminating different accounts of the AB. To this end, we employed RSVP tasks with two kinds of target continuity. One was the spread-of-sparing condition, in which three targets were presented continuously without intertarget distractors (the TTT condition). The performance levels for the first and third targets in this condition were defined as T_1 and T_2, to enable comparison with the corresponding targets in the conventional dual-target AB task. The target between T_1 and T_2 in the TTT condition was called T_{inter}. Another condition was the conventional AB condition, in which two targets, T_1 and T_2, were presented in the stream with an intertarget distractor, called D_{inter}, which was presented immediately after T_1 (the TDT condition). Importantly, we manipulated the time interval between T_2 and the preceding T_{inter} or D_{inter}, such that this interval could be either 0 ms (i.e., no interval, referred to as TT_0T or TD_0T), short (200 ms: $TT_{200}T$ or $TD_{200}T$), or long (500 ms: $TT_{500}T$ or $TD_{500}T$). This time interval was filled with a blank screen. Note that this manipulation is different from the apparently similar manipulations in previous studies that have compared conditions in which either a distractor or a blank time window was presented immediately after T_1 (before T_2). The AB effect on T_2 was observable in some of these studies for the blank condition (Chun & Potter, 1995; Lagroix et al., 2012; Nieuwenstein, Potter, & Theeuwes, 2009; Nieuwenstein, Van der Burg, et al., 2009; Seiffert & Di Lollo, 1997), but this effect was completely absent in other studies (e.g., Raymond et al., 1992).

Different accounts of the AB lead to different predictions concerning our manipulation (see Table 1). The resource accounts predict that, as compared to the long-interval conditions (i.e., outside the AB), an AB should occur in both the TTT and TDT conditions when T_2 is presented during the AB

Table 1 $T_2 \mid T_1$ performance predicted by different attentional blink theories for the present design, with different durations of the blank interval between $T_1 + 1$ (T_{inter} or D_{inter}) and T_2

RL	DS	eSTST	Present Data
TT_0T < TDT	$TT_0T > TD_0T$	$TT_0T > TD_0T$	$TT_0T > TD_0T$
$TT_{200}T < TD_{200}T$	$TT_{200}T > TD_{200}T$	$TT_{200}T < TD_{200}T$	$TT_{200}T < TD_{200}T$

RL = resource limitation accounts; DS = distractor-based selection accounts; eSTST = the episodic simultaneous-type, serial-token model period. Moreover, a more severe AB effect would be expected for T_2 in the TTT condition than in the TDT condition, due to the larger memory load in the TTT condition (three targets) than in the TDT condition (two targets). In contrast, the distractor-based selection accounts predict a larger AB effect in the TDT condition than in the TTT condition, due to the existence of an intertarget distractor in the former case. For the eSTST model, a spread of sparing would be expected in the TT_0T condition only. When a short time interval is inserted between T_2 and the preceding targets (i.e., in the $TT_{200}T$ condition), the inhibitory process of attention, initiated by the memory encoding of the preceding targets, would cause an AB effect on T_2. A similar phenomenon would be predicted by the eSTST model in the TD_0T or $TD_{200}T$ condition, due to the discontinuity of target input caused by D_{inter}. This implies that the inhibitory effect of attention should occur earlier in the $TD_{200}T$ condition (where it is initiated by the presence of D_{inter}) than in the $TT_{200}T$ condition (where it is initiated by the presence of the blank screen after T_{inter}). This is because T_{inter} provides an additional source of excitation to attention, which delays the peak of the inhibitory process (i.e., when this inhibition would reach maximum). In addition, according to the eSTST model, T_{inter} in the TTT condition could induce interference to the consolidation of T_1, and therefore prolong memory encoding of T_1 (and T_{inter}) in the TTT condition as compared to the TDT condition. This interference could produce stronger and/or sustained suppression on the subsequent T_2, leading to a more severe AB in the $TT_{200}T$ condition than the $TD_{200}T$ condition when T_2 and the preceding items are interrupted by a short blank interval.

In addition, since the resource limitation accounts assume that the T_2 performance is modulated by the load imposed on mechanisms engaged to consolidate pre-T_2 targets, they predict that the central processing mechanism is more likely to have spare resources to process T_2 when T_{inter} is missed, as compared to the situation in which T_{inter} is correctly reported. This assumption can be investigated by applying a principle called *within-trial contingency* in the data analysis (Dell'Acqua, Jolicœur, Luria, & Pluchino, 2009). That is, T_2 performance should be lower when the report accuracy is analyzed only in the condition in which T_{inter} is correctly reported than when it is analyzed irrespective of the accuracy of T_{inter} report. The eSTST model has a similar prediction; it predicts that the load of memory consolidation would be reduced when T_{inter} was not successfully processed, leading to less suppression on T_2 processing. In contrast, the distractor-based selection accounts would not expect to find an influence of T_{inter} performance on the AB, since they do not assume any form of memory-encoding-related limitation or suppression.

