

Prior entry explains order reversals in the attentional blink

Christian N. L. Olivers · Frederic Hilkenmeier ·
Ingrid Scharlau

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Abstract When two targets are presented in rapid succession, the first target (T1) is usually identified, but the second target (T2) is often missed. A remarkable exception to this “attentional blink” occurs when T2 immediately follows the first T1, at lag 1. It is then often spared but reported in the wrong order—that is, before T1. These order reversals have led to the hypothesis that “lag 1 sparing” occurs because the two targets merge into a single episodic representation. Here, we report evidence consistent with an alternative theory: T2 receives more attention than T1, leading to *prior entry* into working memory. Two experiments showed that the more T2 performance exceeded that for T1, the more order reversals were made. Furthermore, precuing T1 led to a shift in performance benefits from T2 to T1 and to an equivalent reduction in order reversals. We conclude that it is not necessary to assume episodic integration to explain lag 1 sparing or the accompanying order reversals.

Keywords Visual attention · Awareness · Attentional blink · Prior entry · Order errors

To study the time course of attention, researchers have made use of the rapid serial visual presentation (RSVP) task. In this task, observers typically monitor a single stream of objects (e.g., digits) for the occurrence of a target object (e.g., a letter) which they then need to report

afterward. An interesting phenomenon occurs when there are two targets present in the stream, occurring at a varying temporal distance—or *lag*—from each other. It turns out that the second target is often missed when it appears shortly after the first target. This temporary drop in performance at short lags has been termed the *attentional blink* (Raymond, Shapiro, & Arnell, 1992). The standard explanation for the attentional blink has been that processing of the first target (hereafter, T1) consumes vital mental resources that are then unavailable to the second target (T2; Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998; Shapiro, Arnell, & Raymond, 1997).

An intriguing exception to the T2 deficit occurs when T2 is presented immediately following T1, at lag 1. In this case, T2 performance is typically maximal (as long as no other cost-inducing mechanisms, such as spatial and task-switching ones, come into play; see Visser, Bischof, & Di Lollo, 1999). This exception has become known as *lag-1 sparing* (Potter, Chun, Banks, & Muckenhoupt, 1998) and has provided a challenge to theories of the attentional blink. How can T2 be spared at a time when T1 processing—and thus resource depletion—should be maximal? Lag 1 sparing becomes even more intriguing when we consider the accompanying finding of order reversals: Not only is T2 often spared, but on a substantial proportion of trials (often 25% or more; see, e.g., Chun & Potter, 1995; Hommel & Akyürek, 2005; Wyble, Bowman, & Nieuwenstein, 2009) it also is perceived as having appeared *before* T1, even though, in reality, it appears later—typically, by around 100 ms. Hardly any order reversals occur at later lags. What causes these remarkable reversals, and can they tell us something about what causes lag 1 sparing?

The predominant explanation of lag 1 sparing has been that T1 and T2 are somehow processed “together” (Chun & Potter, 1995), within the same attentional “glimpse” (Chua,

C. N. L. Olivers (✉)
Vrije Universiteit Amsterdam,
Van der Boechorststr. 1,
1081 BT Amsterdam, Netherlands
e-mail: CNL.Olivers@psy.vu.nl

F. Hilkenmeier · I. Scharlau
University of Paderborn,
Paderborn, Germany

Goh, & Hon, 2001) or “window” (Visser et al., 1999). Almost without exception, such explanations involve some form of *attentional gating*. An attentional filter is set up that gates the transition of targets from a high-capacity but labile stage of sensory representation to a limited-capacity but stable stage of short-term memory. Normally, when T1 fills the second stage, the gate closes, and T2 is denied access. However, post-T1 closing is not immediate, and its sluggishness allows T2 to slip in. Note that the sluggish gate in itself does not explain why, in this case, both T1 and T2 can be processed at the second stage, whereas the limitations of this stage are exactly the explanation for the attentional blink in the first place. To explain this, the two targets are assumed to be combined into a single episodic representation, referred to as “batch” (Jolicoeur, Tombu, Oriet, & Stevanovski, 2002), “integrated event” (Akyürek, Riddell, Toffanin, & Hommel, 2007; Hommel & Akyürek, 2005; Kessler et al., 2005), “object file” (Akyürek, Toffanin, & Hommel, 2008), or “token” (Bowman & Wyble, 2007; Craston, Wyble, Chennu, & Bowman, 2009). By integrating the two targets into a single representation, the load on the second stage is reduced. The occurrence of order reversals appears to support the idea of episodic integration: Since both targets are bound to one and the same memory trace, order information is lost, and observers will have to guess which target came first.

Attentional enhancement and prior entry

The alternative view is that gating is in itself a sufficient explanation of lag 1 sparing—and of the attentional blink, for that matter. In Olivers and Meeter’s (2008) *boost and bounce theory*, for example, a gating mechanism causes attention to the stream to be enhanced whenever a target is encountered (the boost) and to be suppressed whenever a distractor is encountered (the bounce). In accord with earlier studies, the attentional response is transient and takes some time to develop—not unlike the supposed sluggishness of the attentional gate mentioned earlier. It appears that attention peaks around 100 ms after target detection and then gradually dissipates or becomes suppressed (Bachmann & Oja, 2003; Cheal & Lyon, 1991; Hikosaka, Miyauchi, & Shimojo, 1993; Kristjánsson, Mackeben, & Nakayama, 2001; Mackeben & Nakayama, 1993; Müller & Rabbitt, 1989; Nothdurft, 2002; for a recent review, see Olivers, 2010; Posner & Cohen, 1984; Scharlau, Ansorge, & Horstmann, 2006; Shimozaki, Chen, Abbey, & Eckstein, 2007; Suzuki & Cavanagh, 1997; Weichselgartner & Sperling 1987; Wyble, Bowman, & Potter, 2009).

In case of an RSVP stream with two targets, the dynamics are then as follows. T1 generates an attentional

boost, which peaks after 100 ms, when the post-T1 item appears. This post-T1 item is thus maximally enhanced. When it turns out to be a distractor, the consequence will be a strong inhibitory response, measured as the attentional blink. However, when the post-T1 item turns out to be T2, lag 1 sparing is found. In fact, the theory predicts that the sparing may spread to subsequent targets, as long as there is no distractor signal telling the attentional-gating system to close or disengage. Indeed, several studies have demonstrated sparing at later lags (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Nieuwenstein & Potter, 2006; Olivers, Van der Stigchel, & Hulleman, 2007). Of further importance, because the theory assumes attentional gating, and not attentional capacity limitations, to be the primary cause of the attentional blink, there is also no need to assume episodic integration of T1 and T2. The question then remains as to what causes the order reversals.

Our hypothesis is that order reversals are best explained through *prior entry*. The idea behind prior entry is that if an object receives attention, it is processed faster (Maylor & Hockey, 1985; Scharlau, 2006; Shore, Spence, & Klein, 2001; Wundt, 1887). As Titchener (1908) described it, “the object of attention comes to consciousness more quickly than the objects we are not attending to” (p. 251). Prior entry is, for example, demonstrated in temporal order judgment tasks, in which observers judge which of two target objects appeared first. Attention is manipulated by cuing one of the targets. The typical finding is that the precued and, thus, presumably attended object is more likely to be seen as appearing first, even when it appears second. Interestingly, Scharlau, Ansorge, and Horstmann (2006) recently investigated the time course of prior entry and found that the effect reaches its optimal point when the cue precedes the target by 100–200 ms. This interval corresponds roughly to the typical stimulus onset asynchronies (SOAs) used in the RSVP streams of the attentional blink task. We therefore argue that, at lag 1, T1 causes an attentional enhancement of T2. As a consequence, T2 receives more attention than does T1 itself and, thus, may benefit from faster processing (see Potter, Staub, & O’Conner, 2002). This leads to prior entry on a substantial number of trials, with order reversals as a result.

