Categorical similarity modulates temporal integration in the attentional blink

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Attentional blink (AB) speaks to a phenomenon that, when reporting two targets in a rapid serial visual presentation, the second target (T2) is often missed if it followed the first target (T1) within an interval of less than 500 ms. An interesting exception is the preserved performance of T2 at Lag 1 position (Lag-1 sparing), or even in an extended period, which recently has been termed *temporal integration*. Both T1 and T2 can be successfully reported but with a loss of their temporal order. The integration has been attributed to the temporal distance between the two targets. However, previous studies on temporal perception have revealed that similarity between two stimuli modulated their temporal order judgment, suggesting that temporal integration is affected by stimulus characteristics. In the present study, we investigated whether stimulus characteristics modulated temporal integration in the AB. We manipulated the categorical similarity between T1 and T2 targets and found that the order reversals were significantly higher in the same-category condition than that in the different-category condition. Our results thus provided clear evidence for the contribution of categorical similarity to the temporal integration in the AB.

Introduction

Observers frequently miss the second target (T2) if two targets (T1 and T2) are presented in a rapid serial visual presentation (RSVP) within an interval of less than 500 ms. This well-known phenomenon has traditionally been called attentional blink (AB), representing a deficit in the temporal aspects of attention (Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). Empirical evidence in this field has suggested that AB phenomenon may reflect a central bottleneck of information processing. Only the T1 gains the privileged access to the capacity-limited resources (perception, attention, or memory), and the processing of T2 is suppressed to protect the ongoing processing of T1. However, an interesting exception is that, when T2 appears in the serial position immediately after the T1 (Lag 1), T2 performance at Lag 1 is much higher than those at other lags during the critical blink interval. Under certain circumstances, T2 performance at Lag 1 is as good as or even better than performance at long lags outside of the AB interval (Visser, Bischof, & Di Lollo, 1999). It is typically referred to as the Lag-1 sparing (Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999).

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Many theoretical and computational models have been proposed to account for the mechanisms underlying AB and Lag-1 sparing (for a review, see Dux & Marois, 2009). For example, early resource-limitation theories proposes that, due to the sluggish close of attentional gate, two consecutive targets may be processed in the same attentional window and undergo consolidation together, resulting in the Lag-1 sparing (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Potter, Staub, & O'Connor, 2002). The temporal gap between T1 and T2 is the determinate factor for the occurrence of Lag-1 sparing if there are no switches in the spatial location, task type, or stimulus type between two targets (Visser, Bischof, & Di Lollo, 1999). On the contrary, the temporal loss of control (TLC) model (Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005) emphasizes that the RSVP processing is governed by an attentional set configured to select targets and exclude distractors. This attentional set is endogenously controlled by a central executive processor. Once T1 is detected and processed, the central control over attentional set is lost and the attentional set can be exogenously reconfigured by the incoming stimuli. If the T1 + 1 item is a distractor, the attentional set needs to be reconfigured and causes a blink. If the T1 + 1 item is also a target (T2), the original attention set is unchanged and as a result T2 is also processed efficiently, which accounts for Lag-1 sparing. A somewhat different approach is the boost-and-bounce theory proposed by Olivers and Meeter (2008). In this model, detection of T1 elicits a temporary attentional boost, facilitating the processing of T1, as well as that of the upcoming stimuli. If the incoming item is a distractor, the attentional boost of this distractor will trigger a strong suppression ("bounce") of the subsequently presented item and an AB occurs. if the T1 + 1 item is T2, it will benefit from the original attentional boost and will be encoded successfully, resulting in Lag-1 sparing. Similarly, the episodic simultaneously type/serial token (eSTST) model proposes that Lag-1 sparing occurs if T1 and T2 appear in the same attentional episode.

A recent model put forward by Akyürek and his colleagues (Akyürek & Hommel, 2005; Hommel & Akyürek, 2005; Akyürek, Eshuis, Nieuwenstein, Saija, Başkent, & Hommel, 2012) offers an alternative explanation of Lag-1 sparing. Their temporal integration model emphasizes that temporal integration plays a central role in performance at Lag 1 in the AB task. In the literature of AB, Lag-1 sparing is often accompanied with a loss of temporal order information of targets. That is, T1 and T2 are both correctly identified but reported in a reversed order. The temporal integration account explains the order reversals by suggesting that the targets may have been integrated together into the same perceptual episode (Akyürek & Hommel, 2005). However, a crucial aspect of the temporal integration model, which distinguishes it sharply from other models, is that it predicts a kind of unique error report, namely, an integrated percept comprising both T1 and T2 (i.e., seeing only a single merged target stimulus). This prediction was verified by their empirical study (Akyürek et al., 2012). They adopted a modified attentional blink task in which the two targets could be combined perceptually into a possible target stimulus itself. The results revealed that, when T1 and T2 appeared consecutively (T2 at Lag 1), participants frequently reported an integrated stimulus and the reports of integrations occurred more frequently than order reversals. When the possibility to report the integrated percept was removed, order reversals consequently tripled, suggesting that temporal integration is the primary cause of order reversals in AB. The temporal integration in RSVP is not restricted to Lag 1. In another study, they further revealed an occurrence of three-target temporal integration that spanned an interval of 240 ms, showing an extended temporal integration (Akyürek & Wolff, 2016). These empirical findings suggested that temporal integration plays a crucial role in Lag-1 sparing. However, the factors that affect the temporal integration remains to be determined.

Previous research on temporal perception has already found that temporal integration is affected by various factors, such as stimulus duration (Di Lollo, 1980), stimulus intensity (Di Lollo, Clark, & Hogben, 1988; Long & Beaton, 1982), spatial proximity (Di Lollo & Hogben, 1987), emotion (Bocanegra & Zeelenberg, 2011), and sensory modality (Swisher & Hirsh, 1972). For example, two studies adopted a temporal order judgment (TOJ) task, in which participants were asked to report which target appears first. The results showed that temporal resolution was worse when the targets were grouped into one single perceptual object than when they did not group together. Baek et al. (2007) found that similarity based on the luminance polarity reduced the temporal resolution at the cued location in a typical TOJ task. TOJ performance was better when two targets were in different luminance polarities than in same luminance polarity. Nicol et al. (2009) further revealed that TOJ performance was susceptible to target distinctiveness (i.e., similarity based on shape). It was more difficult to discriminate the targets' temporal order when they were in the same shape than when they were in different shapes. Taken together, these results suggested that similarity between targets facilitated the temporal integration and thus reduced the temporal resolution, resulting in a deficit in reporting their temporal order.