The boost-and-bounce theory assumes that the more attentional engagement is on T_1, the greater the suppression (i.e., the bounce) on the subsequent T_2 elicited by the distractor(s) between T_1 and T_2. To directly investigate this assumption, we manipulated the magnitude of the T_1-induced attentional enhancement effect by varying the difficulty of T_1 perceptual processing. We set up a "difficult" and an "easy" condition of T_1 perceptual processing by presenting T_1 with or without external noise. Table 2 lists the predictions concerning the T_1 noise manipulation by different accounts of the AB.

The underlying assumption of this noise manipulation is that the difficulty of target (T_1) perceptual processing forces the visual system to deploy more attentional resources to increase the signal-to-noise ratio of the target. This idea is consistent with the argument that a critical function of attention in perceptual processing is to exclude external noise in the target region (Dosher & Lu, 2000a, 2000b; Lu & Dosher, 2000; Lu, Lesmes, & Dosher, 2002). Empirical work has also demonstrated that the impact of attention upon perceptual processing can be enhanced by the perceptual difficulty of target processing. For example, the attention effect was larger in a conjunction feature discrimination task than in a simple feature detection task (Briand, 1998; Briand & Klein, 1987). According to Nakayama and Mackeben (1989), the impact of increased attention induced by a target would peak about 100–150 ms after target onset and last for several hundred milliseconds. The attention spared from processing a noise-added T_1 could, for a short time window, enhance the processing of subsequent items in the RSVP task. The boost-and-bounce theory's boost procedure is based on Nakayama and Mackeben's attentional account. Therefore, this theory predicts that a stronger boost would be induced by T_1 in the noise condition than in the no-noise condition in a continuously presented target stream. This enhanced boost effect would benefit the processing of subsequent targets, leading to increased T_2 performance in the TTT condition.

Alternatively, however, if the boost-and-bounce theory assumes a weaker T_1 representation in the noise condition, relative to the no-noise condition, it would predict an opposite pattern for the T_1 noise manipulation, relative to the prediction listed above. That is, T_1 in the noise condition would induce a weaker boost as well as a weaker bounce when compared to the no-noise condition. Therefore, T_2 performance should be lower in the T_1 noise condition than in the no-noise condition

Table 2 $T_2 \mid T_1$ performance predicted by different attentional blink theories for the noise manipulation when no blank interval is inserted between $T_1 + 1$ item and T_2

Target Type	BB	RL	eSTST	Present Data
TT_0T	noise > no noise	noise > no noise	noise > no noise	noise > no noise
TD_0T	noise < no noise	noise > no noise	noise > no noise	noise > no noise

BB = the boost-and-bounce theory; RL = resource limitation accounts; eSTST = the episodic simultaneous-type, serial-token model for the TTT situation. This pattern would be reverse in the TDT situation.

For the resource accounts, it is generally assumed that increasing the difficulty of T_1 processing leads to more severe central-resource depletion for T_2 encoding. However, the noise manipulation in the present study would increase the processing difficulty of T_1 at the perceptual rather than the central level—that is, at working memory encoding. In addition, this noise manipulation might increase the attentional enhancement effect induced by T_1, which might facilitate the processing of T_2 presented within the T_1-induced attentional window. Therefore, the resource accounts predict higher T_2 performances in the T_1 noise than in the no-noise condition when T_2 is presented shortly after T_1 onset. The eSTST model assumes that targets that are presented in a brief attentional window compete with each other at the perceptual processing level to enter central processing (Wyble et al., 2011). When noise reduced the trace of the T_1 representation, a T_2 presented shortly after T_1 would have an increased opportunity of winning the competition with T_1, as compared to the no-noise condition. Therefore, the eSTST model predicts better T_2 performance in the T_1 noise condition than in the no-noise condition, but only when T_2 is presented shortly after T_1. Table 2 summarizes the main predictions for the noise manipulation provided by the different accounts.

Method

Participants

Eighteen participants were tested in the present study. Two of them were excluded from the analysis due to their low T_1 report accuracy (less than 30%) in at least one experimental condition. Therefore, 16 participants were included in the final data analysis (13 female, three male; ranging from 18 to 24 years old, overall T_1 performance ranging from 72% to 95%). All of the participants were university students and were paid for taking part in the study. All reported normal or corrected-to-normal vision and were naive to the aims of the study. Informed consent was obtained from each participant. This study was carried out in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Psychology, Peking University.