A similar mechanism has been proposed within the recent *episodic simultaneous type serial token* theory (eSTST; Wyble, Bowman, & Nieuwenstein, 2009). Within this theory, lower-level sensory representations of the two targets (so-called *types*) are bound to high-level episodic representations (so-called *tokens*; see Kanwisher, 1987). In an earlier version of the theory (STST; Bowman & Wyble, 2007), episodic encoding was assumed to be serial and limited in capacity, and lag 1 sparing, as well as order reversals, were accounted for through episodic integration.

Within eSTST, however, episodic memory consolidation is cascaded such that T1 and T2 are always assigned separate episodic representations. Since memory consolidation is no longer the limiting factor, order reversals are explained through a mechanism similar to prior entry: The stronger the type representation, the faster it is bound to a token. Thus, a strong T2 may be consolidated more rapidly than T1.

In the present study, we tested the prior-entry hypothesis as an alternative explanation of lag 1 order reversals. The experimental procedure is illustrated in Fig. 1. Observers monitored an RSVP stream consisting mainly of black letters and digits (the distractors) for two red target letters (T1 and T2). In the *standard* condition (Fig. 1a), T1 and T2 were the only red items in the stream, and provided the baseline number of order reversals. The crucial condition was the *precue* condition (Fig. 1b), in which a red digit distractor preceded T1. Although it was a distractor, we assumed that since it carried the target-defining property (red), it would nevertheless act as a cue to start attending to the stream (see Folk, Remington, & Johnston, 1992; Nieuwenstein, 2006). Thus, the attentional enhancement would already start *before* T1, rather than with T1. In effect, this would mean that the relative attentional advantage of T2 over T1 would be reduced, resulting in a reduction in the number of order reversals. To control for the fact that

the *precue* condition contained three red items, whereas the *standard* condition contained only two, we also included a *postcue* condition (Fig. 1c), in which a red digit distractor followed T2 (instead of preceding T1).

Experiment 1: cuing T1 reduces order reversals

Method

Participants

Twelve university students (3 male, 1 left-handed, 18–26 years of age) with (corrected-to-) normal vision participated for course credits or € 7/hr.

Stimulus, design, and procedure

Stimulus generation and response recording were done using E-Prime (Psychology Software Tools, Pittsburgh, PA). Backgrounds were gray (40 cd/m²). After a 1,000-ms blank period, a 0.50.5° black fixation cross was presented for 1000 ms in the center of the display and, subsequently, was replaced by a rapid serial presentation of 24 digits and letters, presented in Courier New (approximately 0.8° × 0.8° in size). The letters I, O, Q, and S were excluded, as was the number 1. No two consecutive digits could be the same. Each item was presented for 67 ms, followed by a 33-ms blank (SOA = 100 ms). T1 was a red letter placed at position 8–13 in the stream. T2, also a red letter, would always follow at lag 1. The participant’s task was to report the red letters at the end of the trial, unspeeded and with feedback (order errors were counted as correct). The distractors preceding T1 and following T2 would always be digits. In the *standard* condition, both these distractors would be black. In the *precue* condition, the distractor preceding T1 was red. In the *postcue* condition, the distractor following T2 was red. All conditions were randomly mixed in three blocks of 75 trials each (leaving 75 trials per cell in total), preceded by 15 practice trials. The participant was instructed to report the red letters (and to ignore the black letters, black digits, and red digits) in the perceived order. They received feedback after each trial on identification accuracy, but not on order errors. The experiment lasted around 25 min.

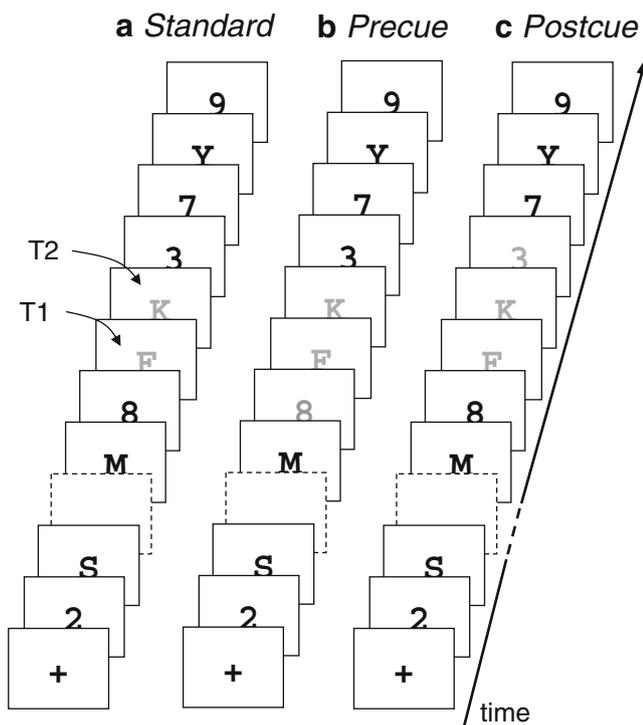


Fig. 1 Outline of the procedure in the present experiments. The targets (T1 and T2) were red (light gray in this graph) letters and were presented in a stream of black distractors, which could be letters or digits. A red digit cue, when present, could precede T1 or follow T2

Results and discussion

Table 1 shows the percentage correct responses for T1 and T2 as a function of cuing condition (*standard*, *postcue*, and *precue*). Since we are interested in the relative amount of attention received by T1 and T2, T2 accuracy is reported unconditional on T1 accuracy, but the pattern of results was

Table 1 Percentages of correct responses for T1, for T2, and for T2 for T1 correct trials only, as a function of cuing condition. Statistical analyses were based on percentage correct T2 for all T1 trials

	Cue Condition		
	Standard	Postcue	Precue
T1	75.8	76.8	78.7
T2	91	89.6	72
T2 T1	90.4	88.8	71.5

virtually identical when T2 performance was analyzed contingent on T1 accuracy. A repeated measures ANOVA with the same factors revealed a target×cuing condition interaction, $F(2, 22) = 15.19$, $MSE = 0.006$, $p < .001$. Whereas in the standard and postcue conditions, performance was better for T2 than for T1, $t(11) = 4.79$, $p < .001$, and $t(11) = 4.57$, $p < .001$ respectively, in the precue condition, T2 performance was numerically worse than that for T1 (although not significantly so, $t < 1.5$). The findings indicate that the precue (prior to T1) indeed changes the relative balance of attention between T1 and T2.

Figure 2 shows the percentage of order reversals for those trials on which both T1 and T2 were reported correctly. A repeated measures ANOVA revealed an effect of cuing condition, $F(2, 22) = 10.75$, $MSE = 0.012$, $p = .001$. Separate tests confirmed the pattern that is clear from Fig. 2: There were significantly fewer order reversals in the precue condition than in the standard and postcue conditions, $t(11) = 3.80$, $p < .01$, and $t(11) = 3.24$, $p < .01$, respectively, whereas there was no difference between the latter two, $t < 1$. As predicted by the prior-entry hypothesis, cuing T1 led to fewer order reversals than when no cue was provided or the cue only followed after T2.