Therefore, in the present study, we aimed to investigate whether the categorical similarity affects the temporal integration. Specifically, Experiments 1 and 2 were designed to explore whether categorical dissimilarity reduced the temporal integration in a typical AB paradigm. Experiment 3 was conducted to test whether explicit prior information of target order (i.e., explicitly knowing the order information of targets before the experiment) could eliminate the order reversal. Experiment 4 adopted a within-subject design and aimed to replicate the findings of Experiments 1 and 2 by equating the set size of the categories.

Experiment 1

To replicate the common finding in the literature of AB that order reversals occur more frequently at Lag 1, Experiment 1 adopted a classical RSVP paradigm with alphanumeric stimuli, in which the two targets were taken from the same category (i.e., letter category). Thus, Experiment 1 was similar to that of Hommel and Akyürek (2005), except that the stimuli and timing information of the RSVP were slightly different.

Methods

Participants

Nineteen new undergraduate or graduate students (14 females; mean age = 22.6 ± 2.1 years; 18 right-handed) participated in the experiment. All had normal or corrected-to-normal vision and provided written informed consent prior to the study.

The same group of participants also completed the Experiment 3. The order of completion of these two experiments was counterbalanced across participants.

Apparatus and stimuli

All stimuli were displayed on an Asus 24-in. monitor (resolution: 1,024 × 768 pixels; refresh rate: 100 Hz) using Psychtoolbox 3 (Brainard, 1997) for MATLAB (Mathworks, Inc., Natick, MA, USA). The viewing distance was about 90 cm. All stimuli were presented on the gray background (8.63 cd/m^2) and displayed at the center of the screen. A black dot subtending 0.28° (0.26 cd/m^2) served as the fixation point. T1 and T2 (5.03 cd/m^2) were randomly chosen from a letter category. The letter category consisted of 22 uppercase letters (excluding O, I, Z, and B to avoid possible confusion with digitals). T1 and T2 targets were always different in each trial. Distractors (2.79 cd/m^2) consisted of six digits (excluding 0, 1, 2, and 8 to avoid possible confusion with letters). Targets and distractors were in Verdana font, subtending 0.80° in height and 0.77° in width.

Procedure and design

Participants initiated each trial by pressing the space key. Each trial began with the presentation of a black fixation for 1,000 to 2,000 ms. Then, a 22-item RSVP stream appeared at the fixation and in a presentation rate of 10 items/s with no gap between items (Figure 1). Each stream consisted of two targets (T1 and T2) and 20 distractors. T1 appeared randomly in the serial positions 7 to 11 of the stream. T2 followed the T1 and occurred equally often at one of the eight serial positions (1–8) after T1 (Lags 1–8). Participants were instructed to report the two targets in the correct order by pressing the corresponding keys at the end of the trial. No feedback was given.

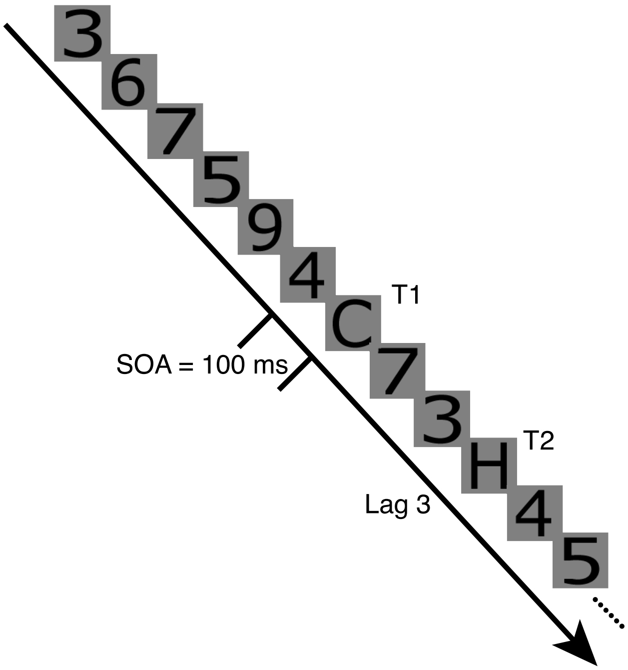

Figure 1. Illustration of stimuli and procedure of Experiment 1.

The experiment consisted of 160 trials, 20 for each lag. Before the experiment, participants completed a practice block of 10 to 20 trials. During the practice, sound feedback was given.

Results and discussions

AB magnitude and Lag-1 sparing

For each participant, we first calculated the conditional T2 performance (T2|T1, the percentage of correctly reported T2 given that T1 was correctly reported, irrespective of whether the order of them was correct or not) separately for each lag. The T2|T1 performance for each participant was then analyzed using a one-way repeated-measures analysis of variance (ANOVA) with lag (1–8) as a within-subject factor. As shown in Figure 2a, a standard AB was found (main effect of lag: $F(7, 126) = 15.92$, $p < 0.001$, $\eta_p^2 = 0.469$).

AB magnitude was calculated as the decrease of T2|T1 accuracy at Lag 3 relative to T2|T1 accuracy at Lag 8 [$(\mathrm{T2|T1}_{lag8} - \mathrm{T2|T1}_{lag3}) / \mathrm{T2|T1}_{lag8}$] (Willems, Saija, Akyürek, & Martens, 2016). The AB magnitude was 0.30 ± 0.06 (see Figure 5a).