Design and stimuli

The experiment had a 2 (noise manipulation: T_1 noise vs. no noise) × 2 (target type: TTT vs. TDT) × 3 (blank interval preceding T_2: 0 vs. 200 vs. 500 ms) within-participants factorial design. We used a skeletal RSVP paradigm (Duncan, Ward, & Shapiro, 1994; McLaughlin, Shore, & Klein, 2001) in which a total of four items—T_1, T_{inter} or D_{inter}, T_2, and a distractor as a T_2 mask—were included in each trial. The duration of each item was set to 50 ms. Three levels of blank interval were employed: (1) The blank interval between T_{inter} or D_{inter} and T_2 was 0 ms, leading to a T_1–T_2 SOA of 100 ms; (2) a brief blank screen of 200 ms was inserted, leading to a T_1–T_2 SOA of 300 ms; (3) a blank screen of 500 ms was inserted after T_{inter} or D_{inter}, leading to an outside-AB SOA of 600 ms.

The targets in each trial were Arabic numbers ranging from 2 to 9, and different numbers were used for T_1 and T_2. The distractors were selected from 16 English letters (A, E, F, G, H, K, L, M, N, R, T, U, V, W, X, and Y). All of these characters subtended 0.9° horizontally and 0.6° vertically (26 × 17 pixels) and were displayed in Courier New font. Each of the characters was presented in light gray (RGB: 192, 192, 192) at the center of a dark gray (RGB: 64, 64, 64) background.

The T_1 with external noise used in the T_1 noise condition was created by increasing or decreasing the luminance of each of the 26 × 17 pixels, with the added values being consistent with a Gaussian distribution that had a mean value of 0 (i.e., the T_1s had equal overall luminances with or without noise). The standard deviation for the distribution of luminance for the noise added to T_1 ranged from 5% to 10%, which was to ensure that different number targets had similar signal-to-noise ratios (3:1). Targets with and without noise are illustrated in Fig. 1.

Participants were tested individually in a soundproof and dimly lit room. They were seated in front of a Dell 19-in. CRT monitor (1,024 × 768 resolution, 100-Hz refresh) with their heads mounted on a chinrest. The eye-to-monitor distance was 70 cm. Presentation of the stimuli and recording of participants' responses were controlled by a program written in MATLAB with the Psychophysics Toolbox extension (Brainard, 1997).

Procedure

As is depicted in Fig. 2, each trial consisted of a sequence of four items: T_1 was followed by a distractor (D_{inter}) in the TDT condition or by an extra target (T_{inter}) in the TTT condition, and T_2 was always followed by a distractor. The trial began with the presentation of a fixation cross at the center of the screen for 500 ms, followed by a blank screen with a randomly selected duration of 400, 500, or 600 ms. T_1 and T_{inter} (or D_{inter}) were then each presented for 50 ms at the same position. Depending on the SOA between T_1 and T_2, T_2 either was presented immediately after T_{inter} (or D_{inter}; i.e., SOA = 100 ms) or was delayed for 200 or 500 ms (i.e., SOA = 300 or 600 ms). That is, a blank screen was inserted between T_{inter} (or D_{inter}) and T_2.

Fig. 1 Target numbers. Top: Targets without noise. Bottom: Targets with external noise

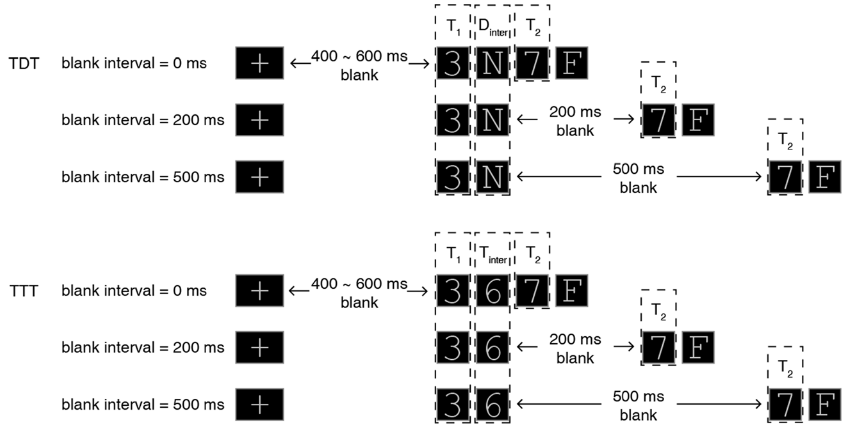

Fig. 2 Experimental conditions and the procedure. Visual displays were at the center of the screen, illustrated from the left to the right in the figure. Each frame in the RSVP stream was presented for 50 ms

A final distractor was presented immediately after T_2. The durations of T_2 and the final distractor were also 50 ms. Responses were collected by asking participants to select each of the target numbers sequentially—that is, T_1 and T_2 in the TDT condition, and T_1, T_{inter}, and T_2 in the TTT condition—from a set of the numbers from 2 to 9 presented on screen. However, in the data analysis, report accuracy was computed irrespective of the order of report.

