N a a a a k:

D a Z a · X a Z · Sa Ma

A a The attentional blink (AB) refers to the finding that performance on the second of two targets (T1 and T2) in a rapidly presented stimulus stream is impaired when the targets are presented within 200–500 ms. This study investigates whether a negative attentional set, a form of top-down control, has an additional detrimental effect, and whether its influence is modulated by task demands. A negative attentional set was elicited through presentation of a pre-T1 distractor (D1), which belonged to the same category as T2. The presence of D1 impaired T2 performance, and this negative effect was generally larger inside than outside the AB. Moreover, this D1 effect remained constant or was augmented when the demand on T1 processing was enhanced. These findings demonstrate that a negative attentional set is maintained even though the central system is engaged in the in-depth processing of T1 during the AB.

K Attentional blink · Attentional set · Temporal processing · Top-down control · RSVP

The attentional blink (AB) refers to the phenomenon that identification of the second of two targets (T1 and T2) in a rapid serial visual presentation (RSVP) stream is impaired when the targets are presented at a target onset asynchrony of about 200–500 ms (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). This deficit is generally explained in terms of limited-capacity processing resources, which are exhausted by T1 (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1997b; Vogel, Luck, & Shapiro, 1998). All items in an RSVP stream receive some initial processing before their representations are transferred to and consolidated in working memory for conscious report. When working memory is occupied by T1 and by possibly one or two other items, insufficient resources are available for the consolidation of T2, and T2 performance is thus impaired. However, several recent studies have questioned this limited-capacity account (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Martens & Wyble, 2010; Nieuwenstein & Potter, 2006; Olivers & Meeter, 2008; Olivers, van der Stigchel, & Hulleman, 2007; Taatgen, Juvina, Schipper, Borst, & Martens, 2009). To our knowledge, Di Lollo et al. were the first to shift the theoretical focus from

Lollo, 2006; Olivers et al., 2007; Olivers & Watson, 2006). The positive attentional set is assumed to bias attention toward stimuli with specified properties, while the negative attentional set is assumed to inhibit the processing of stimuli with particular properties. The important role of positive attentional set in RSVP tasks has been demonstrated, for example, by Nieuwenstein, Chun, van der Lubbe, and Hooge (2005) and Nieuwenstein (2006). In these studies, T2 performance was enhanced when T2 was precued by distractors in the same color as the targets, thus (partially) matching the target-defined attentional set. In multitarget RSVP, Nieuwenstein (2006) and Olivers et al. (2007) also found that a target would recover from the AB when it was preceded by another item that shared certain characteristics with the target.

Similarly, the negative attentional set plays a role in the AB (e.g., Loach & Mari-Beffa, 2003; Maki & Padmanabhan, 1994; Martens, Munneke, Smid, & Johnson, 2006; Martens & Valchev, 2009; Olivers & Meeter, 2008; Olivers et al., 2007; Zhang, Zhou, & Martens, 2009). Maki and Padmanabhan (1994), for example, used an AB task in which T1 was a white letter and T2 was a black digit among black letter distractors. The target digit was shown at the beginning of each trial. Participants were instructed to remember this digit and to decide whether it was presented in the RSVP stream, in addition to detecting T1. They performed this task repeatedly for over 10 days, and T2 performance was improved with practice. When distractors in the RSVP stream were changed into a mixture of letters and digits in the test session, performance on T2 detection dropped substantially. The authors argued that participants used an inhibitory attentional set against the distractors, and by including digits in the distractor set in the test session, the digit T2 was also inhibited.

Recently, Olivers and Watson (2006) manipulated the colors of T1, T2, and the distractors, such that the color of T2 could match the color of either T1 or the distractors, or be an unrelated color. The RSVP stream consisted of 15–20 letters, followed by a frame of colored dots (T2) and a mask. The T1, which was a letter with a color different from that of the distractors, appeared on the first (i.e., lag 1 condition) or the eighth (lag 8 condition) temporal position from the end of the RSVP stream. Participants had to identify the T1 and enumerate the colored dots. Irrespective of the lag between T1 and T2, the lowest T2 performance was obtained when the color of T2 matched the color of the leading distractors. Given that there were no distractors intervening between T1 and T2 at lag 1, the authors argued that the inhibitory effect on T2 must be due to a negative attentional set induced by the color of leading pre-T1 distractors. A similar inhibition mechanism was implemented in a computational model by Olivers and Meeter (2008) as the cause of the AB.