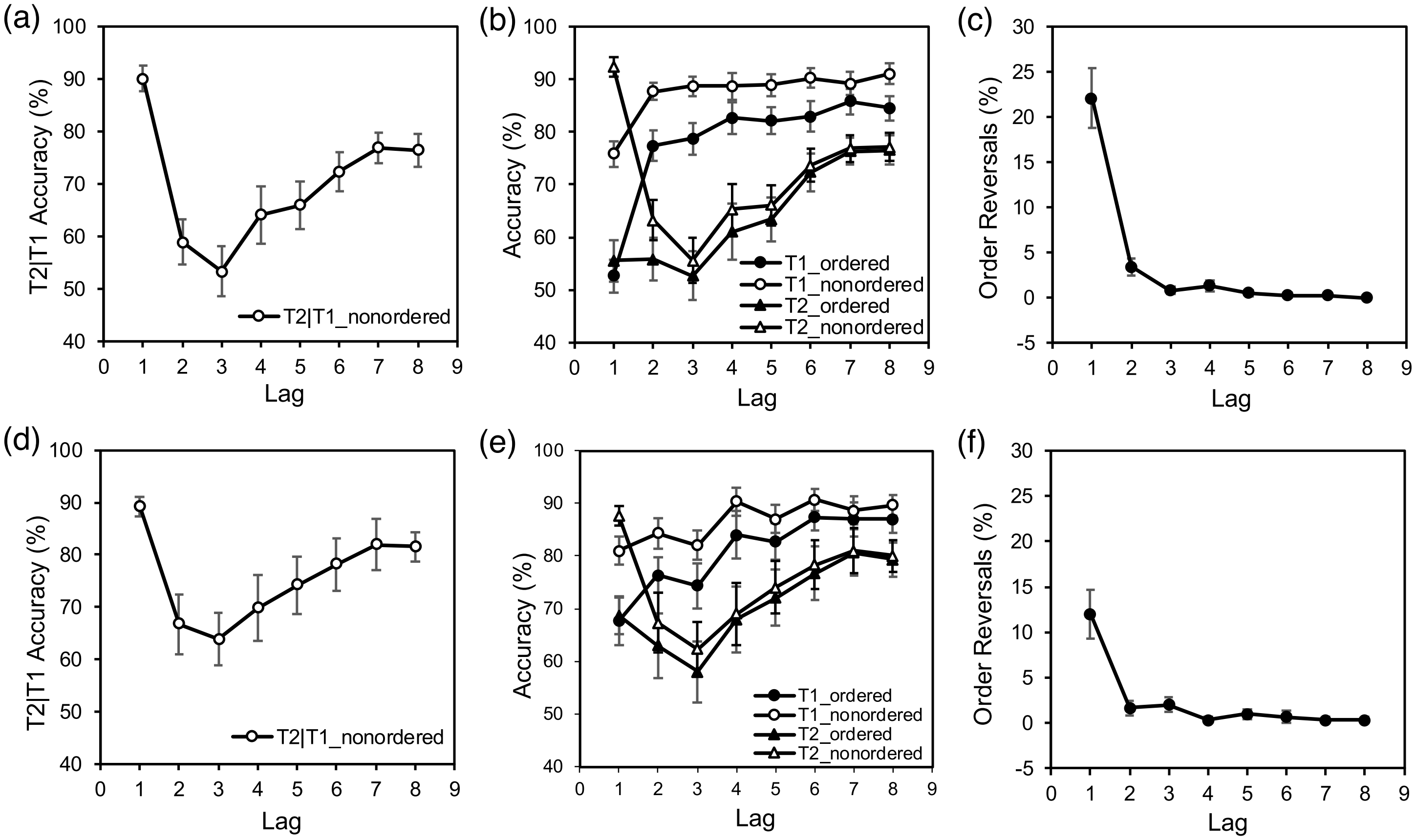

Figure 2. Results of Experiments 1 and 2. (a) Conditional T2|T1 performance in Experiment 1, irrespective of the temporal order. (b) Unconditional T1 and T2 performance in Experiment 1, where “ordered” denotes that both the identity and temporal position were correctly reported (e.g., T1_ordered: T1 was correctly reported as first target) and “nonordered” denotes that only the identity was correctly reported (e.g., T1_nonordered: T1 was correctly reported, irrespective of its temporal position). (c) Order reversals in Experiment 1. (d) Conditional T2|T1 performance in Experiment 2. (e) Unconditional T1 and T2 performance in Experiment 2. (f) Order reversals in Experiment 2. Error bars represent ± *SEM*.

The Lag-1 sparing effect was calculated as the difference between T2|T1 accuracy at Lag 1 and T2|T1 accuracy at Lag 3 [$(\mathrm{T2|T1}_{\mathrm{lag1}} - \mathrm{T2|T1}_{\mathrm{lag3}})$]. There was a clear Lag-1 sparing effect (36.70% ± 5.06%) (see Figure 5b). T2|T1 accuracy was high at Lag 1 and then dropped by around 34% at Lag 2 and Lag 3, satisfying the criteria suggested by Visser et al. (1999). Note that Lag 3, rather than Lag 2, was used to calculate the AB magnitude and Lag-1 sparing because the T2|T1 accuracy was lowest at Lag 3 in the present study.

Temporal order effect on T1 and T2 performance

To explore the temporal order effect in AB, we adopted a similar analysis as that used in Hommel and Akyürek (2005) and calculated the unconditional T1 and T2 performance for each lag (e.g., unconditional T2 performance referred to the percentage of correctly reported T2, irrespective of whether T1 was correctly reported or not), according to two different accuracy criteria. When applying the lenient accuracy criterion, trials were considered to be correct if the identity (which letter) of the target was correctly reported, irrespective of its temporal position. When applying the strict accuracy criterion, trials were considered correct only if both the identity and temporal position (e.g., T1 was reported as the first target) of the target were correctly reported. Then, the unconditional T1 and T2 performance were separately submitted to a two-way ANOVA with criterion (lenient and strict) and lag (1–8) as the within-subject factors.

For the unconditional T1 performance, as shown in Figure 2b, there was a significant interaction between criterion and lag ($F(7, 126) = 13.33$, $p < 0.001$, $\eta_p^2 = 0.425$). The main effect of criterion ($F(1, 18) = 56.11$, $p < 0.001$, $\eta_p^2 = 0.757$) and lag ($F(7, 126) = 26.04$, $p < 0.001$, $\eta_p^2 = 0.591$) was also significant. When using the lenient criterion, T1 performance decreased significantly at Lag 1 (main effect of lag: $F(7, 126) = 9.50$, $p < 0.001$, $\eta_p^2 = 0.345$; $\mathrm{T1}_{\mathrm{lag1}}$ vs. $\mathrm{T1}_{\mathrm{lag8:}}$ $t(18) = -5.51$, $p < 0.001$, Cohen’s $d = 1.264$). When using the strict criterion, T1 performance declined remarkably at Lag 1 to Lag 3 (main effect of lag: $F(7, 126) = 32.77$, $p < 0.001$, $\eta_p^2 = 0.645$; $T1_{lag1}$ vs. $T1_{lag8}$: $t(18) = –11.21$, $p < 0.001$, Cohen's $d = 2.571$; $T1_{lag2}$ vs. $T1_{lag8}$: $t(18) = –2.34$, $p = 0.031$, Cohen's $d = 0.536$; $T1_{lag3}$ vs. $T1_{lag8}$: $t(18) = –2.20$, $p = 0.041$, Cohen's $d = 0.505$).