The target type (TTT vs. TDT) was blocked to make sure that (1) participants knew explicitly how many targets to report for the current trial and (2) participants in the TTT condition processed T_{inter} at the same level as T_1 and T_2; in other words, if the two conditions were mixed, this would prevent participants from applying the strategy of processing D_{inter} for the TDT condition during the processing of T_{inter} for the TTT condition. Given that the TTT block and the TDT block each lasted about 45 min, each participant was tested in two separate sessions, at the same time of day on adjacent days. Half of the participants were tested with TTT stimuli first and the other half with TDT stimuli first. Trials with different SOAs and T_1 manipulations (T_1 noise and no noise) were randomly mixed within each block.

Each condition had 48 trials. Thus, the TTT block had 288 (2 × 3 × 48) trials. In addition to the 288 critical trials, the TDT block also included 96 filler trials in which T_1 and T_2 were presented as the first and second items in a sequence. This was done to make sure that, overall, participants paid attention to all of the first three positions in the test sequences, as in the TTT block.

Results

T_1 report accuracy

An analysis of variance (ANOVA) was conducted on T_1 report accuracy with Noise Manipulation (T_1 noise vs. no noise), Target Type (TDT vs. TTT), and Blank Interval (0 vs. 200 vs. 500 ms) as three within-participants factors. These (and all later) results can be found in Table 3. As is shown in Fig. 3 (left panel), T_1 report was not affected by target type (82.5% in the TDT condition and 83.6% in the TTT condition), $F(1, 15) < 1$, but it decreased severely when T_1 was presented with external noise (70.2%) versus when it was not (95.9%), $F(1, 15) = 88.29$, $p < .001$, $\eta^2_p = .85$. This noise effect interacted with target type, $F(1, 15) = 8.50$, $p < .01$, $\eta^2_p = .36$. Since no blank-interval-related main effect or interaction was significant, *p*s > .1, we collapsed T_1 report accuracy over blank intervals to further analyze the interaction between the noise manipulation and target type. When no noise was added to T_1, T_1 accuracy was higher in the TDT condition (97.4%) than in the TTT condition (94.3%), $p < .05$, $\eta^2_p = .37$, indicating that T_1 competed less with other items in the TDT condition than in the TTT condition (Potter, Staub, & O'Connor, 2002). This effect of intertarget competition (i.e., T_1 vs. T_{inter}, as compared with T_1 vs. D_{inter}) could be accounted for by a mechanism of resource limitation (Jolicœur & Dell'Acqua, 1998; Wyble et al., 2011) or semantic interference (Taylor & Hamm, 1997). This difference disappeared when T_1 was presented with noise, $p > .1$. No other effects reached significance.

T_2 report accuracy

T_2 reports conditionalized on correct report of T_1 ($T_2 \mid T_1$) were entered into the ANOVA with the three within-participants factors. The main effect of target type was significant, $F(1, 15) = 10.69$, $p < .01$, $\eta^2_p = .42$. As is shown in Fig. 3 (right panel), overall, $T_2 \mid T_1$ performance was higher in the TDT conditions (76.5%) than in the TTT conditions (71.1%). The main effect of noise manipulation was also significant, $F(1, 15) = 6.78$, $p < .05$, $\eta^2_p = .31$, suggesting that $T_2 \mid T_1$ report accuracy was higher when external noise was added to T_1 (75.4%) than when T_1 had no noise (72.3%). The main

Table 3 Percentages of correct responses for T_1, T_{inter}, and T_2

Target Type	Noise Manipulation	Blank (ms)	$p(T_1)$	$p(T_{inter})$	$p(T_2)$	$p(T_{inter} \mid T_1)$	$p(T_2 \mid T_1)$	$p(T_2 \mid T_1 \ \& \ T_{inter})$
TTT	T_1 noise	0	72.3%	88.5%	78.6%	87.5%	74.2%	72.9%
		200	73.3%	99.5%	66.4%	99.3%	61.7%	61.5%
		500	73.0%	99.2%	84.1%	99.4%	81.9%	81.8%
	No noise	0	93.1%	84.0%	68.1%	83.0%	67.6%	63.8%
		200	94.5%	99.2%	61.2%	99.5%	60.5%	60.4%
		500	95.3%	99.5%	81.5%	99.4%	80.7%	80.9%
TDT	T_1 noise	0	66.1%		70.6%		62.9%	
		200	67.8%		86.3%		82.0%	
		500	68.8%		91.3%		89.6%	
	No noise	0	97.0%		51.8%		51.1%	
		200	97.7%		81.9%		81.8%	
		500	97.7%		92.1%		91.8%	

effect of the blank interval was also significant, $F(2, 30) = 34.58$, $p < .001$, $\eta^2_p = .69$. Pairwise comparisons showed that the $T_2 \mid T_1$ report accuracy was lower when the duration of the blank interval was 0 ms (63.9%) than when the duration was 200 ms (71.5%), $p < .05$, $\eta^2_p = .79$. $T_2 \mid T_1$ report accuracy in the 0-ms blank interval condition and the 200-ms interval condition were both lower than when the blank interval lasted for 500 ms (86.0%), $ps < .001$, $\eta^2_p = .79$.

