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Four-dot masking produces the attentional blink

R. Dell'Acqua [a,*], A. Pascali [b], P. Jolicoeur [c], P. Sessa [b]

[a] *Department of Human Sciences and Center for Neuroscience, University of Ferrara, Via Savonarola 38, 44100 Ferrara, Italy*
[b] *Department of Developmental Psychology, University of Padova, Via Venezia 8, 35100 Padova, Italy*
[c] *Department of Psychology, University of Montreal, Succursale Centre-ville, Montreal QC, Canada H3C 3J7*

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Abstract

When two target stimuli (T1 and T2) are presented sequentially within half a second of each other, identification accuracy is often poor for T2. This phenomenon, known as attentional blink (AB), can be observed generally only if the stimulus terminating the presentation of T2 acts as an interruption mask. Recent evidence suggests that even four small dots surrounding a target item can exert masking effects, provided the target onset occurs at an unattended spatial location. In order to test whether an AB could be observed under conditions of four-dot masking of T2, five rapid serial visual presentation streams of letters were synchronously displayed on each trial of the present experiment. T1 and T2 were digits presented at unpredictable locations and unpredictable temporal intervals. T2 was followed by either a blank field, a letter, or four-dots. No AB was observed when T2 was not masked, but robust and equally sized ABs were observed when T2 was followed by both the letter mask and the four-dots.

Keywords: Masking; Attentional blink

1. Introduction

When human observers try to identify two sequential targets (T1 and T2) embedded in a rapid serial visual presentation (RSVP) stream of spatially overlapping distractors, identification is usually good for T1 but severely limited for T2. This effect, termed attentional blink (AB; Raymond, Shapiro, & Arnell, 1992), is particularly evident when the temporal interval separating the onsets of T1 and T2 is shorter than about 600 ms, and it is generally sharply reduced at longer intervals. Recently, important insights into the nature of the AB effect have come from studies in which the masking parameters defining T1 and T2 have been systematically manipulated. Giesbrecht and Di Lollo (1998), for example, embedded T1 and T2 letters in RSVP streams of digit distractors. Masking of T2 was implemented in this paradigm by presenting either no mask following T2, a distractor digit simultaneously with T2, or a distractor digit trailing T2. In these authors' view, the simultaneous digit was intended to produce masking of T2 by integration (i.e., as though noise was added to signal at a sensory level, slowing T2 processing; see Bachman & Allik, 1976; Scheerer, 1973), whereas the delayed digit was intended to produce masking of T2 by interruption (i.e., as though the mask took over the mechanisms required by both T2 and the delayed mask, interrupting T2 processing; see Breitmeyer & Ogmen, 2000; Spencer & Shuntich, 1970). The results showed a close-to-nil AB, and an overall optimal level of T2 identification performance when T2 was not masked. A clear AB was observed with the delayed mask, with worse T2 identification performance at short compared to long T1–T2 intervals. Finally, when the mask was superimposed with T2, presumably masking T2 by integration rather than interruption, there was no AB. Although the integration mask lowered the accuracy of report of T2, there was no modulation of this effect by the lag between T1 and T2 (see also Brehaut, Enns, & Di Lollo, 1999, for analogous findings).

To account for these results, Giesbrecht and Di Lollo (1998) proposed the object substitution theory of masking, according to which masking of T2 in the AB occurs because, while attention is committed to the processing of T1 at short T1–T2 lags, the representation of the temporarily unattended T2 is substituted in the

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[*] Corresponding author. Tel.: +39-49-8276545; fax: +39-49-8276511.
E-mail address: dar@unife.it (R. Dell'Acqua).