For the unconditional T2 performance, the interaction between criterion and lag was also significant ($F(7, 126) = 80.58$, $p < 0.001$, $\eta_p^2 = 0.817$) (Figure 2b). The main effect of criterion ($F(1, 18) = 113.08$, $p < 0.001$, $\eta_p^2 = 0.863$) and lag ($F(7, 126) = 11.20$, $p < 0.001$, $\eta_p^2 = 0.383$) was also significant. When using the lenient criterion, T2 performance was remarkably high at Lag 1 and dropped dramatically at Lags 2 to 5 (main effect of lag: $F(7, 126) = 19.17$, $p < 0.001$, $\eta_p^2 = 0.516$; $T2_{lag1}$ vs. $T2_{lag8}$: $t(18) = 5.73$, $p < 0.001$, Cohen's $d = 1.315$; $T2_{lag2}$ vs. $T2_{lag8}$: $t(18) = –3.94$, $p = 0.001$, Cohen's $d = 0.905$; $T2_{lag3}$ vs. $T2_{lag8}$: $t(18) = –5.11$, $p < 0.001$, Cohen's $d = 1.172$; $T2_{lag4}$ vs. $T2_{lag8}$: $t(18) = –2.64$, $p = 0.016$, Cohen's $d = 0.607$; $T2_{lag5}$ vs. $T2_{lag8}$: $t(18) = –3.35$, $p = 0.004$, Cohen's $d = 0.768$). However, when using the strict criterion, T2 performance was significantly impaired at Lags 1 to 5 (main effect of lag: $F(7, 126) = 12.77$, $p < 0.001$, $\eta_p^2 = 0.415$; $T2_{lag1}$ vs. $T2_{lag8}$: $t(18) = –5.46$, $p < 0.001$, Cohen's $d = 1.253$; $T2_{lag2}$ vs. $T2_{lag8}$: $t(18) = –5.49$, $p < 0.001$, Cohen's $d = 1.258$; $T2_{lag3}$ vs. $T2_{lag8}$: $t(18) = –5.30$, $p < 0.001$, Cohen's $d = 1.216$; $T2_{lag4}$ vs. $T2_{lag8}$: $t(18) = –3.28$, $p = 0.004$, Cohen's $d = 0.753$; $T2_{lag5}$ vs. $T2_{lag8}$: $t(18) = –3.56$, $p = 0.002$, Cohen's $d = 0.818$).

The results thus replicated the main findings of Hommel and Akyürek (2005). T1 and T2 performance under the strict accuracy criterion declined significantly compared with those under the lenient accuracy criterion. Furthermore, these effects were more evident at the short lags.

Order reversals

We then calculated the order reversals (trials in which both targets were correctly identified but in a reversed order), a sensitive measure of temporal integration of T1 and T2 (Akyürek & Hommel, 2005), separately for each lag. Order reversals were then analyzed using a one-way ANOVA with lag (1–8) as the within-subject factor. As shown in Figure 2c, the main effect of lag was significant ($F(7, 126) = 36.96$, $p < 0.001$, $\eta_p^2 = 0.672$). Compared with Lag 8, the order reversals were significantly higher at Lags 1 and 2 ($t(18) = 6.71$, false discovery rate (FDR)-adjusted $p < 0.001$, Cohen's $d = 1.539$, and $t(18) = 3.64$, FDR-adjusted $p = 0.007$, Cohen's $d = 0.834$, respectively) and disappeared at other lags (all $ps > 0.05$).

Therefore, in Experiment 1, when targets belonged to the same category, order reversals were evident at Lags 1 and 2.

Experiment 2

Experiment 2 aimed to investigate whether the order reversals would decrease if T1 and T2 were taken from different categories, which could reduce the categorical similarity between them.

Methods

Participants

Fifteen healthy undergraduate or graduate students (12 females; mean age = 22.2 ± 2.1 years; all right-handed) participated in this experiment. All had normal or corrected-to-normal vision and provided written informed consent prior to the study.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design of Experiment 2 were similar to those in Experiment 1 except for the following changes. In Experiment 2, T1 and T2 were taken from two different categories (letter and symbol category). The assignment of categories to T1 and T2 in each trial was randomized across trials. The letter category was the same as that used in Experiment 1, and the symbol category consisted of five symbols (#, $, %, &, *). Participants were instructed to report the two targets in the correct order. Before the experiment, participants were told that one of the targets was a letter and the other a symbol. However, order information of the two targets in each trial was not provided to participants.

Results and discussions

The analysis was the same as that used in Experiment 1.

AB magnitude and Lag-1 sparing

As shown in Figure 2d, a standard AB was found (main effect of lag: $F(7, 98) = 7.63$, $p < 0.001$, $\eta_p^2 = 0.353$). The AB magnitude was 0.22 ± 0.05 (see Figure 5a), and the Lag-1 sparing was 25.33% ± 4.18% (see Figure 5b).

Temporal order effect on T1 and T2 performance

For the unconditional T1 performance, significant main effects were obtained for both criterion ($F(1, 14) = 16.28$, $p = 0.001$, $\eta_p^2 = 0.538$) and lag ($F(7, 98) = 6.55$, $p < 0.001$, $\eta_p^2 = 0.319$). The interaction between criterion and lag was also significant ($F(7, 98) = 4.87$, $p = 0.003$, $\eta_p^2 = 0.258$) (Figure 2e). We then conducted the one-way AVONA with lag (1–8) as the within-subject factor, separately for each criterion. When using the lenient criterion, T1 performance decreased significantly at Lags 1 and 3, as compared with Lag 8 (main effect of lag: $F(7, 98) = 3.73$, $p = 0.007$, $\eta_p^2 = 0.210$; T1_{lag1} vs. T1_{lag8}: $t(14) = -2.63$, $p = 0.020$, Cohen's $d = 0.680$; T1_{lag3} vs. T1_{lag8}: $t(14) = -3.22$, $p = 0.006$, Cohen's $d = 0.830$). Nevertheless, under the strict criterion, T1 performance dropped dramatically at Lags 1 to 3 (main effect of lag: $F(7, 98) = 7.82$, $p < 0.001$, $\eta_p^2 = 0.359$; T1_{lag1} vs. T1_{lag8}: $t(14) = -3.70$, $p = 0.002$, Cohen's $d = 0.955$; T1_{lag2} vs. T1_{lag8}: $t(14) = -3.51$, $p = 0.003$, Cohen's $d = 0.905$; T1_{lag3} vs. T1_{lag8}: $t(14) = -3.54$, $p = 0.003$, Cohen's $d = 0.913$).