There was also a significant interaction between target type and blank interval, $F(2, 30) = 38.71$, $p < .001$, $\eta^2_p = .72$. Since target type did not interact with noise manipulation and the three-way interaction between target type, noise manipulation, and blank interval was not significant, $ps > .1$, we collapsed $T_2 \mid T_1$ report accuracy over the noise manipulation to further analyze the interaction between the target type and blank interval. Bonferroni-corrected pairwise comparisons showed that $T_2 \mid T_1$ report accuracy was higher in the TT_0T condition (70.9%) than in the TD_0T condition (57.0%), when the duration of the blank interval was 0 ms (i.e., a spread-of-sparing effect), $p < .001$, $\eta^2_p = .61$. This pattern was reversed when the duration of the blank interval was 200 ms, with higher $T_2 \mid T_1$ report accuracy in the $TD_{200}T$ condition (81.9%) than in the $TT_{200}T$ condition (61.1%), $p < .001$, $\eta^2_p = .69$. The reversed pattern was also observed when the blank interval was 500 ms (90.7% vs. 81.3%), $p < .001$, $\eta^2_p = .65$. We also conducted a test to specifically investigate whether the target type showed different patterns of AB deficit in $T_2 \mid T_1$ report accuracy when the blank interval was 200 ms, as compared to the conditions in which the blank interval was 500 ms (i.e., T_1–T_2 SOAs of 300 vs. 600 ms). We found not only a significant main effect of blank interval (the AB effect), $F(1, 15) = 41.57$, $p < .001$, $\eta^2_p = .73$, but also an interaction between target type and blank interval, $F(1, 15) = 11.73$, $p < .01$, $\eta^2_p = .44$. The $T_2 \mid T_1$ report deficit for the 200-ms versus the 500-ms blank interval was more severe in the $TT_{200}T$ condition (with a differential effect of 20.2%) than in the $TD_{200}T$ condition (with a differential effect of 8.8%), indicating that the AB effect in the 200-ms blank interval condition (i.e., a T_1–T_2 SOA of 300 ms) was larger in the TTT condition than in the TDT condition.

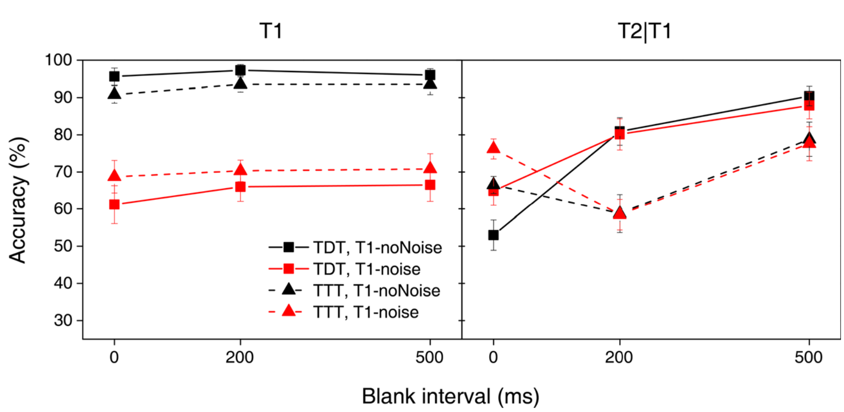

Fig. 3 Mean accuracies of T_1 (left panel) and $T_2 \mid T_1$ (right panel), reported as a function of blank interval. Error bars represent one standard error of the mean

The interaction between noise manipulation and blank interval was significant, $F(2, 30) = 14.97$, $p < .001$, $\eta^2_p = .50$. The 0-ms blank condition was the only condition in which the $T_2 \mid T_1$ report accuracy was higher for T_1 with noise (68.5%) than for T_1 without noise (59.4%), $p < .001$, $\eta^2_p = .63$. No effects were found of noise manipulation when the blank interval was 200 or 500 ms.

There was no interaction between target type and noise manipulation, $F(1, 15) < 1$, indicating that changing the T_1 signal-to-noise ratio had the same effect on $T_2 \mid T_1$ report accuracy irrespective of whether T_1 was followed by D_{inter} or T_{inter}.

The same pattern of effects was observed when the above statistical analyses were conducted for the T_2 report accuracy conditionalized on correct report of both T_1 and T_{inter} ($T_2 \mid T_1$ & T_{inter}). Moreover, the same pattern of effects was observed when T_2 report accuracies were corrected by taking into account the difference in the chance level for guessing T_2 in the TTT and TDT conditions (i.e., there were three opportunities to guess T_2 in the TTT condition, as opposed to only two in the TDT condition, given that the order of reporting targets was discounted when the report accuracies were computed).