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visual system by the representation of the delayed mask. A central tenet of the object substitution theory is related to the class of visual mechanisms mediating masking of T2 in the AB. Substitution of T2 in the AB is mediated by late visual processing mechanisms (Di Lollo, Bischof, & Dixon, 1993; Di Lollo, Enns, & Rensink, 2000), and this hypothesis is corroborated by the evidence that when the processing of T2 is interfered with at early visual processing stages, as consensually assumed when T2 is masked by integration, an AB is not observed. Attributing a major role to late visual mechanisms in mediating T2 substitution in the AB has a number of important implications concerning the type of masking stimuli that ought to give rise to conditions favorable to observe an AB effect when applied to T2. Enns and Di Lollo (1997) argued that, under particular conditions, even four small dots surrounding a target item can produce object substitution masking of the target. Interestingly, testing whether an AB can be observed under conditions in which T2 is four-dot masked provides a crucial benchmark for the object substitution theory. In Giesbrecht's and Di Lollo (1998) experiments, the delayed digit and the T2 letter shared a large portion of contour when spatially superimposed. Contour proximity has a modulatory effect on the strength of early forms of masking (e.g., Scheerer, 1973). This leaves open the possibility that masking of T2 in the AB may be restricted to conditions in which both early and late visual processing mechanisms are engaged as a consequence of the mask presentation. The four-dots used by Enns and Di Lollo (1997) instead did not overlap spatially with the targets. Furthermore, contour proximity did not modulate the strength of four-dot masking. Therefore, masking of T2 by four-dot in an AB design may be a particularly appropriate way to test whether an AB is observed under conditions in which early masking effects on T2 can plausibly be excluded. If Giesbrecht's and Di Lollo (1998) object substitution theory is correct, an AB should be observed when T2 is masked by four-dots.

One property of four-dot masking poses a problem when the four-dot mask is implemented in a RSVP design. Four-dot masking is maximally effective when spatial attention is not allocated to the position occupied by the to-be-masked target (Di Lollo et al., 2000; Enns & Di Lollo, 2000). Thus, a standard RSVP paradigm in which single items are serially displayed in the same spatial position cannot serve the present purpose. We overcame this difficulty by using the paradigm that is illustrated in Fig. 1.

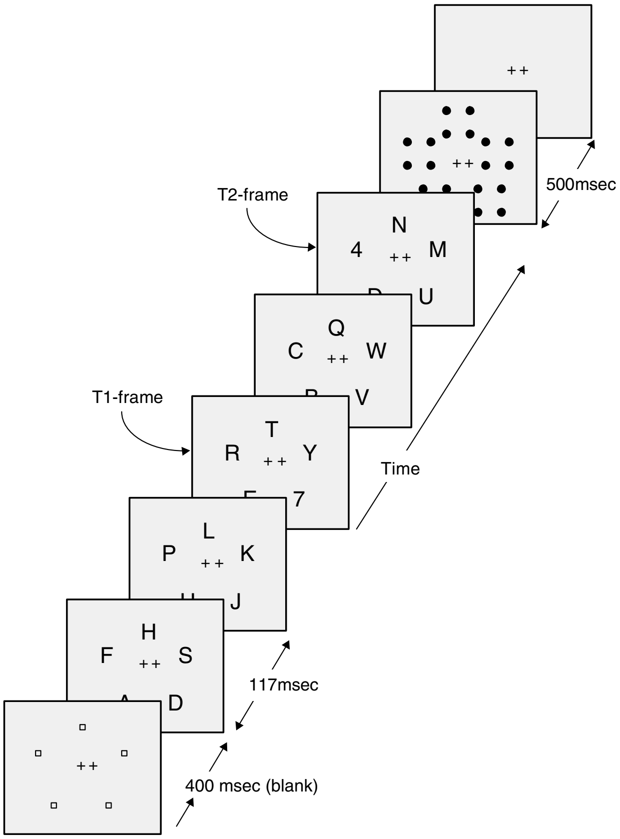

Fig. 1. Example of the trial sequence of events (see method for details). T1 and T2 were digits presented in the same stream, or in different streams, and at one of four different stimulus onset asynchronies. Each frame was composed of five characters and lasted 117 ms. When presented in different streams (i.e., in different spatial locations), the separation between T1 and T2 was either 4° of visual angle (when T1 and T2 were in adjacent locations), or 6.8° (when T1 and T2 were in non-adjacent locations). T2 and each of the letters presented concurrently with T2 were followed by the presentation of a masking stimulus. In this particular example, the masking stimulus is the four-dot mask.