Figure 3 presents two other results that support the idea that order reversals are the consequence of the relative balance

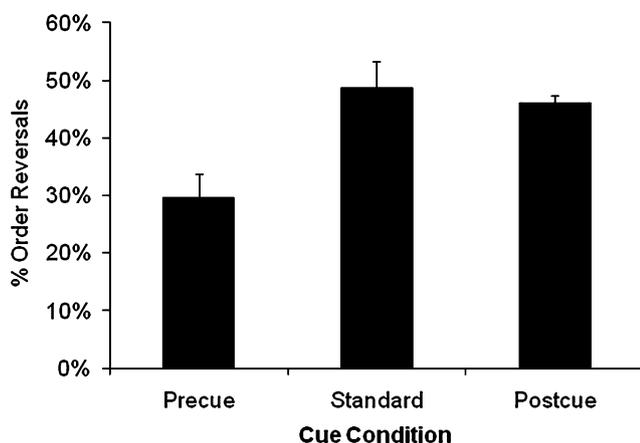


Fig. 2 Order reversals in Experiment 1 as a percentage of trials on which both T1 and T2 were reported correctly

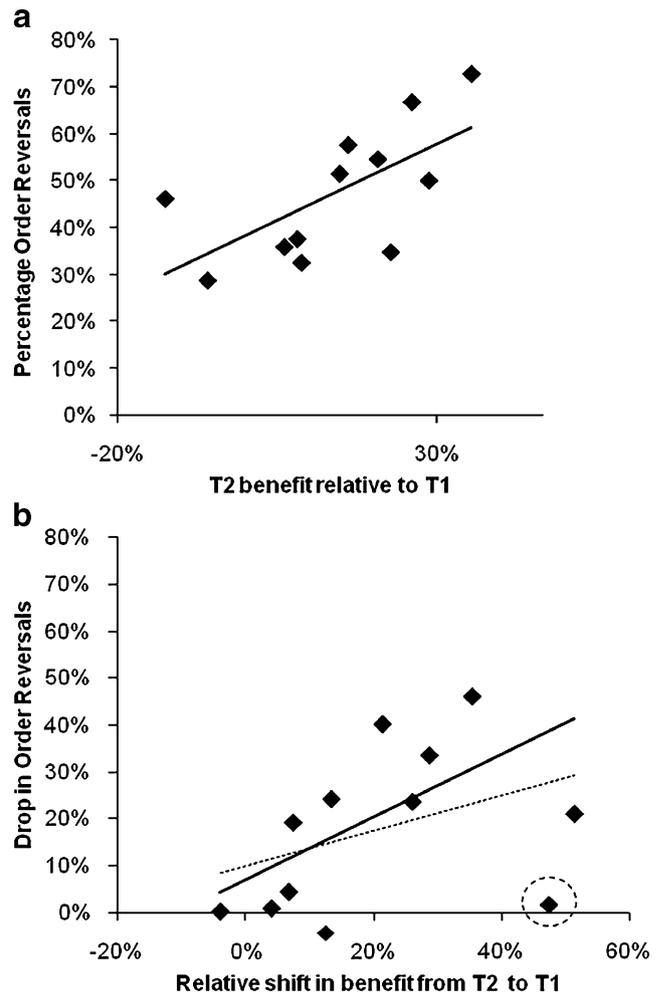


Fig. 3 (a) Average percentage of order reversals for each participant, plotted against the average benefit of T2 over T1 (percentage of correct T2 responses minus percentage correct T1 responses), as averaged over the standard and postcue conditions in Experiment 1 (which were very similar in performance), together with the linear regression line. (b) Drop in order reversals due to the precue (average percentage of order reversals in the standard and postcue condition minus the average percentage order reversals in the precue conditions), plotted against the shift in benefit caused by the precue (the average T2 benefit in the standard and postcue conditions minus the T2 benefit in the precue condition), together with the linear regression line both including the circled outlier (dashed) and excluding the circled outlier (solid; see main text)

in attention paid to T1 and T2. Figure 3a plots the percentage of order reversals for each participant (averaged across the similar standard and postcue control conditions) against the relative benefit of T2 over T1 for that participant. The Spearman correlation coefficient between these two measures was .636, $p < .02$, one-tailed.¹ The correlation suggests that the more accurate T2 is, as compared with T1, the higher the likelihood of an order error is.

¹ We preferred Spearman's over Pearson's coefficient because of scale distortions in accuracy data, as well as the use of difference scores, resulting in data that are not normally distributed.

The prediction, then, is that the more successful the precue is in shifting the balance back to T1, the stronger the reduction in order errors should be. This assumes first that the precue works for T1 in largely the same way as T1 works as a cue for T2. Evidence for this comes from correlating T1 performance in the precue condition with average T2 performance in the standard and postcue conditions, while partialling out basic T1 performance (i.e., averaged across the standard and postcue conditions). This yielded a Spearman correlation coefficient of .64, $p < .02$, suggesting that the cue indeed acted on T1 in a similar way as T1 acts on T2. Figure 3b then plots the reduction in order reversals as a function of the shift in accuracy from T2 to T1 as caused by the precue condition (relative to the average of the standard and postcue control conditions). From the graph, it appears that the greater the change in accuracy is—to the benefit of T1—the greater the reduction in order reversals is. Spearman's correlation coefficient measured .551, which was reliable under a one-tailed test, $p < .05$. From eyeballing the graph, the correlation appears to be underestimated because of a potential outlier (as circled). This participant scored very low on T2 accuracy when T1 was precued (40%, which was more than 2 standard deviations below mean T2 accuracy for this condition). Without this data point, the correlation was .735 and highly reliable, $p = .01$ (two-tailed).

The results indicate that the occurrence of order reversals at lag 1 is modulated by the relative amount of attention received by the two targets, as follows directly from the prior-entry hypothesis. Order reversals occur when the activity of T2's representation is strong enough for it to overtake T1 in the race for awareness. When the attentional balance between the two targets changes, either through cuing or through observer variability, the number of order reversals changes with it.

Note further that for a number of participants, the proportion of order reversals exceeded 50%. This is not to be expected when, due to integration, order information is simply lost on a number of trials and observers guess. One could argue that these high proportions of order reversals just reflect random fluctuations around a mean of 50% or below, but we believe that this is not the case here. First, those participants who had high numbers of order reversals in the standard condition, also had high numbers of order reversals in the postcue condition ($r = .75$), indicating substantial consistency within observers. Second, we believe it is no coincidence that it is exactly these observers with high numbers of order reversals who, overall, also demonstrated the larger benefits for T2 (as shown in Fig. 3). To us, such high rates of order reversals appear to suggest that observers perceive a clear order; it just happens to be the wrong one.

Although the presence of a precue changed the relative balance between the two targets (as was intended), there

was no absolute increase in T1 performance, but a decrease in T2 performance instead. The cuing benefit for T1 may be offset by an overall decrease in target detection caused by the same cue or by a specific decrease for T2. One reason for the overall decrement in performance may be that the precue, since it looks like a target, also gains access to visual short term memory, thus reducing the chances that T1 and T2 will enter. This may be especially detrimental to the later target. Visual short-term memory capacity, estimated at three to four items (Cowan, 2001), should, in principle, be sufficient to accommodate both targets and the cue, but this capacity may vary across individuals. Another possible cause is the ambiguous nature of the cue: It carries the target-defining feature but is, in essence, a distractor. The initial enhancement may be quickly followed by inhibition that may have affected both targets, or, when it occurs late, especially T2. Finally, as has been shown by Potter et al. (2002), at very short lags, there appears direct competition between T1 and T2, such that a relatively stronger T1 may result in a relatively weaker T2. However, we note that in the next few experiments, under similar precuing conditions, the pattern was somewhat different in that while T2 performance decreased, performance for T1 increased at the same time. To check whether the overall drop in performance in the present experiment was real, we ran the precue and postcue conditions again with 8 new observers (the standard condition was left out since the main experiment had shown that it resembled the postcue condition). As before, the precue condition resulted in a deterioration of performance for T2, relative to the postcue condition (78% vs. 95%), $t(7) = 4.57$, $p < .01$, but now the same condition resulted in an increase in T1 performance, from 72% to 85%, $t(7) = 4.43$, $p < .01$. At the same time, order reversals decreased from 52% in the postcue condition to 27% in the precue condition, $t(7) = 3.98$, $p < .01$. We conclude that the overall worse performance in the precue condition, as measured in the main experiment, was probably moot.