However, whether the attentional set operates normally during the AB period is still controversial. According to Baddeley's (1986) influential model, the working memory system contains a central executive that is important for most cognitive tasks. de Fockert, Rees, Frith, and Lavie (2001) found that a concurrent working memory load degraded the ability of inhibiting distractor information in a conflict resolution task. In line with this logic, Di Lollo and his colleagues proposed a temporary loss of control (TLC) theory for the AB (e.g., Di Lollo et al., 2005; Kawahara, Kumada, & Di Lollo, 2006). According to the TLC account, maintaining an attentional set is a general executive control task that requires the functioning of the central control system. This central system exerts top-down control over the input filter that selects targets from the input stream. In other words, the input filter is configured according to the current task demands, and its configuration is maintained by top-down control. The TLC account also assumes that top-down control is required for the consolidation of a selected target within working memory. Thus, while T1 is being consolidated, the control over the attentional set is temporarily lost, and the input filter is now at the mercy of bottom-up input. Consequently, the selection of T2 is impaired. Only when T1 processing is finished and the control system recovers from its temporary loss of control will the performance recover from the AB.

According to the TLC account, control over positive as well as negative attentional sets is lost during the AB; according to one theoretical alternative, the boost-and-bounce model (e.g., Olivers & Meeter, 2008; Olivers & Watson, 2006), a negative attentional set can continue to exert its influence during the AB, affecting T2 performance. According to another model (Salvucci & Taatgen, 2008), this occurs because selection and consolidation belong to different processing modules. Moreover, in the boost-and-bounce theory, the negative attentional set is a core module that directly brings about the AB effect. The purpose of the present study is to distinguish the TLC hypothesis from these theoretical alternatives. To this end, we used a paradigm in which the negative attentional set could be established on a trial-by-trial basis by presenting a special pre-T1 distractor (D1). This D1 was from the same stimulus category as T2 but had a different identity. Because participants were required to ignore D1, a negative attentional set could be set up to function against any items belonging to the same category, regardless of whether items were presented inside or outside the AB. Using this paradigm, in a previous study (Zhang et al., 2009) we demonstrated that T2 performance within the AB was indeed impaired; the present experiments sought to extend this finding.

The TLC account and its alternatives made different predictions regarding the effect of D1 on T1 processing.

Specifically, if more demanding T1 processing led to a smaller D1 effect, this would suggest that the control over the negative attentional set and the in-depth processing of T1 competed for the same pool of resources or a central bottleneck, and this would support the TLC model. If, however, the demands of T1 processing did not reduce the D1 effect, this would suggest that control over the attentional set was relatively independent of the system implementing in-depth target processing, and this would favor theoretical alternatives such as the boost-and-bounce model.

To this end, we manipulated the demand on T1 processing (Exps. 2 and 3) to examine whether the depth of T1 processing would affect the effect of negative attentional set elicited by D1 on T2 performance. Before going on to these two experiments, however, we present one experiment that replicated our previous results and ruled out an alternative account for the D1 effect, according to which it was due to D1 intrusions on T2 report.

E 1

In a previous study, we found that D1 (an Arabic digit or a Chinese number character) evoked an inhibition-related N2 component in event-related potentials (ERPs), peaking at about 300 ms poststimulus (Zhang et al., 2009). Nevertheless, D1 had no apparent effect on the processing of the following T1, since the P300 evoked by T1 was intact. Importantly, the presence of D1 delayed the appearance of N2pc (N2 posterior contralateral; see Eimer, 1996; Luck & Hillyard, 1994) to the laterally presented T2, which was another Arabic digit. Given that N2pc has been shown to be sensitive to attentional selection (Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004; Kiss, Van Velzen, & Eimer, 2008), the delay of N2pc suggested that the online processing of T2 can be inhibited by a category-specific negative attentional set elicited by D1 and that this attentional set can be defined at an abstract, conceptual level. A further behavioral experiment ruled out the possibility that the D1 effect is due to the general mechaensitiF(cha7(this1.2519TD[(T1)-187.7(p18.4(nt)13.2(io)18.9(na)20.8(l)-213.7(s)0(e)3
th.(n)-4(o)-.4(63.9(sam-.4(64d)-19(G),519TD[(T1)-187.7(pb00)-317e)-o)-