Five synchronous RSVP streams of letters were displayed on each trial. T1 and T2 were to-be-reported digits embedded in the same stream, or in different streams. The positions of the streams coincided with the vertices of an imaginary pentagon inscribed in a circle with a diameter of 7.5° of visual angle. The pentagon was rotated randomly around its center from trial to trial. When T1 and T2 were presented in different streams, and when T1 was correctly identified, we assumed that spatial attention was temporarily allocated to the position occupied by T1, such that the unpredictable position occupied by a T2 presented shortly after T1 was purportedly unattended. T2 and the letters displayed simultaneously with T2 were always followed by a single masking stimulus. The masking stimulus was either a blank field (no mask), a letter (backward pattern mask), or four-dots, as shown in Fig. 2.

2. Experiment

2.1. Method

2.1.1. Observers

The five observers were either academic staff or graduate students in the Department of Psychology at the University

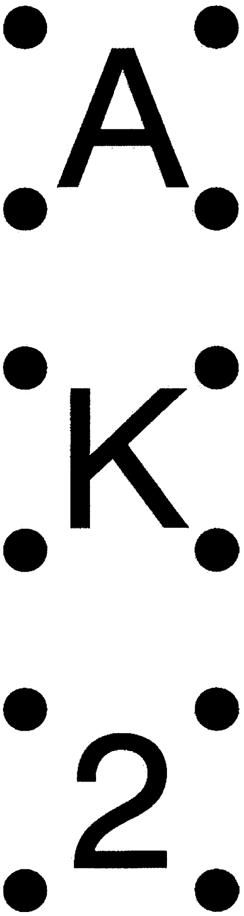

Fig. 2. Magnified examples of four-dot masks and stimuli used in the present experiment. The four-dot masks and the stimuli are reproduced as they would appear if displayed simultaneously (although it never occurred during the experiment). The stimuli are to scale with those used in the experiment.

of Padua. All were experienced RSVP observers, and ranged in age from 25 to 36 years. All had normal acuity.

2.1.2. Stimuli

The stimuli were black (7 cd/m^2) characters displayed on a light grey background (30 cd/m^2). The stimuli were all letters of the English alphabet except G, I, O, U, Z, X, and the digits 2–9. The stimuli were presented on a 17 in. CRT monitor controlled by a Pentium IV CPU and MEL 2.0 software. Height and width of the characters were 1.1° and 1.0°, respectively. The viewing distance was 50 cm and set by a chinrest. Each dot composing the four-dot mask was a filled black circle with a 0.3° diameter. The four-dots were arranged at the vertices of an imaginary square with sides that were 1.6° long. The minimal distance between stimuli contour and dot contour was 0.2°.

2.1.3. Procedure

The experiment was conducted in a sound-attenuated and dimly lit room. Each trial began with a cue frame consisting of a pair of horizontally arrayed plus signs presented at the center of the monitor. The plus signs were surrounded by five small 0.1° squares that marked the five locations of the streams. The plus signs provided feedback on performance in the previous trial, and acted as a fixation point in the current trial. The left plus sign indicated performance for T1 identification, and the right plus sign indicated performance for T2 identification. Subjects were explicitly instructed to keep their gaze on the fixation point throughout a trial. Each trial was initiated by a press of the spacebar on the computer keyboard placed in front of the subject. Upon trial start, the five placeholders disappeared and, after a 400 ms blank interval, the streams began to be presented. There were 5–7 frames (each composed of five distractor letters lasting 117 ms, 0 ms ISI) prior to the onset of the frame containing T1, and a variable number of frames (i.e., either 0, 1, 3, or 6) following the T1-frame prior to the onset of the frame containing T2. The number of frames prior and following the T1-frame was selected randomly at run time. Subjects were informed that T1 and T2 were never the same digit on a given trial. A single masking frame lasting 500 ms followed the T2-frame. The masking frame could be a blank field, a set of five distractor letters, or five four-dot masks. On each trial, T1 could be presented with equal probability in one of the five streams. On one third of the trials, T1 and T2 were presented within the same stream. On the other two thirds of the trials, T1 and T2 were presented in different streams. When presented in different streams, T1 and T2 could appear with equal probability either in adjacent streams or in non-adjacent streams, corresponding to a T1–T2 spatial distance of either 4.0° or 6.8°, respectively. At the end of each trial, subjects used the numeric keypad on the computer keyboard, and pressed two keys corresponding to the identity of T1 and T2, guessing when uncertain. The order in which the responses were entered was not taken into consideration. The experiment was divided in four 1-h sessions, organized in two sessions per day on two consecutive days. A single session was composed of 10 blocks of 36 trials each. Each block was a cycle through each possible factorial combination of the levels of SOA (117, 234, 468, 819 ms), spatial distance (0°, 4.0°, 6.8°), and mask type (no mask, letter, four-dot). Each session was preceded by a practice block of 36 trials. Each observer contributed 2880 experimental responses composed of 1440 responses to T1 and 1440 responses to T2.