Experiment 2: including long lags does not alter the pattern of results

In Experiment 1, the lag between T1 and T2 was always 1. This may have induced a mode of processing that is atypical of common dual-target RSVP tasks, in which T1 and T2 are presented at various lags. This would mean that the order reversals as found here might have little in common with the order reversals as found for lag-1 in the attentional blink paradigm. Strategic influences have been known to affect RSVP processing and order reversals (Akyürek et al., 2007, 2008), with observers apparently allocating longer intervals of attention to the targets when

Table 2 Percentages of correct responses for T1, for T2, and for T2 for T1 correct trials only, as a function of cuing condition and lag. Statistical analyses were based on percentages of correct T2 for all T1 trials

	Lag 1		Lag 8	
	Precue	Postcue	Precue	Postcue
T1	78	70	78	74
T2	76	87	65	48
T2/T1	75	82	64	44

they deem this beneficial and possible. To be able to generalize the findings to the typical lag 1 case, we repeated Experiment 1 but included a lag 8 condition on 50% of the trials.

Method

Participants

Sixteen university students (3 male, all right-handed, 18–25 years of age) with (corrected-to-) normal vision participated for course credits or € 7/hr. One participant was dropped from the analyses because of less than 15% accuracy on T2 at lag 8.

Stimulus, design, and procedure

The experiment was the same as Experiment 1, except for the following changes. The standard condition (without cues) was left out, since Experiment 1 showed that it resembled the postcue condition in terms of performance. Instead, a lag 8 condition was added. Participants first practiced 10 trials. They then performed four blocks of 60 trials each. On half the trials the T1–T2 lag was 1; on the other half, it was 8 (randomly mixed). In total, there were 60 trials per cell. The experiment lasted about 25 min.

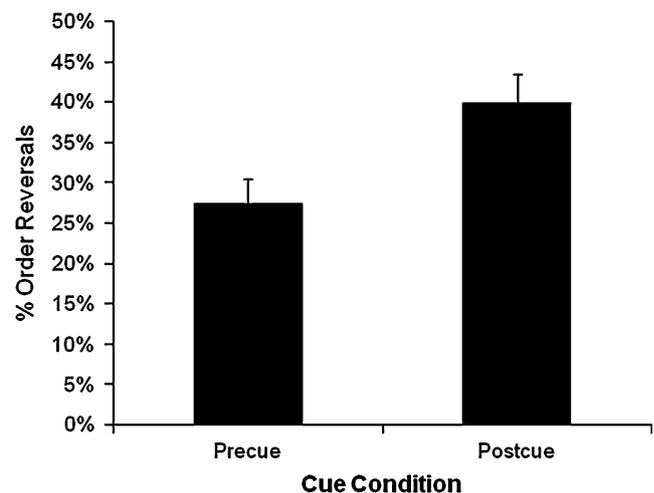
Results and discussion

Table 2 shows the percentage of correct responses for T1 and T2 as a function of cuing condition (postcue and precue) and lag (1, 8). For T1, a repeated measures ANOVA revealed a main effect of cuing, $F(1, 14) = 5.60$, $MSE = 0.012$, $p < .05$, since performance improved after a precue. There were no effects involving lag ($ps > .1$). For T2, there was a main effect of lag and a lag×cuing condition interaction, $F(1, 14) = 32.44$, $MSE = 0.034$, $p < .001$, and $F(1, 14) = 90.16$, $MSE = 0.004$, $p < .001$. Overall, T2 performance was worse at lag 8, than at lag 1. Moreover, at lag 8 it was worse in the postcue condition than in the precue condition, $t(14) = 7.22$, $p < .001$

(whereas at lag 1, it was the other way around, as we will see below). It seems that T2 performance at lag 8 had not fully recovered yet from the attentional blink. Although somewhat unexpected, this is not unique (e.g., Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Lunau & Olivers, 2010; Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005). Furthermore, it seems that at this long lag, T2 suffers from the immediately following postcue. This is not inconsistent with the current framework. We assume that T2 triggers a strong attentional enhancement of the postcue. The enhanced postcue then masks or competes with T2 (see Potter et al., 2002). Note that we assume that exactly the same occurs under standard circumstances at lag 1, when T1 triggers enhanced processing of T2.

We focus our remaining analyses on lag 1, where the order errors are expected to occur. A repeated measures ANOVA revealed a target×cuing condition interaction, $F(1, 14) = 21.1$, $MSE = 0.007$, $p < .0001$. Whereas in the postcue condition, performance was better for T2 than for T1, $t(14) = 4.2$, $p < .001$, in the precue condition, T2 performance was numerically worse than that for T1 (although not significantly so, $t < 1.1$). Moreover, performance on T1 was better when precued, $t(14) = 2.67$, $p < 0.02$, whereas performance on T2 was worse when T1 was precued, $t(14) = 3.81$, $p < .01$, as compared with the respective postcue conditions. The findings indicate that the precue again changed the relative balance of attention between T1 and T2, now leading to a significant improvement for T1.

Figure 4 shows the percentage of order reversals at lag 1 for those trials on which both T1 and T2 were reported correctly, as a function of cuing condition. At lag 8, hardly any order reversals were made (on average, 1%). At lag 1, there were significantly fewer order reversals in the precue condition (27.4%) than in the postcue condition (39.9%),

**Fig. 4** Order reversals at lag 1 in Experiment 2 as a percentage of trials on which both T1 and T2 were reported correctly

$t(14) = 2.83, p < .02$. The proportion of order errors did not differ significantly from Experiment 1, $F < 1.4, p > .25$, nor was there a cuing \times experiment interaction, $F < 1, p > .59$.

We performed the same correlation analyses as in Experiment 1. First, there was a significant Spearman correlation of .51, $p < .03$, between T1 performance in the precue condition and T2 performance in the postcue condition (with basic T1 performance in the postcue condition partialled out). This again suggests that the cue enhances attention for T1 like T1 enhances attention for T2.

Figure 5a shows the relationship between the proportion of order reversals for each participant in the postcue condition against the relative benefit of T2 over T1 for that participant. The Spearman correlation coefficient between these two measures was .784, $p < .01$, one-tailed. Figure 5b shows that the relative shift in performance from T2 to T1, as caused by the precue condition, correlated with reductions in order reversals (albeit more weakly than in Experiment 1). The Spearman's correlation coefficient was .48, $p < .05$, one-tailed.

The results indicate that introducing more uncertainty into the temporal spacing of T1 and T2 has little effect on the results. Even though T2 was now as likely to arrive at lag 8 as at lag 1, the proportion of order errors remained similar, as did the effect of cuing on these order errors. We conclude that the results are likely to apply to lag 1 conditions in other dual-target RSVP tasks, such as those measuring the attentional blink.