For the unconditional T2 performance, there were significant main effects of criterion ($F(1, 14) = 25.97$, $p < 0.001$, $\eta_p^2 = 0.650$) and lag ($F(7, 98) = 6.66$, $p < 0.001$, $\eta_p^2 = 0.322$). There was also revealed a significant interaction between criterion and lag ($F(7, 98) = 17.73$, $p < 0.001$, $\eta_p^2 = 0.559$) (Figure 2e). When using the lenient criterion, T2 performance was remarkably high at Lag 1 but dropped dramatically at Lags 2 to 4 (main effect of lag: $F(7, 98) = 8.21$, $p < 0.001$, $\eta_p^2 = 0.370$; T2_{lag1} vs. T2_{lag8}: $t(14) = 2.83$, $p = 0.013$, Cohen's $d = 0.730$; T2_{lag2} vs. T2_{lag8}: $t(14) = -2.64$, $p = 0.019$, Cohen's $d = 0.681$; T2_{lag3} vs. T2_{lag8}: $t(14) = -4.36$, $p = 0.001$, Cohen's $d = 1.127$; T2_{lag4} vs. T2_{lag8}: $t(14) = -2.617$, $p = 0.020$, Cohen's $d = 0.676$). However, when using the strict criterion, T2 performance was significantly impaired at Lags 1 to 4 (main effect of lag: $F(7, 98) = 6.52$, $p < 0.001$, $\eta_p^2 = 0.318$; T2_{lag1} vs. T2_{lag8}: $t(14) = -2.65$, $p = 0.019$, Cohen's $d = 0.685$; T2_{lag2} vs. T2_{lag8}: $t(14) = -3.26$, $p = 0.006$, Cohen's $d = 0.842$; T2_{lag3} vs. T2_{lag8}: $t(14) = -4.52$, $p < 0.001$, Cohen's $d = 1.168$; T2_{lag4} vs. T2_{lag8}: $t(14) = -2.71$, $p = 0.017$, Cohen's $d = 0.700$).

Order reversals

As shown in Figure 2f, order reversals decreased significantly as the lag increased ($F(7, 98) = 13.80$, $p < 0.001$, $\eta_p^2 = 0.496$). Compared with Lag 8, the order reversals were significantly higher at Lag 1 ($t(14) = 4.25$, FDR-adjusted $p = 0.006$, Cohen's $d = 1.097$). However, there were no significant order reversals at Lags 2 to 7 (all $ps > 0.05$).

Therefore, in Experiment 2, order reversals were only evident at Lag 1 when T1 and T2 belonged to different categories.

Comparison between Experiments 1 and 2

The AB magnitude and Lag-1 sparing did not differ significantly between Experiments 1 and 2 (two-sample *t* test: $t(32) = 0.85$, $p = 0.403$, Cohen's $d = 0.299$, and $t(32) = 1.67$, $p = 0.104$, Cohen's $d = 0.588$, respectively) (see Figure 5), suggesting that categorical similarity had no significant effect on the AB magnitude and Lag-1 sparing.

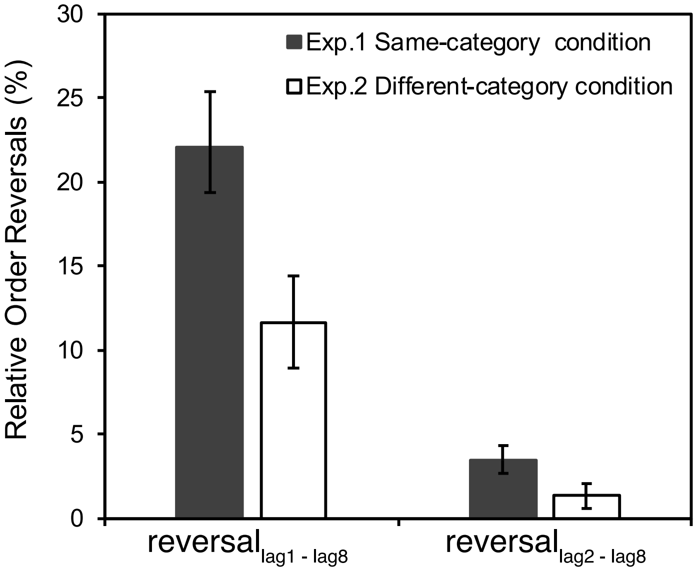

Figure 3. Relative order reversals at Lags 1 to 2 in Experiments 1 and 2. $\text{Reversal}_{\text{lag1-lag8}}$ means order reversals at Lag 1 minus order reversals at Lag 8. Error bars represent ± *SEM*.

To directly test how categorical similarity affected temporal integration, we calculated the relative order reversals at Lag 1 ($\text{reversal}_{\text{lag1}} - \text{reversal}_{\text{lag8}}$) and Lag 2 ($\text{reversal}_{\text{lag2}} - \text{reversal}_{\text{lag8}}$), separately for Experiments 1 and 2. The relative order reversals were then submitted to a two-way ANOVA with categorical similarity and lag as between-subject and within-subject factors, respectively. The main effects of lag ($F(1, 32) = 47.90$, $p < 0.001$, $\eta_p^2 = 0.599$) and categorical similarity ($F(1, 32) = 6.25$, $p = 0.018$, $\eta_p^2 = 0.163$) were significant, suggesting that there were more order reversals when targets belonged to the same category (Experiment 1) than those when targets belonged to different categories (Experiment 2). A significant interaction between categorical similarity and lag was also found ($F(1, 32) = 3.97$, $p = 0.05$, $\eta_p^2 = 0.110$) (Figure 3). Relative order reversals at Lag 1 in Experiment 1 were significantly higher than those in Experiment 2 ($t(32) = 2.35$, $p = 0.025$, Cohen's $d = 0.826$). However, order reversals at Lag 2 did not differ significantly between Experiment 1 and Experiment 2 ($t(32) = 1.66$, $p = 0.107$, Cohen's $d = 0.583$).

Taken together, the present results suggested that categorical similarity modulated the temporal integration.