T_{inter} report accuracy

T_{inter} reports conditionalized on the correct report of T_1 ($T_{inter} \mid T_1$) were entered into the ANOVA with Noise Manipulation and Blank Interval as two within-participants factors. The main effect of noise manipulation was marginally significant, $F(1, 15) = 3.76$, $p = .07$, $\eta^2_p = .20$, indicating that $T_{inter} \mid T_1$ report accuracy was slightly higher when external noise was added to T_1 (95.4%) than when T_1 had no noise (93.5%). The main effect of the blank interval was highly significant, $F(2, 30) = 61.81$, $p < .001$, $\eta^2_p = .80$. Pairwise comparisons showed that $T_{inter} \mid T_1$ report accuracy was lower when the blank interval after T_{inter} was 0 ms (85.2%) than when it was 200 ms (99.4%), $p < .05$, $\eta^2_p = .79$, or 500 ms (99.4%), $ps < .001$, $\eta^2_p = .79$. The T_{inter} performance was extremely high due to the lack of a backward mask in the 200-ms and 500-ms blank interval conditions. The interaction between noise manipulation and blank interval was significant, $F(2, 30) = 4.55$, $p < .05$, $\eta^2_p = .23$. The 0-ms blank interval was the only condition in which the $T_{inter} \mid T_1$ report accuracy was higher for T_1 with noise (87.5%) than for T_1 without noise (83.0%), $p < .05$, $\eta^2_p = .23$; this pattern was similar to that found for T_2 performance. No effects were found for the noise manipulation when the blank interval after T_{inter} was 200 or 500 ms.

The within-trial contingency effect

Since T_{inter} report was almost 100% correct when the blank interval was 200 or 500 ms, we only included the 0-ms blank interval when analyzing the within-trial contingency effect on T_2 performance in the TTT condition. Following Dell'Acqua et al. (2009), we compared T_2 report accuracy conditionalized on correct T_1 report ($T_2 \mid T_1$) with the accuracy conditionalized on correct report of both T_1 and T_{inter} ($T_2 \mid T_1$ & T_{inter}), with T_1 noise as another within-participants factor. The main effect of T_{inter} consideration was significant, $F(1, 15) = 30.40$, $p < .001$, $\eta^2_p = .67$, with $T_2 \mid T_1$ & T_{inter} report accuracy (68.3%) being lower than $T_2 \mid T_1$ report accuracy (70.9%). This effect indicated that the T_2 report accuracy was higher when the accuracy of T_{inter} report was not taken into consideration (i.e., when the trials with incorrect T_{inter} reports were included and the load on pre-T_2 target consolidation was relatively low). This within-trial contingency effect interacted with the noise manipulation, $F(1, 15) = 8.34$, $p < .05$, $\eta^2_p = .36$, with a slightly less pronounced within-trial contingency effect in the T_1 noise condition (a difference of 1.3%, $p < .05$, $\eta^2_p = .31$) than in the no-noise condition (a difference of 3.8%, $p < .001$, $\eta^2_p = .62$). The main effect of noise manipulation was significant, $F(1, 15) = 12.88$, $p < .001$, $\eta^2_p = .46$, consistent with the previous analyses.

Discussion

The main findings of the present study can be summarized in Tables 1 and 2. T_2 report accuracy was higher in the TT_0T condition than in the TD_0T condition, when all items were presented consecutively. However, when there was a blank time interval (200 or 500 ms) between T_{inter} (or D_{inter}) and T_2, T_2 report accuracy was higher in the TDT condition than in the TTT condition. Adding external noise to T_1 did not affect this pattern of effects. However, adding external noise to T_1 did improve T_2 report accuracy, irrespective of whether the intermediate item was T_{inter} or D_{inter}. In the following paragraphs, we compare these findings with the predictions made by the different theoretical accounts depicted in Table 1 and discuss the implications of these findings for the debate between the previous AB accounts.

The attenuated T_2 report deficit in the TT_0T condition, as compared to the TD_0T condition, replicated the typical spread of lag 1 sparing (Di Lollo et al., 2005; Kawahara, Kumada, & Di Lollo, 2006; Nieuwenstein & Potter, 2006; Olivers et al., 2007). As we indicated in the introduction, this effect creates a difficulty for the resource accounts. The resource accounts argue that increasing the memory load of target processing by increasing the number of targets should lead to more severe mental resource deficits. Therefore, a more severe AB, rather than spread of sparing, would be expected by the resource accounts in the TTT versus the TDT condition, irrespective of the level of time interval between the intermediate item and T_2. Similarly, the semantic interference account, which assumes more severe intertarget interference in the TTT condition than in the TDT condition, also has difficulty interpreting the spread of sparing.