2.2. Results

The analyses concentrated on the proportion of correct responses to T1, and on the proportion of correct responses to T2 conditional on a correct response to T1. These values were corrected for guessing using the formula (x-chance)/(1-chance), where $x = p(\mathrm{T1})$ and chance = 1/8 for T1 accuracy results, and $x = p(\mathrm{T2}|\mathrm{T1})$ and chance = 1/

7 for T2 accuracy results. Data were submitted to analysis of variance (ANOVA), in which SOA, spatial distance, and mask type were considered within-subject factors.

2.2.1. T1 performance

The proportion of correct responses to T1 for each SOA and spatial distance is reported in Table 1. The analysis revealed a significant effect of SOA ($F_{3,12} = 5.1$, $p < 0.02$), a significant effect of spatial distance ($F_{2,8} = 8.2$, $p < 0.02$), and a significant interaction between these two factors ($F_{6,24} = 6.6$, $p < 0.01$). No other factor or interaction was significant (all Fs < 1). As Table 1 suggests, the significant interaction was due to the slight accuracy decrease at the shortest SOA when T1 and T2 were presented in the same position. When the data from this condition were temporarily excluded from the analysis, the main effects and the interaction between SOA and spatial distance were no longer significant (Fs < 1).

2.2.2. T2 performance

The mean proportion of correct responses to T2 is plotted in Fig. 3. Results for different T1–T2 spatial distances are in different panels. The analysis revealed significant main effects of all factors (SOA: $F_{3,12} = 15.1$, $p < 0.01$; spatial distance: $F_{2,8} = 37.6$, $p < 0.01$; mask type: $F_{2,8} = 9.9$, $p < 0.01$), significant two-way interactions (SOA by spatial distance: $F_{6,24} = 15.9$, $p < 0.01$; spatial distance by mask type: $F_{4,16} = 10.8$, $p < 0.01$), and a significant three-way interaction between SOA, spatial distance and mask type ($F_{12,48} = 3.0$, $p < 0.03$).

We interpret the results as follows. As is evident from the top panel of Fig. 3, SOA effects on T2 performance, when T1 and T2 were presented in the same location, were characterized by a modest accuracy decrease as SOA was lengthened. The middle and the bottom panels of Fig. 3 suggest instead that SOA effects were generally reversed (i.e., accuracy decrease as SOA was shortened) when T1 and T2 were presented in different spatial locations. Furthermore, mask type effects seemed rather negligible when T1 and T2 were presented in the same location, whereas mask type variations generated large performance modulations when T1 and T2 were presented in different locations. Under these conditions (see middle and bottom panels of Fig. 3), T2 accuracy was only marginally affected by SOA variations when T2 was not masked, whereas a marked SOA-dependent decrease in accuracy was observed when T2 was followed by either the letter mask or the four-dot mask. Two different aspects of the present results are of interest. When T2 was masked (by either a letter or four-dot), and T1 and T2 were presented in different locations, SOA functions related to the different types of mask were very similar. In addition, when T2 was masked, SOA effects under different T1–T2 location conditions seemed more pronounced at short compared to long T1–T2 spatial distance. To corroborate this interpretation, we performed additional analyses focusing on the aspects of the present experimental picture which