Experiment 3: the effects are attentional in nature

So far, we have attributed the reduction in order reversals to an attentional enhancement of T1 as induced by the precue. The precue triggers attention because it carries the target-defining property (Nieuwenstein, 2006). However, an alternative explanation is that the precue primes T1 on a lower, more sensory processing level (e.g., Maljkovic & Nakayama, 1994). The redness of the cue might automatically prime the redness of T1, regardless of the fact that observers have an attentional set for T1. Such a stimulus-driven mechanism would also strengthen T1 and thus lead to reductions in order reversals. To test the hypothesis that the cuing effects are at least partly attentional in nature, we asked observers to look for targets that were either red or green. The crucial condition was, then, the one in which a cue preceded T1 but was not of the same color. For example, the precue might be red, but T1 was green. The cue was still expected to trigger an attentional response (since it carried a relevant color), but it could now no longer directly prime T1 on a sensory level. As before, we included a postcue control condition. We presented all possible color combinations, such that the cues might

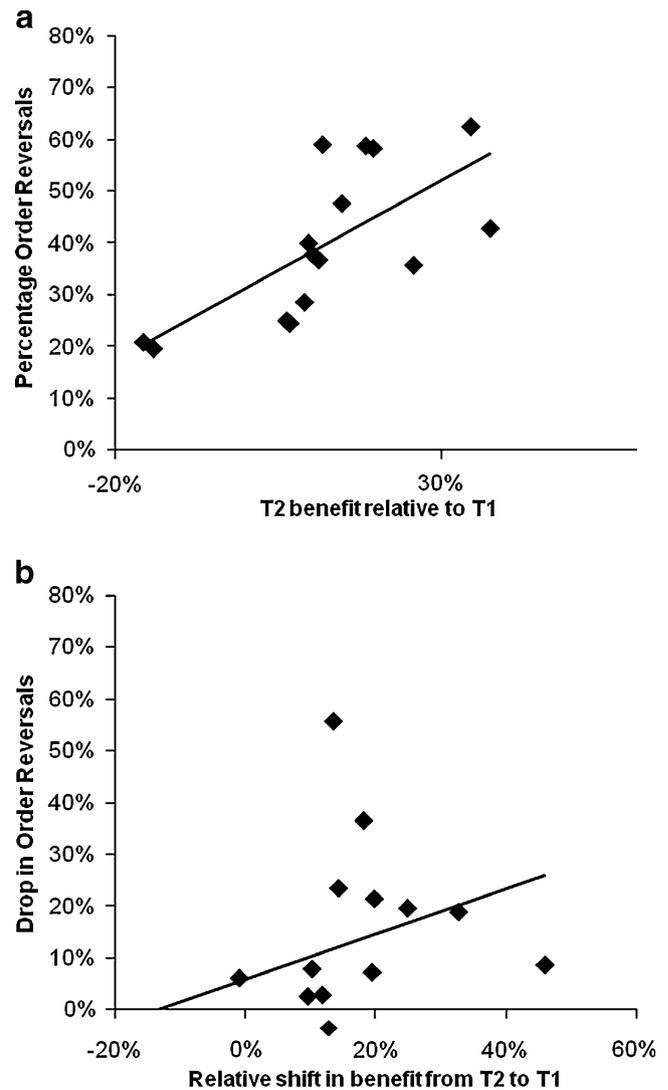


Fig. 5 (a) Average percentage of order reversals for each participant, plotted against the average benefit of T2 over T1 (percentage of correct T2 responses minus percentage of correct T1 responses) in the postcue condition in Experiment 2, together with the linear regression line. (b) Drop in order reversals due to the precue (average percentage of order reversals in the postcue condition minus the average percentage of order reversals in the precue conditions), plotted against the shift in benefit caused by the precue (the average T2 benefit in the postcue condition minus the T2 benefit in the precue condition), together with the linear regression line

match T1, T2, neither, or both, whereas T1 might or might not match T2 in color.

Method

Participants

Fourteen university students (3 male, 2 left-handed, 18–25 years of age) with (corrected-to-) normal vision participated for course credits or € 7/hr.

Stimulus, design, and procedure

The experiment was the same as Experiment 1, except for the following changes. The standard condition (without cues) was again left out. T1 and T2 could now be either red or green, as could the cue (whereas the distractors were still black). All color combinations were possible. In the targets of the same color condition, T1 and T2 were either both red or both green. The precue or postcue could then be of the same color (e.g., red when both targets were red) or of the other color (e.g., green when both targets were red). The targets could also differ in color (e.g., a red T1 followed by a green T2). The precue or postcue could then match either of them (e.g., a red precue when T1 was also red but T2 was green). Together, this resulted in eight different cue (precue vs. postcue) and color combinations. All combinations were repeated 50 times, randomly mixed within five blocks of 80 trials each, preceded by 20 practice trials. The experiment took approximately 40 min.

Results and discussion

Table 3 shows the percentages of correct responses for T1 and T2 as a function of color combination (eight levels: T1 and T2 of the same or a different color; cue of the same or a different color, as compared with either or both of the targets) and cuing condition (two levels: precue and postcue). A repeated measures ANOVA with the same factors revealed several interactions: First, there was a target×cuing condition interaction, $F(1, 13) = 49.08$, $MSE = 0.018$, $p < .001$. Whereas, on average, in the postcue condition, performance was better for T2 than for T1 (90% vs. 74%), $t(13) = 4.03$, $p < .01$, in the precue condition, the pattern was reversed: T2 performance was significantly worse than that for T1 (71% vs. 80%), $t(13) = 3.29$, $p < .01$. Moreover, as in Experiment 2, performance on T1 tended to be better when precued, $t(14) = 2.00$, $p = .066$, whereas performance on T2 was worse when T1 was precued, $t(14) = 8.54$, $p < .001$, as compared with the respective postcue conditions. As in Experiments 1 and 2, this result indicates that the precue changes the relative

balance between T1 and T2. Target identification and cuing effects did depend on the specific color combination, leading to target×color combination, cuing condition×color combination, and target×cuing condition×color combination interactions, $F(3, 39) = 8.54$, $MSE = 0.003$, $p < .001$, $F(3, 39) = 6.49$, $MSE = 0.003$, $p = .001$, and $F(3, 39) = 3.49$, $MSE = 0.003$, $p < .05$. As can be seen from Table 3, precues shifted the balance of performance in favor of T1 for all color combinations, but this effect was stronger when the precue matched T1 in color (average shift in performance from T2 to T1: 29%), as compared with when it differed from T1 in color (average shift in performance from T2 to T1: 21%). The pattern of results was very similar when T2 performance was analyzed contingent on T1 accuracy.

Figure 6 shows the percentage of order reversals for those trials on which both T1 and T2 were reported correctly, as a function of cuing condition and color combination. A repeated measures ANOVA revealed main effects of cuing condition, $F(1, 13) = 22.06$, $MSE = 0.018$, $p < .001$, and color combination, $F(3, 39) = 4.64$, $MSE = 0.007$, $p < .01$, but no interaction, $F < 1.2$, $p > .3$. As is clear from Fig. 6, the precue reduced the number of order reversals, relative to the postcue condition. Separate *t* tests confirmed that this was true for all color combinations, $t_s > 2.3$, $p_s < .05$, except when the cue was the same as T2, $t(13) = 1.8$, $p = .09$. Incidentally, the latter condition is also the condition in which the shift in T1/T2 balance was the smallest (19.7%; see Table 2). We take this as evidence that when the precue matches T2 in color, it will, apart from cuing attention toward T1, also strengthen T2. Overall, the number of order reversals was reduced when T1 and T2 differed in color, especially in the postcue condition. This accords well with the fact that, in this condition, T2 performance was not as strong, as compared with T1, as was the case when both targets shared a color (note that in the same-color target conditions, T2 performance exceeded T1 by, on average, 20%, whereas in the different-color target conditions, T2 exceeded T1 by only 11%, resulting in a significant target×color combination interaction, $F(1, 13) = 19.39$, $MSE = 0.003$, $p =$

Table 3 Percentages of correct responses for T1, T2 and T2 for T1 correct trials only, as a function of cuing condition and color combination. Statistical analyses are based on T2 for all T1 trials

	Targets of the same color				Targets of different color			
	Precue Same	Postcue Same	Precue Different	Postcue Different	Precue Same as T1	Postcue Same as T1	Precue Same as T2	Postcue Same as T2
T1	83.3	68.7	75.7	75.1	82.7	75.7	79.1	76.4
T2	74.3	92.0	69.6	91.6	67.1	86.4	71.0	88.0
T2 T1	74.2	91.0	67.7	90.8	64.2	85.3	69.0	86.8