Experiment 3

The results of Experiment 2 suggested that categorical dissimilarity attenuated the temporal integration. Experiment 3 was thus conducted to

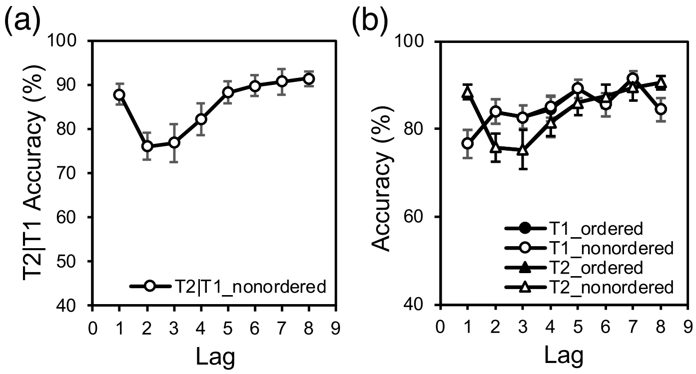

Figure 4. Results of Experiment 3. (a) Conditional T2|T1 performance, irrespective of the temporal order. (b) Unconditional T1 and T2 performance. As the order information of two targets was explicitly provided to the participants before the experiment, the temporal positions of T1 and T2 targets were always correctly reported. Error bars represent ± *SEM*.

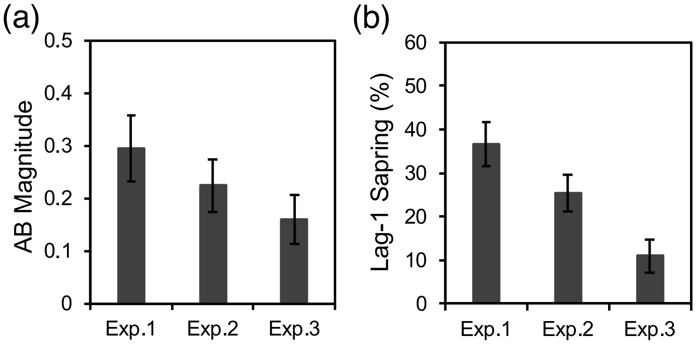

Figure 5. (a) AB magnitude in each experiment. AB magnitude was calculated as the decrease of T2|T1 accuracy at Lag 3 relative to T2|T1 accuracy at Lag 8 $[(T2|T1_{lag8} - T2|T1_{lag3}) / T2|T1_{lag8}]$. (b) Magnitude of Lag-1 sparing in each experiment. It was calculated as the difference between T2|T1 accuracy at Lag 1 and T2|T1 accuracy at Lag 3 $[(T2|T1_{lag1} - T2|T1_{lag3})]$. Error bars represent ± *SEM*.

investigate whether explicitly knowing the order information of targets could further reduce the order-reversal effect.

Methods

Participants

The same group of participants in Experiment 1 also completed Experiment 3. The order of completion of these two experiments was counterbalanced across participants.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design were identical to those in Experiment 2 except for the following changes. To reduce the task difficulty or cognitive load, T1 was always randomly chosen from the 22 letters of the letter category, and T2 was always randomly chosen from the five symbols of the symbol category. Before the experiment, Participants were explicitly instructed to know that T1 was always a letter, and T2 was always a symbol.

Results and discussions

The analysis was the same as that used in Experiment 2.

AB magnitude and Lag-1 sparing

Similar to previous experiments, a standard AB was found (main effect of lag: $F(7, 126) = 8.57$, $p < 0.001$, $\eta_p^2 = 0.322$) (Figure 4a), even though the order information of T1 and T2 targets was informed in advance. The AB magnitude was 0.16 ± 0.05 (Figure 5a), and the Lag-1 sparing was 10.96% ± 3.74% (Figure 5b).

Temporal order effect on T1 and T2 performance

For the unconditional T1 performance, there was only a significant main effect of lag ($F(7, 126) = 5.61$, $p < 0.001$, $\eta_p^2 = 0.237$). No other main effect or interaction was found ($F(1, 18) = 2.12$, $p = 0.163$, $\eta_p^2 = 0.105$, and $F(7, 126) = 2.12$, $p = 0.163$, $\eta_p^2 = 0.105$, respectively) (Figure 4b).

For the unconditional T2 performance, there was also a significant main effect of lag ($F(7, 126) = 8.68$, $p < 0.001$, $\eta_p^2 = 0.325$). No other main effect or interaction was found ($F(1, 18) = 1.00$, $p = 0.331$, $\eta_p^2 = 0.053$, and $F(7, 126) = 1.00$, $p = 0.331$, $\eta_p^2 = 0.053$, respectively) (Figure 4b).

Order reversals

When participants were instructed explicitly about the temporal order information of T1 and T2, order reversals no longer occurred (maximum order reversals $< 0.3\%$).

Comparison between Experiment 2 and Experiment 3

There was no significant difference in the AB magnitude between Experiments 2 and 3 ($t(32) = 0.94$, $p = 0.353$, Cohen's $d = 0.326$) (Figure 5a). However, the Lag-1 sparing was significantly stronger in Experiment 2 than in Experiment 3 ($t(32) = 2.56$, $p = 0.016$, Cohen's $d = 0.884$) (Figure 5b), suggesting that when the target order information was explicitly provided to participants, the Lag-1 sparing decreased.

The relative order reversals from Experiments 2 and 3 were submitted to a two-way ANOVA with order information (unknown and known) and lag (1–2) as between-subject and within-subject factors, respectively. The results revealed a significant interaction between order information and lag ($F(1, 32) = 18.20$, $p < 0.001$, $\eta_p^2 = 0.363$), as well as a significant main effect of lag ($F(1, 32) = 18.20$, $p < 0.001$, $\eta_p^2 = 0.363$) and order information ($F(1, 32) = 24.64$, $p < 0.001$, $\eta_p^2 = 0.435$). Further, post hoc t test showed that relative order reversals at Lag 1 were significantly higher in Experiment 2 than in Experiment 3 ($t(14) = 4.25$, $p = 0.001$, Cohen's $d = 0.884$). It further suggested that explicit prior knowledge of the target order could eliminate the order reversals.

Comparison between Experiment 1 and Experiment 3

No significant difference was found in the AB magnitude between Experiments 1 and 3 ($t(18) = 1.91$, $p = 0.073$, Cohen's $d = 0.438$) (Figure 5a). There was a significantly stronger Lag-1 sparing effect in Experiment 1 than in Experiment 3 ($t(18) = 4.82$, $p < 0.001$, Cohen's $d = 1.105$) (Figure 5b). The relative order reversals from Experiments 1 and 3 were submitted to a two-way repeated-measures ANOVA with experiment (Experiments 1 and 3) and lag (1–2) as within-subject factors. The results revealed a significant interaction between experiment and lag ($F(1, 18) = 38.00$, $p < 0.001$, $\eta_p^2 = 0.679$), as well as a significant main effect of lag ($F(1, 18) = 38.00$, $p < 0.001$, $\eta_p^2 = 0.679$) and experiment ($F(1, 18) = 45.53$, $p < 0.001$, $\eta_p^2 = 0.717$). Post hoc t test showed that relative order reversals at Lag 1 and Lag 2 were significantly higher in Experiment 1 than in Experiment 3 (Lag 1: $t(18) = 6.71$, $p < 0.001$, Cohen's $d = 1.539$; Lag 2: $t(18) = 3.64$, $p = 0.002$, Cohen's $d = 0.834$).