2 to 9, with the restriction that D1 and T2 were not the same in a particular trial. The D1 in one trial could thus be T2 in another trial. In contrast, D1 and T2 in Experiment 1b were drawn from two separate digit sets, 2–5 and 6–9, respectively, and were counterbalanced between participants. The participants were explicitly instructed which digit set was for D1 and which was for T2.

Presentation software (www.neurobs.com) was used to control stimulus presentation and to record behavioral responses. For each experiment, stimuli were presented on a 17-in. CRT monitor with a resolution of 1,024 × 768 pixels and an 85-Hz refresh rate. A chinrest was used to stabilize the head and to keep the viewing distance at about 60 cm.

The RSVP stream contained 25 items, consisting of Arabic digits (excluding 0 and 1) and capital English letters (excluding I, O, Q, and Z). Each item subtended about 0.3° × 0.4° in visual angle, and items were presented for 82 ms without an interstimulus interval. All stimuli were in white (with the RGB values [255, 255, 255]) against a dark background ([0, 0, 0]), except for T1, which was presented in red ([255, 0, 0]; see Fig. 1). Two consecutive letters were never identical. The temporal position of T1 varied randomly between Serial Positions 8 and 12 in the RSVP stream. Participants were instructed to ignore any item appearing before T1.

Participants pressed the space bar to initiate each trial. After a fixation cross of 1,000 ms, the RSVP stream was presented. At the end of each stream, a string of eight letters were first presented, and the participant had to decide which letter was T1; then, a string of eight digits were presented (or the four digits of the response set, for Exp. 1b), and the participant had to decide which digit was T2. Participants were instructed to respond as accurately as possible, and feedback was provided immediately after each target response.

Trials from different conditions were randomly mixed and then divided into three testing blocks, with a short break between blocks. Each participant performed 24 practice trials prior to formal testing. Participants completed the task in approximately 30 min.

Results

Experiment 1a: T1 performance The overall accuracy in reporting T1 was 96.1% (see Fig. 2a). A repeated measures ANOVA with D1 condition (D1 absent or D1 at lag −1 or −3) and T2 lag (1, 2, 3, or 8) as within-participants factors revealed no significant main effects or interactions (*p*s > .1).

Experiment 1a: T2 performance Figure 2b shows the percentages of correct T2 report, given correct report of T1 (T2|T1), for each condition. A 3 (D1 condition) × 4 (T2 lag) ANOVA on T2|T1 showed a main effect of T2 lag, *F*(3, 51) = 14.10, *p* < .001, with higher accuracies at lags 1 (69.3%) and 8 (73.2%) than at lags 2 (54.2%) and 3 (56%), reflecting the AB effect. The main effect of D1 condition was also significant, *F*(2, 34) = 80.91, *p* < .001, such that performance accuracy was highest in the D1-absent condition (79.8%), intermediate in the D1 lag −3 condition (66.7%), and lowest in the D1 lag −1 condition (43%). Bonferroni-corrected pairwise comparisons showed that the differences between the three D1 conditions were all significant, *p*s < .05. Thus, the appearance of D1 impaired T2 performance in general (i.e., the D1 effect).