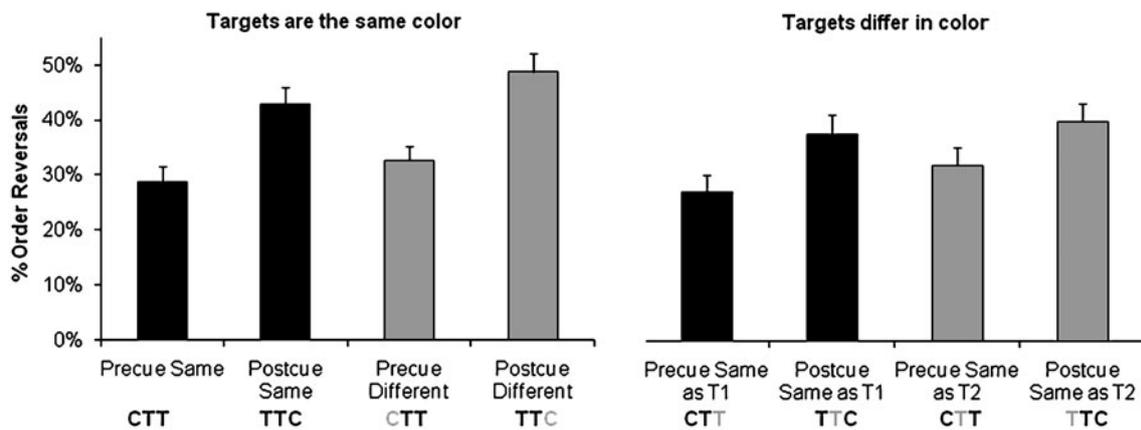


Fig. 6 Order reversals in Experiment 2 as a function of different cue conditions, split up for the various color combinations. The specific color combinations are illustrated by the black and gray Ts (targets) and Cs (cues)

.001). One then needs to explain why T2 was less strong when it differed in color from T1. One obvious explanation is that T1 may not be such a strong attentional cue to T2 when they differ in color. Another possibility is that lower-level sensory priming is weaker between differently colored targets. In any case, whatever the cause of the weaker T2, it resulted in fewer order errors, consistent with the prior entry framework. Alternatively, the color difference may contribute to the discriminability of the targets, which would aid in judging or remembering the temporal order. Consistent with this, Hommel and Akçürek (2005) manipulated the luminance of T1 and T2 independently, so that both could appear equally bright, T1 could appear brighter than T2, or vice versa. They found that most order reversals occurred when T1 and T2 were of equal brightness, with significantly fewer reversals when T1 was brighter than T2 or vice versa. Note, however, that a mere increase in target discriminability in the present experiment should have resulted in better target identification. This was not clearly the case for T1 and certainly was not the case for T2.

The Spearman correlation between T1 performance in the precue condition and T2 performance in the postcue condition (regardless of color combination, with basic T1 performance partialled out) was again positive, at .35, although this time it failed to reach significance, $p = .11$. Figure 7a plots the percentage of order reversals for each participant against the relative benefit of T2 over T1 for that participant, averaged across all color combinations. The Spearman correlation coefficient between these two measures was .735, $p < .01$, two-tailed, and indicates that the stronger T2 was, relative to T1, the higher the likelihood of an order error was. Figure 7b shows the reduction in order reversals as a function of the shift in accuracy from T2 to T1 as caused by the precue conditions (relative to the postcue conditions), averaged across all color combinations. As in Experiments 1 and 2, it appears

that the greater the change in accuracy—to the benefit of T1—the greater the reduction in order reversals. Here, Spearman's correlation coefficient measured .714, $p < .01$, two-tailed.

The results confirm the pattern found in Experiments 1 and 2: Precuing T1 shifts the balance of performance toward T1 and, concurrently, reduces order reversals. The important new result is that this effect is, to a great extent, attentional in nature, and not due solely to low-level sensory priming. Cues that matched the observers' attentional set but did not match T1 in color were still effective in changing relative target detection performance, as well as changing the number of order reversals. We cannot fully exclude a sensory-priming component though, since the data show hints of weaker effects when the cue did not match T1 and, at the same time, matched T2. But we conclude here that the cuing effects were predominantly attentional in nature, and that, in line with the prior-entry hypothesis, attended targets were more likely to be reported first.

General discussion

When T1 and T2 are presented in immediate succession in an RSVP stream (within approximately 100 ms), identification of T2 is usually found to be relatively intact. This lag 1 sparing phenomenon stands in stark contrast to the attentional blink—the often substantial dip in performance when T2 occurs a little later, at lag 2 or 3. In all the present experiments, we found strong lag 1 sparing, with T2 identification even outperforming T1 identification.

Because of their contrasting nature, lag 1 sparing and the attentional blink initially received separate explanations (Chun & Potter, 1995; Jolicoeur et al., 2002; Raymond et al., 1992; Visser et al., 1999). It was thought that whereas the attentional blink occurs because T1 takes away

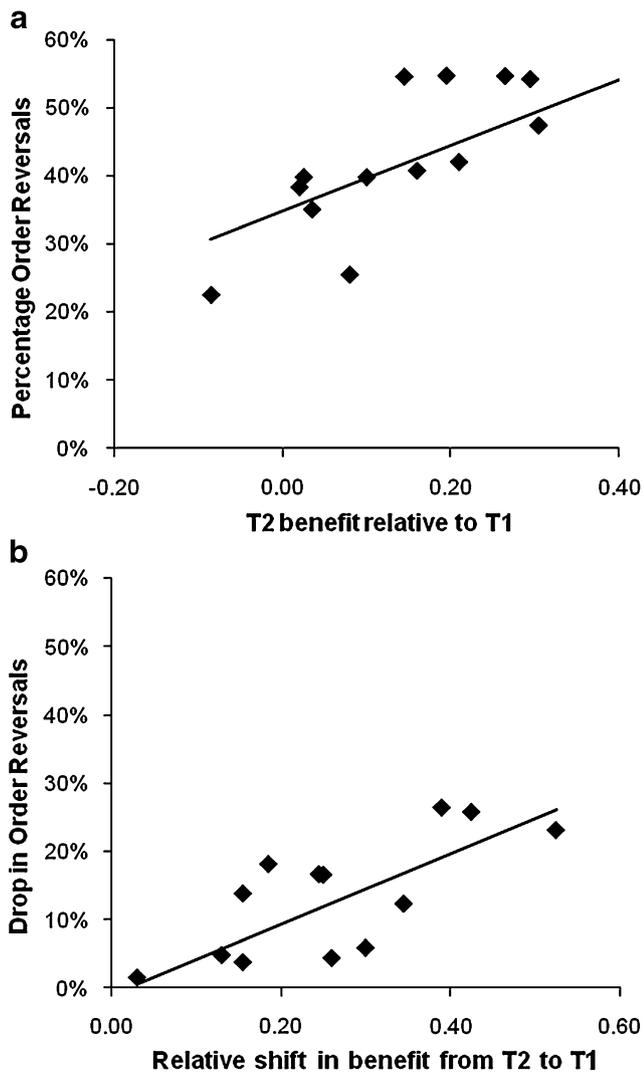


Fig. 7 (a) Average percentage of order reversals across all color combinations for each participant, plotted against the average benefit of T2 over T1 (percentage of correct T2 responses minus percentage of correct T1 responses) in the postcue condition, together with the linear regression line. (b) Average drop in order reversals across all color combinations due to the precue (percentage of order reversals in the postcue condition minus the percentage of order reversals in the precue condition), plotted against the shift in relative T2 benefit caused by the precue (the T2 benefit in the postcue conditions minus the T2 benefit in the precue condition), together with the linear regression line