Taken together, these results suggested that categorical dissimilarity between T1 and T2, or explicit prior knowledge of the target order, could attenuate the order reversals and Lag-1 sparing but had no effects on the AB magnitude.

It should be noted that it is impossible to conduct an omnibus ANOVA to test whether there was an overall difference in the AB magnitude, Lag-1 sparing, or order reversals across all three experiments because Experiments 1 and 3 were conducted on the same group of participants while Experiment 2 was conducted on a new group of participants.

Experiment 4

One may argue that the modulation of categorical similarity on temporal integration, as revealed in the previous experiments, might be due to the low-prevalence effect (Hout, Walenchok, Goldinger, & Wolfe, 2015; Papesh & Guevara Pinto, 2019; Wolfe, Horowitz, & Kenner, 2005). That is, targets with a low prevalence (or frequency) are less likely to be detected than targets with a high prevalence or frequency. First, although the set size (i.e., number of candidate items) of T1 was the same in Experiments 1 and 3 (i.e., 22 letters), the set size of T2 was always smaller in Experiment 3 (5 symbols) than in Experiment 1 (22 letters) because the breadth of these two categories was unequal. Second, although the assignment of categories to T1 and T2 was counterbalanced in Experiment 2, it was not counterbalanced in Experiment 3. Thus, the set size of T1 in Experiment 2 (22 letters plus five symbols) was still larger than that in Experiment 3 (22 letters). Third and most important, the set sizes of T1 and T2 in Experiment 1 (22 letters) were also different from those in Experiment 2 (22 letters plus five symbols). Detecting infrequent targets might produce an exacerbated AB, which thus leads to different order reversals across experiments. Meanwhile, there were several empirical studies showing a modulation effect of the set size of T1 on the AB magnitude (Crebolder, Jolicœur, & McIlwaine, 2002; Shapiro, Raymond, & Arnell, 1994). Therefore, the decrease of order reversals in Experiments 2 and 3 might be alternatively due to the larger set size of T1 in Experiment 2 and smaller set size of T2 in Experiment 3, respectively.

Experiment 4 was conducted to replicate the basic findings of Experiments 1 and 2 but used a within-subject design. Importantly, to exclude the alternative explanation based on the low-prevalence effect, we adopted digit category and symbol category as the target category and letter category as the distractor category. The assignment of the category to T1 and T2 was counterbalanced. The set sizes of the digit category and symbol category were equal, seven items for each category.

Methods

Participants

Nineteen new undergraduate or graduate students (seven females; mean age = 22.5 ± 2.9 years; all right-handed) participated in the Experiment 4. All had normal or corrected-to-normal vision and provided written informed consent prior to the study. One participant was excluded from further analysis due to the low T1 accuracy (less than 70%).

Apparatus and stimuli

The apparatus and stimuli were similar to those used in Experiments 1 and 2, except for the following

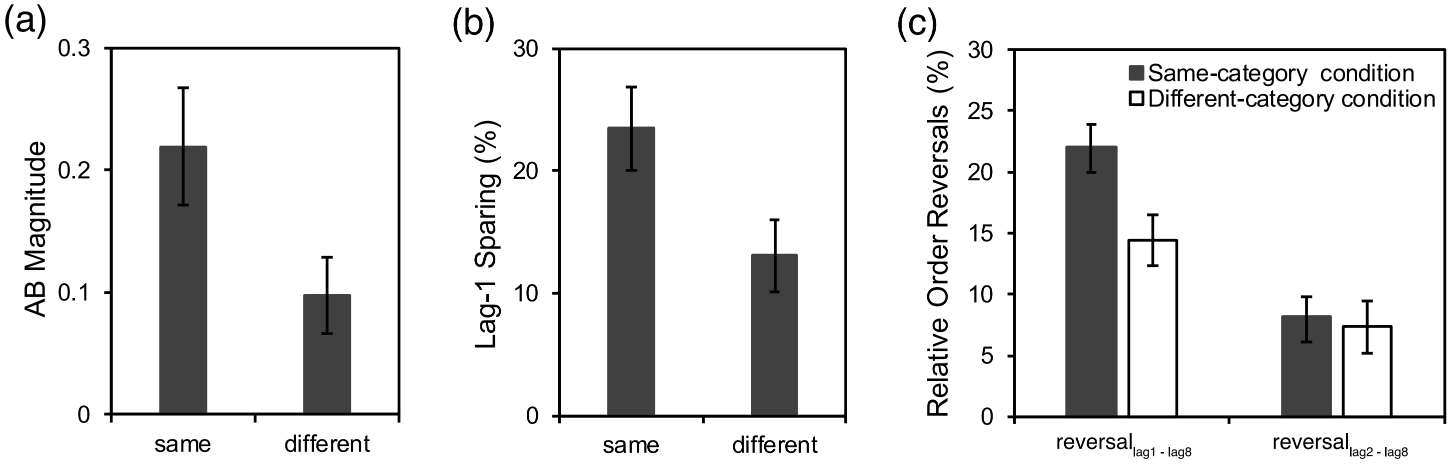

Figure 6. Results of the same- and different-category conditions in Experiment 4. (a) AB magnitude. (b) Magnitude of Lag-1 sparing. (c) Relative order reversals at Lags 1 to 2. Error bars represent ± *SEM*.

changes. There were seven candidate items for both two target categories (digit and symbol category). The digit category contained 2, 3, 5, 6, 7, 8, and 9. The symbol category contained #, $, ?, *, =, <, and >. Distractors consisted of 21 letters (A, C–H, J–N, P, Q, R, T–Y).

Procedure and design

There were two sessions in Experiment 4, one for the same-category condition and the other for the different-category condition. At the beginning of each session, the participants were instructed which condition was about to be conducted, but they were not informed about the order information about the targets. Each session consisted of 160 trials. The order of sessions was counterbalanced across participants. In the session of the same-category condition, for each trial, T1 and T2 were both randomly taken from either the digit category or the symbol category, whereas for each trial in the session of the different-category condition, T1 and T2 were randomly taken from the digit category and symbol category, respectively, or vice versa. The assignment of categories to T1 and T2 was randomized across trials within each session. T1 appeared randomly in the serial positions 7 to 11 of the 22-item RSVP stream. T2 target followed the T1 target and occurred equally often at one of the four serial positions (1, 2, 3, and 8) after T1 (Lag 1, Lag 2, Lag 3, and Lag 8). Participants were instructed to report the two targets in the correct order.