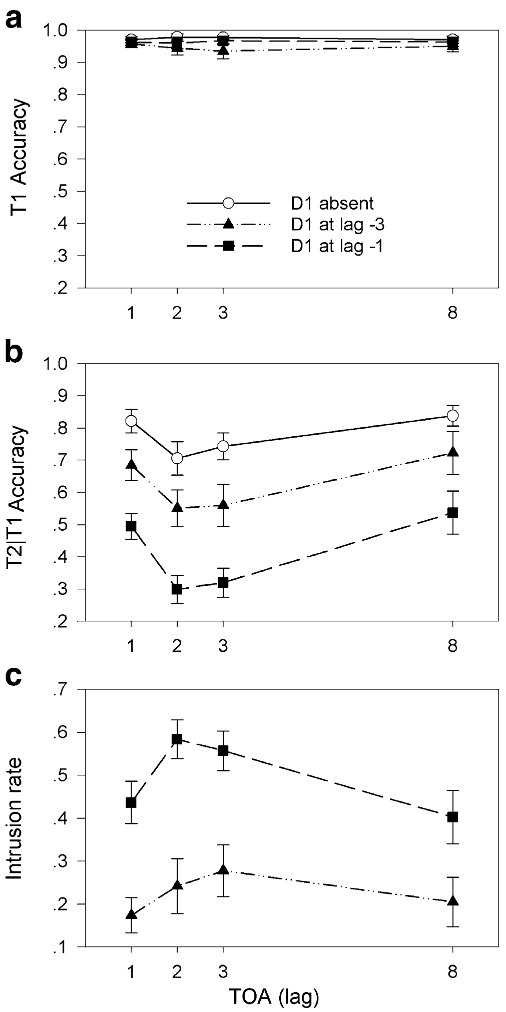


Fig. 2 Results of Experiment 1a. (**a**) T1 identification performance (T1 accuracy). (**b**) T2 identification performance for trials on which T1 was correctly reported (T2|T1 accuracy). (**c**) Intrusion rate (D1 being reported as T2) for trials on which T1 was correctly reported. Error bars show standard errors of the means

The interaction between D1 condition and T2 lag was also significant, *F*(6, 102) = 3.05, *p* < .01. To evaluate how D1 modulated the T2 lag effect, the decrement of T2 performance was calculated by subtracting T2|T1 accuracies with D1 present from those with D1 absent. An

ANOVA with T2 lag and D1 lag as two within-participants factors showed a significant main effect of T2 lag, *F*(3, 51) = 4.41, *p* < .01, with the largest decrement at lag 3 (30.1%), the smallest decrement at lag 8 (19.4%), and intermediate decrements at lags 1 (22.2%) and 2 (27.9%). Thus, D1 impaired T2 performance more severely inside than outside the AB. The main effect of D1 lag was also significant, *F*(1, 17) = 60.17, *p* < .001, with a larger decrement for D1 lag −1 (36.8%) than for lag −3 (13%). The interaction between T2 lag and D1 lag did not reach significance, *F*(3, 51) = 2.09, *p* > .1, indicating similar patterns of the D1 effect for D1 at lags −1 and −3.

Experiment 1a: Intrusion error rates Closer inspection of the responses showed that the D1 digit was reported as T2 on 36% of all trials in which D1 was present and T1 was correctly reported. The rate of this intrusion was calculated as the proportions of trials on which D1 was reported as T2 (given correct report of T1) relative to trials on which T1 was correctly reported for each combination of conditions. The intrusion rates in different conditions were then entered into an ANOVA with D1 lag (−1 or −3) and T2 lag (1, 2, 3, or 8) as within-participants factors (see Fig. 2c). The results revealed a significant main effect of D1 lag, *F*(1, 17) = 60.49, *p* < .001, with a higher intrusion rate for lag −1 (48.1%) than for lag −3 (19.9%). The main effect of T2 lag was also significant, *F*(3, 51) = 10.59, *p* < .001. Bonferroni-corrected pairwise comparisons showed that intrusion rates for lags 1 (28.2%) and 8 (27.7%) were significantly lower than those for lags 2 (40.1%) and 3 (40%), *p*s < .05. The difference between lags 1 and 8 and the difference between lags 2 and 3 were not significant, *p*s > .1. Thus, when T2 was in the AB, it was more prone to be intruded by D1. The interaction between D1 lag and T2 lag was significant, *F*(3, 51) = 5.65, *p* < .01, with D1 at lag −1 inducing the highest intrusion rate during the AB period (see Fig. 2c).