attentional or mnemonic resources from T2, lag 1 sparing occurs because T1 and T2 are processed within a single attentional episode and are tied to a single memory representation. More recently, the two phenomena have received more integrated explanations, in which the attentional blink is regarded as the failure to create two episodes within a short interval, whereas lag 1 sparing reflects the successful integration of the two targets in a single episode (Bowman & Wyble, 2007; Hommel et al., 2006). In any case, the high incidence of order reversals has

been taken as evidence for the episodic integration of T1 and T2. Here, we have proposed an alternative hypothesis: Lag 1 sparing occurs because the appearance of T1 generates attention toward the stream, to the benefit of T2. Order reversals occur because it takes some time before attention has reached its optimal level and, thus, T2 often receives more attention than T1 itself, is therefore processed rapidly, and may overtake T1 in the race for conscious representation. In support of this prior-entry hypothesis, in three experiments, we found that precuing T1 with a target-like distractor boosted T1 performance, relative to T2, and reduced the number of order reversals. Moreover, the number of order reversals for a particular participant was predicted by how much more accurate he or she was on T2, relative to T1, and the reduction in order reversals was predicted by how much this benefit shifted toward T1 in the precue conditions. Experiment 2 showed that these effects did not depend on the temporal context (i.e., the inclusion of longer lags in the experiment). Experiment 3 showed that the cuing benefits were largely attentional in nature and not due to low-level sensory priming, since cuing benefits occurred for behaviorally relevant cues that were dissimilar to the target.

Could an episodic integration account explain the present findings?

The present findings do not provide direct evidence against episodic integration as an explanation for order reversals in the attentional blink paradigm. In fact, the present findings are largely consistent with an episodic integration account, if we make the following assumptions. First, an episode is of limited duration—typically, long enough to encompass the lag 1 item, but too short to include later items (because, otherwise, there would be no attentional blink at those longer lags). When both targets are included in a single episode, order reversals should occur on 50% of the cases. Second, a precue prior to T1 will start an episode. Because of its early start, it will also end sooner, such that T2 will be more frequently missed. This explains the drop in performance for T2 in the precue conditions, as was found in the present experiments. However, note that order reversals are contingent on *both* T1 and T2 being correct, under the assumption that they would then share the same episode. A simple shift of the episode therefore does not predict a drop in order reversals. An additional assumption has to be made—namely, that on a considerable number of lag 1 trials a *second* episode is triggered in time for T2, such that T2 can be given its own cognitive time stamp. This would explain why, on average, the number of order reversals at lag 1 is somewhat less than 50%. The chances of T2 being assigned its own episode then increase when

the T1 episode finishes early, which may be more often the case after an early start. This, then, explains the reduction in order reversals in the precue condition.

Such a scenario would leave open a number of questions, though. First, it is not immediately clear why, in the standard case, T2 performance exceeds that of T1 at lag 1. This was the case for 10 out of 12 observers in Experiment 1, 13 out of 14 observers in Experiment 2, and 13 out of 14 observers in Experiment 3, whereas those observers who had the highest T2 benefit even exceeded 50% reversals. One could argue that the onset of the T1 episode is actually rather slow. Slow-starting episodes are more likely to include T2 (and thus cause order reversals) but come at a risk of missing T1. However, in the precue condition, such a sluggish start would then have to combine with a relatively rapid end to allow T2 to start a second episode (to explain the reduction in the number of order reversals). Moreover, even a sluggish gate would not allow order reversals to exceed 50%.

Second, it is not clear why the T1 episode would finish sooner in the precue condition than in the standard condition. Many attentional blink theories assume that the T1 episode ends only after T1 consolidation is completed (e.g., Akyürek et al., 2007, 2008; Bowman & Wyble, 2007; Chua, 2005; Chun & Potter, 1995). Furthermore, some have suggested that an episode can be flexibly extended as long as relevant information is entering the system (this is necessary to explain the phenomenon that sparing spreads to lag 2 and even 3 when more targets are presented; Di Lollo et al., 2005; Hommel et al., 2006; Nieuwenstein & Potter, 2006; Olivers et al., 2007; Shih, 2008; Wyble, Bowman, & Nieuwenstein, 2009). Note that here, the relevant T1 information occurs at exactly the same temporal position in both conditions. The episode may indeed start early in the precue condition, but it starts with an irrelevant distractor item. T1 identity information is available only at the same moment as in the standard condition. To solve this, one could argue that the precue generates attention, which may then speed up subsequent processing of T1 and, thus, promote a more rapid end of its consolidation episode. Such an attentional modulation process on top of the process of generating episodic representations may also explain why T2 performance exceeds that of T1 performance in the standard condition (as T1 generates attention for T2). This solution would come close to what we propose here—namely, that the order of report is determined by the amount of attention being paid to the respective targets.

On the basis of the present data, we cannot exclude the possibility that episodic integration occurs too, in addition to prior entry. However, at the very least, we would like to argue that it is not *necessary* to assume episodic integration in order to explain order reversals. If we assume instead, as

many theories have done, that T1 transiently recruits attentional resources or opens an attentional gate, this alone is sufficient to explain order reversals, without having to resort to a limited episodic binding process.

Other methods may shed some light on the involvement of episodic representations at lag 1 and their potential role in order reversals. Recent EEG and MEG studies looked at lag 1 and also lag 2 sparing, but the evidence regarding episodic integration has been mixed. Kihara, Kawahara, and Takeda (2008) looked at the P300 component in response to one, two, or three consecutive targets. The P300 has been thought to reflect working memory updating or consolidation processes, leading to target awareness. By subtracting two-target conditions (e.g., TTD and TDT, with T being a target, D being a distractor) from the three-target condition (TTT), it was shown that each of the targets generated its own P300. These separate P300 responses suggest that sparing is not accompanied by integrated memory representations. However, the validity of this subtraction method may be questioned. It should also work for the two-target (TTD) condition, such that subtracting the single-target condition (TDD) would reveal a peak for T2. Kihara et al. do not report this comparison, but their Fig. 2 suggests that it would generate a negative peak, rather than a P300. In any case, this study did not look at order reversals, and thus, the role of integrated signals in order reversals remains unclear.

Using MEG, Kessler et al. (2005) also concluded that “with regard to WM proper, our findings do not suggest that successive target stimuli are merged into a single neural code” (p. 2573). They found two distinct neuronal responses (the M300, equivalent to the P300) to T1 and T2 presented at lag 1 in prefrontal, as well as right posterior, areas. At the equivalent left posterior area, however, only a single response was found to both targets, but it remained unclear whether this was due to integrated representations or to temporal smearing of the MEG signal (i.e., a relative slowing of the T1 response in this area). Again, order reversals were not analyzed in relation to such effects.

Of most interest is a study by Caldwell-Harris and Morris (2008). They presented a short RSVP of two words and a mask and asked observers to identify the words in the correct order. Order errors were frequent, especially if the reversed order made linguistic sense (e.g., “zip code” instead of “code zip”). The interesting finding was that when asked to rate their confidence about the order, observers hardly ever (4% of the trials) chose the “don’t know” option offered. This is not immediately predicted by an episodic integration account, in which temporal order is assumed to be lost and the observer has to guess. In contrast, the prior-entry account states that one object reaches awareness more rapidly than the other, and thus it

is expected that a phenomenological sense of order is still preserved.