On the contrary, the distractor-based selection accounts can easily accommodate this spread of sparing. These accounts assume that the AB occurs only when an intertarget distractor exists: The distractor preceding T_2 would directly elicit an inhibitory process that suppresses processing of the subsequent target, leading to deteriorated T_2 performance in this condition (Olivers & Meeter, 2008; Raymond et al., 1992; Taatgen et al., 2009). Therefore, a spread of sparing would be expected when no distractor interference exists in the TTT condition. The eSTST model can also accommodate this spread of sparing. As we mentioned above, the eSTST model postulates that the AB is caused by a top-down attentional suppression elicited by T_1 memory encoding. However, continuous visual input of a target stream (e.g., the target stream of the TT_0T condition) might, at the same time, keep the attentional window open by providing a strong activation for attention, overcoming the top-down suppressive effect. Therefore, a spread of sparing instead of an AB would be expected by the eSTST model in the TT_0T condition.

A crucial finding in the present study was that T_2 performance deteriorated in the $TT_{200}T$ condition, as compared to the $TD_{200}T$ condition, when a short blank time interval was inserted between T_{inter} (or D_{inter}) and T_2. This finding was consistent with the prediction of resource accounts and the semantic interference account of the AB, because consolidation of T_1 and T_{inter} in the $TT_{200}T$ condition would deplete more resources and/or induce more severe semantic interference than consolidation of T_1 in the $TD_{200}T$ condition, thus leading to more severely impaired T_2 performance in the former than in the latter situation.

In contrast, the distractor-based selection accounts have difficulties accommodating this finding. According to the boost-and-bounce theory (and the threaded cognition model), D_{inter}, which was presented immediately after T_1, would exert strong inhibition on the processing of the subsequent target. This inhibitory process, lasting for several hundred milliseconds, would impair the processing of a T_2 presented 200 ms after D_{inter}. Thus T_2 performance should be worse in the $TD_{200}T$ condition than in the $TT_{200}T$ condition. Clearly, the present results contradict this prediction. It is worth noting that the boost-and-bounce theory could still postulate that a blank interval preceding T_2 would cause a weak interruption to attentional engagement, due to its “unpredictability,” and might lead to a T_2 deficit in the TTT condition (Olivers & Meeter, 2008; see also Lagroix et al., 2012). However, this putative disruption effect is much weaker than a real distractor (Lagroix et al., 2012; Nieuwenstein, Potter, & Theeuwes, 2009). Thus, a more severe T_2 report deficit in the $TD_{200}T$ condition than in the $TT_{200}T$ condition would still be expected.

The eSTST model postulates that the suppressive effect induced by the memory encoding of targets would succeed in suppressing attention when no new target input appeared. When a blank interval of 200 ms was inserted preceding T_2, the memory encoding of T_1 (and T_{inter}, in the TTT condition) would close the attentional episode initiated by T_1, and the inhibitory process initiated by this encoding would then have the upper hand, preventing the processing of a subsequent T_2. Therefore, the eSTST model can successfully explain the AB effects in both the $TT_{200}T$ and $TD_{200}T$ conditions. Furthermore, as we argued in the introduction, since the eSTST model assumes interference between targets in a single episode, target encoding would be prolonged in the TTT condition, thus resulting in stronger suppression of attention for a longer duration. This predicts a more severe AB in the $TT_{200}T$ condition than in the $TD_{200}T$ condition.

However, although the overarching theory inherent in the eSTST model predicts a larger AB for $TT_{200}T$, the implementation of the model has difficulty simulating the effect. The reason for this difficulty is that the unmasked T_{inter} is simulated as a persisting trace in iconic memory that provides a continuous excitation of attention. Thus, in the model, an unmasked target keeps the attentional gate open, whereas the data collected here suggest that an unmasked T_{inter} is not capable of prolonging the duration of attention. We suggest that the model should be modified such that only the onset of a new target produces an attentional effect; the continued duration of a target, either on the screen or in an unmasked, iconic store, is not sufficient to excite attention. This modification of the model is also supported by the data from Experiment 2 of Nieuwenstein, Van der Burg, et al. (2009), which showed that presenting T_1 continuously on the screen was insufficient to prevent the onset of the AB.

Another crucial modification of the implementation of the eSTST model that is suggested by our data is that the suppression of attention elicited by the memory encoding of pre-T_2 targets may be too strong. With its current parameters, the eSTST model predicts that when the time interval between T_2 and T_{inter} was 0 ms, $T_2 \mid T_1$ performance during the blink should be below 5%, whereas participants here evidenced a far less severe AB. We argue that these modifications are both consistent with the overarching theory of the eSTST model, and our simulations indicate that they allow the model to replicate the deeper AB of the TTT condition.