Experiment 1b: T1 performance T1 performance was analyzed with a 3 (D1 condition) × 3 (T2 lag) ANOVA (see Fig. 3a). The main effect of D1 condition was not significant, *F*(2, 34) = 2.71, *p* = .08. The main effect of T2 lag was, however, significant, *F*(2, 34) = 5.07, *p* < .05, with the accuracy for lag 1 (79.3%) being higher than those for lag 3 (74.8%), *p* < .05, and lag 8 (75.7%), *p* = .052. The interaction between D1 condition and T2 lag was not significant, *F*(4, 68) = 1.04, *p* > .1.

Experiment 1b: T2 performance T2 performance given correct report of T1 was analyzed with a 3 (D1 condition) × 3 (T2 lag) ANOVA (Fig. 3b). The main effect of T2 lag was significant, *F*(2, 26) = 28.65, *p* < .001, with the highest accuracy for lag 1 (80.1%), the lowest for lag 3 (59.2%), and an intermediate value for lag 8 (69.2%)—that is, a typical AB effect. Pairwise comparisons showed that the differences between T2 lags were all significant, *p*s < .05. The main effect of D1 condition was also significant, *F*(2, 34) = 16.76, *p* < .001, with the highest accuracy when D1 was absent (75.3%), the lowest for D1 at lag −1 (62.8%), and an intermediate value for D1 at lag −3 (70.4%). Pairwise comparisons showed that the differences between the D1 conditions were all significant, *p*s < .05. The interaction between D1 condition and T2 lag was not significant, *F* < 1, indicating that the D1 effect did not change across lags.

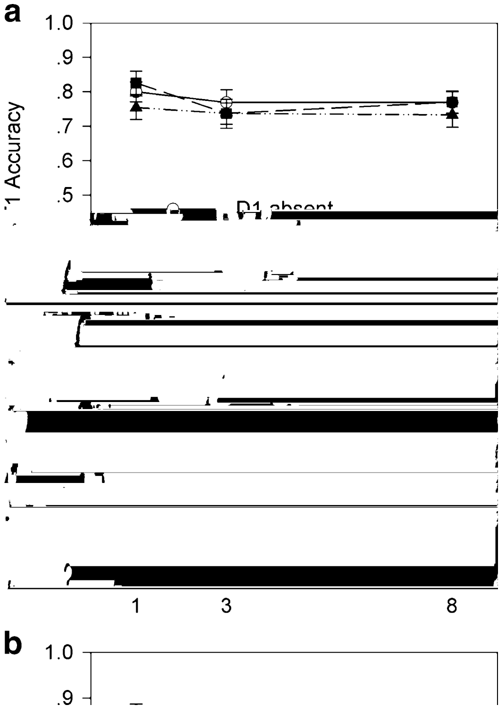


Fig. 3 Results of Experiment 1b. (**a**) T1 identification performance. (**b**) T2 identification performance for trials on which T1 was correctly reported. Error bars show standard errors of the means

Discussion

Replicating the findings in Zhang et al. (2009), this experiment demonstrated that the negative attentional set for the digit category can be elicited not only by special distractor streams in a blocked presentation, as in Olivers and Watson (2006) or Maki and Padmanabhan (1994), but also by the presentation of a pre-T1 D1 on a trial-by-trial basis. Note that we randomly mixed trials from different conditions to control for strategies that participants could appeal to in making responses. Under this circumstance, participants could not know which condition would appear, and they had to adopt the same task set for each trial:

ignoring any digit before T1 and then looking for a digit after T1. Thus, the switch of task set between items in the RSVP stream could be held constant across conditions.

The results showed that the temporal distance between D1 and T1 modulates the negative effect of D1 on T2 performance. This temporal distance effect suggests that T1 competes with nearby items, including D1, before it is consolidated into working memory and visual awareness. The shorter the distance between D1 and T1, the stronger the competition with D1, and the stronger the negative attentional set for the category represented by D1 and the poorer the subsequent T2 performance. Moreover, the D1 effect on T2 lasted for a long period (evident even when T2 was presented at lag 8), and this long-term D1 effect was observed not only for D1 presented at lag −1, but also to a lesser extent for D1 presented at lag −3. Similar long-term inhibitory effects have been observed in other paradigms, such as negative priming (e.g., DeSchepper & Treisman, 1996; Grison, Tipper, & Hewitt, 2005; Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991; Treisman & DeSchepper, 1996). For example, DeSchepper and Treisman found a long-term negative-priming effect lasting for up to weeks.