Models of the attentional blink

Of course, for many theories of the attentional blink, the problem with dropping the episodic integration assumption is that episodic integration also serves to explain lag 1 sparing itself. A single memory consolidation process for both targets is necessary to explain why T2 escapes the limitations of this very same memory consolidation process—limitations that are assumed to cause the attentional blink. Exceptions are the recent theories that propose a stronger role for selection, filtering, or gating mechanisms in explaining the attentional blink (Di Lollo et al., 2005; Nieuwenstein & Potter, 2006; Nieuwenstein, Potter, & Theeuwes, 2009; Olivers, 2007; Olivers & Meeter, 2008; Olivers et al., 2007; Wyble, Bowman, & Nieuwenstein, 2009). These theories assume that as long as incoming information complies with the observer's attentional set, attention is paid to the RSVP stream, and targets can be processed. Only when a signal tells the gating system that the relevant information has ended (Nieuwenstein et al., 2009; Wyble, Bowman, & Nieuwenstein, 2009) or has been replaced with distractors (Di Lollo et al., 2005; Olivers & Meeter, 2008) is attention withdrawn from the stream and does an attentional blink occur.

These theories do not deny that there are limitations in cognitive or perceptual resources. For example, performance may be limited by the capacity of visual short-term memory, which is thought to hold around four items. Furthermore, at very close timing between items (i.e., around or below 100 ms), representations may directly compete with each other within initial perceptual or semantic layers of representation—for example, through forward masking, backward masking, or lateral inhibition. For instance, Potter et al. (2002) found direct trade-offs between T1 and T2 when presented at close temporal range. This pattern was largely replicated here, since the precue caused T1 performance to go up but T2 performance to go down. Interestingly, recent work by Kawahara and Enns (2009) has shown that such trade-offs are independent of the ease with which T1 is selected from the stream, suggesting that selection mechanisms and interitem competition do not tap into the same resources but are dissociable. A straightforward resource competition model would assume that the more difficult T1 is to detect, the stronger will be the resource depletion for T2. It still remains to be determined, then, whether such interitem competition occurs prior to selection or after selection at the memory consolidation stage. There is one study that is suggestive here: Potter, Dell'Acqua, Pesciarelli, Job, and Peressotti (2005) have shown that T2, when presented at

lag 1, can semantically prime T1. Assuming that conceptual representations are created prior to selection, these findings also imply that T2 may already overtake T1 prior to selection, at the stage of semantic encoding.

What most selection theories do deny is that resource limitations or interitem competition plays a pivotal role in the attentional blink. According to Di Lollo et al. (2005) temporary loss of control account, the post-T1 distractor causes the input filter to lose the target description, resulting in a blockage of access to consciousness (although see Olivers & Meeter, 2008, for an argument that this account still needs the resource depletion argument). According to Olivers and Meeter (2008) boost and bounce theory, the attentional blink reflects an inhibitory response to a strongly boosted post-T1 distractor. If the post-T1 item is a target instead (T2), the boost will cause it to be spared and, at the same time, be more strongly represented than T1. This, in turn, could result in prior entry (although the computational model currently has no processing speed implemented yet). Boost and bounce theory thus offers an integrative account of lag 1 sparing, the attentional blink, and order reversals, since all three phenomena appear to depend on the strength of the post-T1 item. The cuing benefits for T1 found here can, then, be explained by assuming that the cue starts up the attentional boost prior to T1, thus restoring the balance between T1 and T2.

An interesting hybrid position is taken by Wyble et al. (2009) in their recent eSTST theory. This theory evolved from the earlier STST theory (Bowman & Wyble, 2007), which claimed that the attentional blink is caused by resource limitations at the level of episodic memory consolidation (which was assumed to be serial in nature). To protect this consolidation process, further selection of subsequent items is inhibited, causing an attentional blink. The episodic process is assumed to be serial, so that the system can assign separate time stamps to important events. In other words, the inhibition is not just the result of a limitation but is, in itself, functional. This argument has been made earlier by Hommel et al. (2006), who argued that the systems tendency to carve up information processing into discrete events makes it behave like a serial model. The new version, eSTST, no longer assumes that episodic coding is severely limited, since multiple traces can be created (near-) simultaneously. This process still causes inhibition of the perceptual input though (hence, an attentional blink will normally occur), in order to separate representations in time. However, when target activation is sufficiently strong (as when two targets are presented in immediate succession), this inhibition may be counteracted, with post-T1 items pushing through the selection layer and with sparing as a result. If a later target is indeed strong, it may be bound to an episodic representation before an earlier-presented target. Note here that the race for binding

is thus decided by activation at the lower layers, in line with prior entry. This way, eSTST combines episodic coding with perceptual selection mechanisms to account for lag 1 sparing, protracted sparing, and order reversals. As in boost and bounce theory, cuing T1 may speed up the enhancement of T1, thus causing it to gain in strength, relative to T2. Importantly, eSTST no longer appears to assume that the merging of representations is what underlies order reversals.

Another relevant model here is the attention cascade model of the attentional blink (Shih, 2008). This model is based on the attentional gating theory of Reeves and Sperling (1986; see also Shih & Sperling, 2002), which assumes that a target or a cue opens an attentional gate, during which multiple items in a stream can be processed. To account for the attentional blink, Shih (2008) extended the theory with a working memory consolidation process that refuses to accept further input while it is busy dealing with a target. In this respect, the model is a straightforward limited-capacity resource model. However, it does not assume that episodic integration accounts for order reversals, but something more akin to the prior-entry hypothesis—namely, that the strongest (rather than the first) item may be reported first. That is, at the output of the consolidation process, the temporal order of stimuli is judged by their relative strengths, with the onset of a stronger stimulus being perceived as earlier than a weaker one. The present cuing effects may be accommodated by assuming that the cue affects the relative strengths of the items. The theory differs from the prior-entry hypothesis in that order appears to be determined at the *output* of memory consolidation, whereas explanations of prior entry assume, rather, that the reversal already takes place before the entry into working memory or other late levels of processing (Bachmann, 1999; Scharlau & Neumann, 2003; Wundt, 1887). Where and exactly when time gets mixed up in the brain remains an intriguing question for the future.

Other effects on order reversals

A handful of other studies have investigated factors that affect the number of order reversals at lag 1. We have already mentioned the study by Caldwell-Harris and Morris (2008), who found that canonical word order (i.e., “zip code” instead of “code zip”) affected perceived order. This occurred even when observers expected order to be reversed.

Akyürek and Hommel (2005) found that order reversals were reduced when T1 duration was increased from 70 to 210 ms. They interpreted this in terms of fixed-size “integration windows.” T1 triggers an episode of fixed duration. When T1 is short, T2 is likely to fall within the window and is integrated with T1, at the expense of order

information. However, when T1 presentation takes too long, T2 misses the boat and is encoded within a separate window (with correct order perception as a consequence). However, the prior-entry account can also explain these data: T1 triggers an attentional boost that peaks at about 100 ms (Nakayama & Mackeben, 1989; Olivers & Meeter, 2008). Thus, T2 is optimally enhanced for T1–T2 SOAs of around 100 ms, but less so for SOAs of around 200 ms. Moreover, even if T2 is still substantially enhanced after 200 ms or so, it now has to make up for double the difference in timing will it ever overtake T1.

Finally, Akyürek and colleagues (Akyürek et al., 2007, 2008) have found that when observers expect to have more time to process the targets, the number of order reversals increases, as compared with a condition in which observers expect to have little time (but stimulus presentation conditions are actually the same). Akyürek and colleagues took this as evidence that observers have control over their integration windows, so that it can be adapted to collect more or less information into a single “object file,” at the expense of order information. The prior-entry account could be adapted to explain these data if we assume that the attentional response to T1 is modulated by expectancies. For example, within the boost and bounce model (Olivers & Meeter, 2008), the balance in the amount of attention received by T1 and T2 shifts more toward the latter when attention is a little slower to develop (for standard SOAs of around 100 ms).

Conclusion

We conclude that order reversals in the attentional blink are most parsimoniously explained through prior entry: A later, strongly attended target may overtake an earlier, less attended one in the race for report.

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