An important point to observe from the data is that performance remains worse for very long lags in the $TT_{500}T$ relative to the $TD_{500}T$ condition. This finding may suggest that the duration of the AB produced by two targets is much longer than the AB produced by a single target, due to the interference between target-related perceptual representations (Wyble et al., 2011) and/or semantic representations (Taylor & Hamm, 1997), although it may also be the case that some participants have difficulty remembering all three items on some fraction of the trials.

A within-trial contingency effect was also observed in our data, replicating previous studies (e.g., Dell'Acqua et al., 2009). That is, T_2 performance was higher when the data were analyzed irrespective of whether or not T_{inter} report was correct than when only the trials with a correct T_{inter} report were considered. This effect could be interpreted by resource accounts, which assume that when T_{inter} was missed, the central processing mechanism should have more spread resources available for processing T_2. The eSTST model could also account for this effect by assuming that the failure of T_{inter} processing leads to reduced memory load and further alleviates the suppression effect induced by memory encoding. However, the within-trial contingency effect provides a difficulty for distractor-based selection accounts, since they do not assume any form of memory-encoding-related limitation or suppression in the mechanism of the AB.

Another interesting finding in the present study was that adding external noise to T_1 impaired T_1 report but improved T_2 report. Since the analyzed T_2 report accuracy was conditionalized on correct T_1 responses, this improvement of T_2 report cannot simply be attributed to a possible compensation mechanism driven by resources saved from T_1 processing. This finding was in accordance with our assumption that the increased perceptual difficulty of T_1 processing recruits more attention to T_1 and benefits the processing of a subsequent T_2 presented at the same location. It also clearly demonstrates that the effect of the T_1 noise manipulation on T_2 processing employed an underlying mechanism different from those in most of the previous studies, which have examined the effect of T_1 difficulty on T_2 performance by manipulating the memory load (Akyürek et al., 2010; Jolicœur & Dell'Acqua, 1998; Ouimet & Jolicœur, 2007; Scalf et al., 2011; Taatgen et al., 2009; Zhang, Zhou, & Martens, 2011), mental rotation (Taatgen et al., 2009; Zhang et al., 2011), or response selection (Giesbrecht, Sy, & Elliott, 2007) associated with T_1 processing. In those studies, more resources were needed to process T_1 in working memory—according to the resource accounts, for example—leaving fewer resources for T_2 processing. In the present study, however, T_1 with external noise would not incur more demand for central memory processing. Because a critical function of attention during perceptual processing is to exclude external noise in the target region (Dosher & Lu, 2000a, 2000b; Lu & Dosher, 2000; Lu et al., 2002), increasing the external noise level of a target might require the visual system to recruit more attentional resources to solve the increased perceptual difficulty. This attentional effect peaks around 100 to 150 ms after T_1 onset and benefits subsequent stimulus processing (Nakayama & Mackeben, 1989)—for example, T_2 encoding shortly after T_1 onset.

The intriguing point was that the beneficial effect of T_1 perceptual difficulty on T_2 performance was essentially the same for T_2 in both the TDT and TTT conditions. The resource accounts can accommodate this finding because T_2 processing in both conditions would benefit from the increased attention associated with T_1 noise. However, the boost-and-bounce theory predicts an interaction between the T_1 noise manipulation and target type: On the one hand, the boost-and-bounce theory may assume that the T_1-triggered attentional enhancement enhances the processing of T_{inter} and T_2 in the TTT condition, but leads to a stronger bounce process for D_{inter} in the TDT condition, impairing further T_2 performance. On the other hand, the boost-and-bounce theory may assume that the decrease of the signal-to-noise ratio of T_1 impairs T_1-triggered attentional enhancement in the TTT condition, but also impairs the bounce in the TDT condition. Clearly, our findings do not fit either of these predictions.

For the eSTST model, the weakened T_1 representation in the noise condition, as compared with the no-noise condition, would induce less interference for the processing of subsequent targets that were presented in a brief time window after T_1. This reduction of interference in the noise condition would lead to increased performance for T_{inter} and for T_2 when T_2 was presented shortly after T_1 (i.e., in the no-blank-interval condition). Our data fit well with this prediction. In addition, if the weakened T_1 representation led to an impaired T_1 semantic trace, the semantic interference account would have the same prediction as the eSTST model regarding our noise effect finding.

To conclude, by manipulating the time interval between T_{inter} (or D_{inter}) and T_2, and by adding external noise to T_1, in the present study we demonstrated that the spread of lag 1 sparing in the TTT condition, as compared with the TDT condition, can be either positive (i.e., better T_2 performance in the former than in the latter condition) or negative (i.e., worse T_2 performance in the former than in the latter condition), depending on whether a blank time interval is interposed between T_{inter} (or D_{inter}) and T_2. This finding is accommodated better by the eSTST model than by conventional resource accounts or distractor-based attentional selection accounts of the attentional blink.

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