As we will discuss in the General discussion, it is difficult to distinguish whether it is the effect of inhibition or the mechanism of inhibition that survives in the AB, but both accounts do not accommodate the notion of loss of control. Although further investigation is needed to dissociate these two accounts, we assume that both of them take their effects in the D1 effect. However, the sustained-reduction-in-activity account could not be the whole story of the D1 effect. According to this account, one would expect the largest D1 effect at lag 1, which is not congruent with the results from, say, Experiment 1a.

Experiment 1a also revealed a high rate of D1 intrusions on T2 report. According to Botella and his colleagues (Botella, Arend, & Suero, 2004; Botella, Barriopedro, & Suero, 2001), two sequential attempts may take place to make a response to a target. The second attempt, "sophisticated guessing," is only employed if the first one, "focal attention," fails to produce an integrated percept. All intrusions are produced by a sophisticated-guessing mechanism, which takes into account the activation levels of candidate items in working memory.

Importantly, the intrusion rate was higher inside than outside the AB in Experiment 1a, demonstrating that the representation of T2 was inhibited more severely within the AB. The intrusion rate was also higher for D1 at lag −1 than at lag −3, suggesting that the representation of T2 was inhibited more severely for the former. However, the higher intrusion rate might also be attributed to the temporal proximity between D1 and T2. Unfortunately, the temporal proximity between D1 and T2 is impossible to dissociate from the temporal proximities between D1 and T1 and between T1 and T2 in this paradigm. Nevertheless, the intrusion rate was reduced when lag 1 sparing occurred, relative to when the AB occurred (i.e., lags 2 and 3), which is inconsistent with the account attributing intrusion errors merely to the temporal proximity between D1 and T1 or between D1 and T2. There are two possible explanations for this reduced intrusion rate at lag 1. One is that the inhibition needs time to become established (see, e.g., Houghton, Tipper, Weaver, & Shore, 1996) and does not reach its maximum at lag 1. Another is that the representation of T2 at lag 1 benefits from the lag 1 sparing in general, and thus has an advantage in competing with the representation of D1, relative to T2 at lag 2 or 3.

In Experiment 1b, the manipulation of drawing D1 and T2 from nonoverlapping sets excluded the possibility of intrusion errors, but the negative effect of D1 on T2 was still evident. This confirmed that the D1 effect could not simply be attributed to intrusion errors. The effect elicited by D1 appears to be due to category-specific inhibition.

Experiment 2

Experiment 2 sought to further distinguish the TLC account from its theoretical alternatives. This was accomplished by examining whether the D1 effect on T2 performance was influenced by T1 processing. In addition to the usual T1 and T2 report, this experiment included a single-task condition, in which only T2 report was required. The processing of T1 could have two possible effects on the negative attentional set elicited by D1. According to the TLC model, T1 processing occupies the central system and disrupts the functioning of the attentional set elicited by D1. The D1 effect on T2 performance should thus be larger in the single- than in the dual-task condition, because the influence of the inhibitory D1 set will not be diminished by the consolidation of T1 in working memory when T2 is encountered. According to an alternative explanation, D1 effects could be smaller under dual- than single-task conditions, because D1 competes with the selection of T1 under dual-task conditions, and this should diminish its effect on T2 performance.

Method

Participants A group of 20 right-handed Peking University students (20–23 years of age, mean = 22.1) were paid for their participation. None of them had been tested in the previous experiment.

Design and procedure This experiment had a 2 (dual vs. single task) × 3 (T2 lag: lag 1, 3, or 8) × 4 (D1 condition: D1 absent or D1 at lag −1, –3, or −5) within-participants factorial design. The only difference between the two task conditions was that, in the single-task condition, T1 was not required to be reported. Other aspects of the stimuli were essentially the same as in Experiment 1a. There were 15 trials for each combination of conditions, with a total of 360 trials.