Table 1
Mean proportion of correct T1 responses (adjusted for guessing)

Mask type	T1–T2 distance (vis. angle)	SOA (ms)			
		117	234	468	819
No mask	0.0°	0.66	0.77	0.77	0.79
	4.0°	0.83	0.81	0.87	0.77
	6.8°	0.78	0.78	0.79	0.85
Letter	0.0°	0.62	0.81	0.79	0.78
	4.0°	0.82	0.86	0.82	0.77
	6.8°	0.80	0.78	0.78	0.76
Four-dot	0.0°	0.78	0.86	0.84	0.79
	4.0°	0.86	0.83	0.85	0.77
	6.8°	0.82	0.83	0.77	0.81

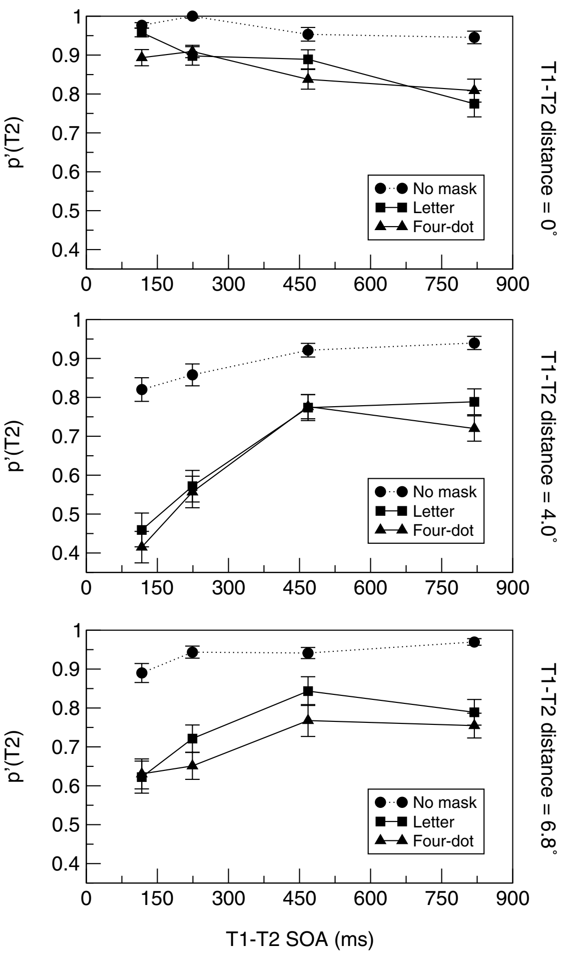

Fig. 3. Probability of correct report of T2, corrected for guessing, given a correct report of T1, at each T1–T2 SOA, for each type of mask. Top panel: T1 and T2 were in the same spatial location; middle panel: T1 and T2 were in adjacent locations; bottom panel: T1 and T2 were in non-adjacent locations.

were critical for the present purposes. When separately analyzed, the results from the T1–T2 same location condition indicated a significant SOA effect ($F_{3,12} = 11.5$, $p < 0.01$), a marginally significant effect of mask type ($F_{2,8} = 2.2$, $p < 0.08$), and no interaction between these factors ($F_{6,24} = 1.6$, $p > .28$). In the T1–T2 different location conditions, an analysis in which the no-mask condition was not taken into consideration revealed a significant effect of SOA ($F_{3,12} = 17.3$, $p < 0.01$), a significant effect of spatial distance ($F_{1,4} = 16.7$, $p < 0.01$), and a significant interaction between SOA and spatial distance ($F_{3,12} = 3.7$, $p < 0.04$). But most importantly, neither the main effect nor any interaction involving mask type were significant (Fs < 1). Interestingly, a separate analysis revealed significant SOA effects on T2 performance under conditions in which T2 was not masked, both at a T1–T2 spatial distance of 4.0° ($F_{3,12} = 5.0$, $p < 0.02$) and at a T1–T2 spatial distance of 6.8° ($F_{3,12} = 6.3$, $p < 0.01$).