Results and discussions

AB magnitude and Lag-1 sparing

A standard AB was found in both conditions (Figure 6). AB magnitude in the same-category condition (0.22 ± 0.05) was significantly higher than that in the different-category condition (0.10 ± 0.03) ($t(17) = 2.58$, $p = 0.020$, Cohen's $d = 0.607$) (Figure 6a). Lag-1 sparing in the same-category condition (23.49% ± 3.41%) was also significantly higher than that in the different-category condition (13.09% ± 2.92%) ($t(17) = 3.42$, $p = 0.003$, Cohen's $d = 0.806$) (Figure 6b).

These results suggested that categorical similarity has a significant effect on both AB magnitude and Lag-1 sparing. Note that these results were not exactly the same as those found in Experiments 1 and 2.

Order reversals

The relative order reversals were calculated in the same way as that in previous experiments and analyzed using a two-way ANOVA with categorical similarity (same and different category) and lag (1, 2) as the within-subject factors. The interaction between categorical similarity and lag was significant ($F(1, 17) = 13.69$, $p = 0.002$, $\eta_p^2 = 0.446$). The main effects of categorical similarity and lag were also significant ($F(1, 17) = 6.18$, $p = 0.024$, $\eta_p^2 = 0.267$, and $F(1, 17) = 59.77$, $p < 0.001$, $\eta_p^2 = 0.779$, respectively). As shown in Figure 6c, the post hoc t test revealed that relative order reversals at Lag 1 in the same-category condition were much higher than those in the different-category condition ($t(17) = 3.70$, $p = 0.002$, Cohen's $d = 0.872$), but there was no significant difference in order reversals between the two conditions at Lag 2 ($t(17) = 0.46$, $p = 0.649$, Cohen's $d = 0.109$). Thus, Experiment 4 replicated the basic findings of Experiments 1 and 2 and excluded the alternative explanation based on the low-prevalence effect. Taken together, our results suggested that the temporal integration was modulated by categorical similarity.

General discussion

In summary, we investigated whether categorical similarity affected temporal integration in a series of four experiments by manipulating the categorical similarity between T1 and T2 (Experiments 1 and 2 in a between-subject design, Experiment 4 in a within-subject design) and order certainty (Experiment 3). The results consistently showed that categorical dissimilarity did attenuate temporal integration and thus provided clear evidence for the contribution of the categorical similarity to the temporal integration during the AB.

There have been many investigations on how the similarity between targets and distractors influenced the AB (Raymond, Shapiro, & Arnell, 1995; for a review, see Dux & Marois, 2009). However, only a few studies have been devoted to directly address how similarity between targets affected the AB, particularly the temporal integration process (Akyürek, Schubö, & Hommel, 2013; Chua, 2005; Hommel & Akyürek, 2005). While most of the AB theories did not take the temporal integration into account, recent empirical evidence suggested that temporal integration does play a role in the temporal attention (Akyürek et al., 2012; Akyürek & Hommel, 2005; Akyürek & Wolff, 2016; Hommel & Akyürek, 2005). A direct evidence was that when task was designed to enable participants to report a combined form of T1 and T2, participants did report the illusory integrated percepts (i.e., seeing only a single merged target stimulus). It suggested that the targets may have been integrated together into the same perceptual episode. Previous research has revealed that endogenous control (Akyürek, Riddell, Toffanin, & Hommel, 2007; Akyürek, Toffanin, & Hommel, 2008) and intervening distractor (Akyürek & Wolff, 2016) modulated temporal integration. Our results further revealed that targets from the same category are more likely to be integrated together than those from different categories, suggesting that temporal integration can also be determined by the stimulus characteristics (i.e., the categorical information). Our finding thus may aid in developing theory about the role of temporal integration in AB.

It should be noted that the current study did not reveal a reliable effect of the categorical similarity on the Lag-1 sparing. Although T2 performance at Lag 1 could be enhanced by temporal integration, other factors such as backward masking, or attentional competition between T1 and T2, would also counteract with the positive contribution of temporal integration to T2 performance at Lag 1 (Willems et al., 2016). Therefore, the change in the magnitude of Lag-1 sparing is not fully indicative of the temporal integration at Lag 1.

One may argue that order reversal is a less direct measure of temporal integration than reporting actual integrated percepts. However, order reversals were certainly in large part due to temporal integration. The direct link between order reversals and temporal integration could be supported by an empirical study. Akyürek et al. (2012) found that, when the possibility to report the integrated percept was removed, order reversals consequently tripled, suggesting that temporal integration is the primary cause of order reversals in the AB. Hence, order reversal is still a valid measure of temporal integration. Note that some contributions from other processes (such as attention) may also exist (Hilkenmeier, Scharlau, Weiß, & Olivers, 2012; Olivers, Hilkenmeier, & Scharlau, 2011).

Another potential confounding factor in our study was that manipulation of target dissimilarity may also affect the targets in terms of masking strength. Indeed, previous research has found that backward or forward masking can affect AB magnitude (Bachmann & Hommuk, 2005; Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Grandison, Ghirardelli, & Egeth, 1997). However, Karabay and Akyürek (2019) found that the difference in the contrast between T1 and T2 had no effect on temporal integration, although it seemed to affect the overall T1 and T2 performance at Lag 1. Despite this, a more definite conclusion requires further investigation.

Of particular relevance to our study, Karabay and Akyürek (2019) showed that temporal integration frequency was significantly lower when targets were in the same color than when they had different colors, which was opposite to our finding. The divergence may be due to various methodological differences. For example, categorical information was a task-irrelevant feature in their study, while the categorical information in our study was task relevant. Items with task-irrelevant features similar to the target were more actively suppressed relative to items with features more distinct from target features (Moher, Lakshmanan, Egeth, & Ewen, 2014; Störmer & Alvarez, 2014), which thus led to less temporal integration. However, further investigation is needed to clarify this discrepancy.

In conclusion, the present study revealed categorical similarity could modulate order reversals in AB, suggesting that the similarity in high-level semantic features can influence the processing of temporal integration.

Keywords: attentional blink, Lag-1 sparing, temporal integration, categorical similarity, temporal order

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