The procedure of presenting stimuli and testing participants was the same as in Experiment 1a, with the following exceptions. Participants were tested in two separate sessions, once in a dual-task condition, and once in a single-task condition. The order of the two sessions was counterbalanced across participants, with a break of about 5 min between the two sessions. Each session began with a practice block of 24 trials.

Results

T1 performance Accuracies in reporting T1 in the dual task were analyzed using a repeated measures ANOVA with D1 condition (D1 absent or at lags −1, –3, or −5) and T2 lag (1, 3, or 8) as within-participants factors. There was a significant main effect of T2 lag, $F(2, 38) = 3.56$, $p < .05$, with T1 accuracy being 93.4%, 93.0%, and 90.7% at lags 1, 3, and 8, respectively. The main effect of D1 condition and the interaction between D1 condition and T2 lag were not significant, $F(3, 57) = 2.36$, $p = .081$, and $F(6, 114) < 1$, respectively.

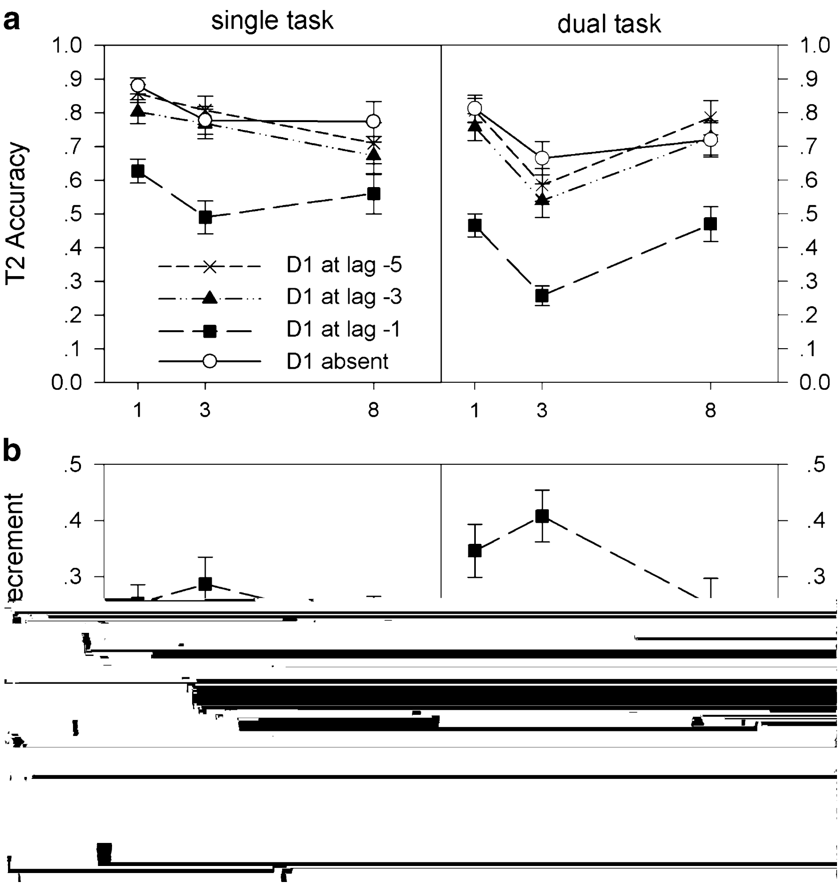
T2 performance For the dual-task condition, trials on which T1 report was incorrect (7.6% in total) were excluded from further analyses. Figure 4a shows T2 performance as a function of D1 lag and T2 lag in the single and the dual tasks, respectively. An ANOVA on T2 performance, with task (single vs. dual), T2 lag (1, 3, or 8), and D1 condition (D1 absent or at lag −1, –3, or −5) as three within-participants factors, showed a significant main effect of task, $F(1, 19) = 12.92$, $p < .01$. T2 performance was better in the single task (72.7%) than in the dual task (63.2%). The main effect of T2 lag was significant, $F(2, 38) = 7.40$, $p < .01$, with the best T2 performance at lag 1 (75.1%), the lowest at lag 3 (61.1%), and an intermediate value at lag 8 (67.7%). The main effect of D1 condition was significant, $F(3, 57) = 105.54$, $p < .001$. T2 performance was best for D1-absent trials (77.1%), lowest for D1 at lag −1 (47.8%), and intermediate for D1 at lags −3 (71.1%) and −5 (75.8%). The interaction between task and D1 condition was significant, $F(3, 57) = 4.66$, $p < .01$, indicating that D1 affected T2 performance differently under different task demands. The interaction between task and T2 lag was also significant, $F(2, 38) = 14.88$, $p < .001$, as was the three-way interaction between task, T2 lag, and D1 condition, $F(6, 114) = 2.11$, $p = .057$. The latter interaction suggests that the D1 effect on T2 performance had different patterns over T2 lags in different tasks (see Fig. 4a).