3. Discussion

When T1 and T2 were presented in different RSVP streams, four-dot masking produced an AB effect that was indistinguishable from the AB effect produced by the typical backward pattern mask used in previous work on the AB. These results suggest that the mechanisms subserving four-dot masking and pattern masking by a trailing character are functionally similar, and that the degree of contour overlap between T2 and the visual item presented following T2 in the RSVP stream plays a minimal role in mediating masking of T2 in the AB. What instead appears to be important to produce an AB effect is the substitution of T2 with a pattern that trails T2 temporally (Enns, Visser, Kawahara, & Di Lollo, 2001), and, in this respect, the object substitution theory of Giesbrecht and Di Lollo (1998) is correct. Substitution of T2 occurs at short lags, while consolidation mechanisms responsible for the transfer of a target perceptual representations to a more durable form of memory are engaged in T1 processing. While waiting for consolidation mechanisms to be freed from T1 processing, the pre-consolidated representation of T2 is vulnerable to replacement by the next visual item in the RSVP stream. This notion is supported by results indicating that incorrect responses to T2 at short lags tend to be non-random, that is, subjects tend to report distractors immediately following T2 (Chun, 1997). Unmasking of T2 is one of the ways to avert substitution of T2 by trailing stimuli during the AB (Giesbrecht & Di Lollo, 1998). The present results showed that an unmasked T2 was minimally, if at all, affected by the AB effect.

The interaction between four-dot masking and the AB observed in the present context has important implications for theories of the AB. Four-dot masking is said to be a unique form of masking, given its insensitivity to target-mask contour proximity and adapting luminance (Di Lollo et al., 2000; Enns & Di Lollo, 1997), and its maximal effectiveness when spatial attention is not allocated to the position occupied by the to-be-masked target (Di Lollo et al., 2000; Enns & Di Lollo, 2000). In these views, the mechanisms subserving four-dot masking are dissimilar from those mediating metacontrast masking, and also from integration masking (e.g., Breitmeyer, 1984), mainly because the four-dot mask has no effect when presented simultaneously with a to-be-masked target. More importantly for the present context, the mechanisms mediating four-dot masking are hypothesized to be late-stage visual mechanisms, influencing earlier stages of visual processing via reentrant feedback loops (Di Lollo et al., 2000). The fact that masking of T2 in the AB is mediated by late-stage processing mechanisms is consistent with evidence indicating that sensory and perceptual stages of visual processing of T2 are unaffected in the AB. Jolicoeur and Dell'Acqua (2000), for instance, have shown that effects generated by the manipulation of the exposure duration of T2 in a skeletal AB design were additive with AB effects, suggesting different loci for the exposure duration effect (i.e., an early locus) and the AB effect (i.e., a later locus). In addition, using behavioral and electrophysiological methodologies, semantic priming effects from missed T2s have been systematically reported with AB paradigms, suggesting that processing of T2 in the AB can proceed unimpeded up to the level of activation of the semantic information conveyed by T2 (Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Shapiro, Driver, Ward, & Sorensen, 1997; Vogel, Luck, & Shapiro, 1998).

One seemingly unexpected result of the present experiment is the statistically significant reverse-AB effect found when T1 and T2 were presented in the same stream (i.e., the decrease in T2 report as SOA was lengthened). Interestingly, Shih (2000) described an experiment in which subjects monitored two simultaneous RSVP streams of letter distractors for identification of T1 and T2 digits. The T1–T2 lag and the relative spatial position of T1 and T2 were systematically manipulated in this experiment. Using T1–T2 SOAs ranging from 80 to 600 ms, T1 and T2 could be presented in the same stream, or in different streams. When T1 and T2 were presented in the same stream, T2 identification accuracy was about 90% at the shortest SOA, and declined progressively to about 65% at the longest SOA, a reverse AB. A standard AB was instead found when T1 and T2 were presented in different streams. Furthermore, when T1 and T2 were presented in the same stream, there was a trade-off between T1 and T2 identification accuracy at short lags: Identification accuracy was lower for T1 than for T2. This combination of patterns, i.e., reverse AB and trade-off between T1 and T2 at short lags under conditions in which T1 and T2 were presented in the same stream, were both replicated in the present experiment. Our interpretation of the reverse AB incorporates Shih's (2000) (see also Reeves & Sperling, 1986) idea that, under conditions in which targets in RSVP are difficult to detect (e.g., because of their visual similarity with distractors), attention allocation to a target occurs more 'sluggishly' compared to conditions in which targets 'pop out' among distractors (e.g., when targets can be easily singled out on the basis of a unique physical feature). Furthermore, our interpretation is based on the notion that a possible cause of the reverse AB may be spatial precuing (e.g., Kristjansson & Nakayama, 2002). [1] Our account of the reverse AB is the following. On a given trial, T1 was likely detected under conditions in which attention was equally divided among all five positions occupied by the RSVP streams. Attention focusing on a target position was however necessary for target identity consolidation (e.g., Visser, Zuvic, Bischof, & Di Lollo, 1999). In this framework, T1 onset drove attention to the position occupied by T1. Due to the high degree of target/distractor visual similarity, attention allocation to the T1 position was rather slow and/or not precise (Shih, 2000), such that when attention was finally focused on the T1 position, T1 was likely, on some but not all trials, to have been already replaced physically (or substituted perceptually) by the stimuli following T1 in the same RSVP stream. When T2 was one of the items immediately following T1, consolidation of T2 occurred more rapidly and/or more efficiently because attention was already focused on the position occupied by T2 (because precued by T1 onset). In all other cells of the present design, namely, at longer T1–T2 lags and when T1 and T2 occupied different spatial positions, T2 consolidation occurred under conditions in which, following T1 presentation, attention had to be redistributed among the RSVP streams, and refocused on the position unpredictably occupied by T2. Note that the general structure of this explanation is consistent with the trade-off between T1 and T2 report occurring at short lags when T1 and T2 occupied the same position. It is in fact reasonable to hypothesize that, when T1 and T2 were presented at the shortest lag and attention was already in focused mode, targets competed for the engagement of consolidation mechanisms, with consolidation being finally operated on the temporally more recent target (i.e., T2). Furthermore, the above explanation is also consistent with findings indicating that a reverse AB was not found when easy-to-detect targets were displayed using multi-RSVP paradigms in which the relative position of T1 and T2 was manipulated. Easy-to-detect targets were indeed used by Visser et al. (1999) (eccentric targets presentation was associated with abrupt onset) and by Kristjansson and Nakayama (2002) (targets were brighter than distractors), and standard AB were found when T1 and T2 occupied the same spatial position. Under these conditions, attention allocation to T1 may be generally fast, with the consequent fast engagement of consolidation mechanisms on the part of T1 at the expenses of T2, that is to wait for consolidation mechanisms to be freed from processing of T1.

Acknowledgements

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[1] The present account could be enriched by including inhibition of return (IOR) as an additional factor to explain the decline in T2 report accuracy at long lags when T1 and T2 were presented in the same stream. However, IOR effects may be ruled out because IOR effects are generally defined as costs affecting the processing of a target when the target presentation occurs in a precued spatial position at long cue-target intervals (e.g., Cheal, Chastain, & Lyon, 1998). Therefore, T2 report at the longest lag should be worse when T1 and T2 occupied the same position with respect to when T1 and T2 occupied different positions. Our results provide minimal support for the hypothesis that IOR might have contributed to determine the level of T2 report. At the longest lag, masked T2 report in the T1–T2 same position amounted to 0.80, and to 0.75 in the T1–T2 different position, with this difference being in a direction opposite to that predicted by the IOR-based account of the reverse AB.

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