To see more clearly how the occurrence of D1 affected T2 performance, we subtracted the accuracy scores in the D1-present conditions from those in the D1-absent conditions. The resulting data, reflecting the decrement in T2 performance due to the presence of D1 (i.e., the D1 effect), are shown in Fig. 4b. It is clear from the figure that the impact of the D1 manipulation on the D1 effect had different patterns in the single and dual tasks. A 2 (task) × 3 (D1 lag) × 3 (T2 lag) repeated measures ANOVA revealed that the main effect of D1 lag was significant, $F(2, 38) = 122.26$, $p < .001$. The closer the D1 lag, the larger was the D1 effect (1.3%, 6%, and 29.3% for D1 lags −5, –3, and −1, respectively). The main effects of task and T2 lag were not significant, $F(1, 19) < 1$ and $F(2, 38) = 1.37$, $p > .1$, respectively. Nevertheless, the interactions between task and T2 lag and between task and D1 lag were significant, $F(2, 38) = 3.39$, $p < .05$, and $F(2, 38) = 6.38$, $p < .01$, respectively. As is shown in Fig. 4b, when D1 occurred at lag −1, the D1 effect was evidently larger in the dual task than in the single task. This was confirmed by a direct comparison between the two tasks, $F(1, 19) = 4.94$, $p < .05$.

Intrusion error rates Intrusion rates (see Fig. 4c) were analyzed with a 2 (task) × 3 (D1 lag) × 3 (T2 lag) repeated measures ANOVA. The main effect of task was significant, $F(1, 19) = 57.32$, $p < .001$, with a lower intrusion rate in the single task (17.3%) than in the dual task (27.5%). The main effect of D1 lag was significant, $F(2, 38) = 140.78$, $p < .001$, with the highest intrusion rate for D1 at lag −1 (43.5%), the lowest for D1 at lag −5 (8.7%), and an intermediate value for D1 at lag −3 (15.0%). The main effect of T2 lag was significant, $F(2, 38) = 7.60$, $p < .01$, with a higher intrusion rate for lag 3 (27%) than for lag 1 (19.3%) or lag 8 (20.9%). Moreover, as is shown in Fig. 4c, the interaction between task and D1 lag was significant, $F(2, 38) = 13.86$, $p < .001$, indicating that the differences between D1 conditions for the single task were smaller than those for the dual task. The interaction between task and T2 lag was also significant, $F(2, 38) = 11.55$, $p < .001$, indicating that the differences between different T2 lag conditions were more evident for the dual task than for the single task. The interaction between D1 lag and T2 lag was also significant, $F(4, 76) = 3.87$, $p < .01$, replicating findings in Experiment 1. It is clear from Fig. 4c that D1 at lag −1 induced the highest intrusion rate for T2 at lag 3. The three-way interaction between task, D1 condition, and T2 lag was not significant, $F(4, 76) < 1$.

Discussion

The pattern of results for the dual task replicated that of Experiment 1a. The presence of D1 impaired T2 perfor-



F . 4 Results of Experiment 2. (**a**) T2 identification performance (T2 for the single task, and T2 T1 for the dual task). ( ) Decrement of T2 performance for conditions with D1 present after subtraction of performance in conditions with D1 absent. ( ) Intrusion rate (D1 being reported as T2). Error bars show standard errors of the means. Left panels, single task; right panels, dual task

mance, especially when D1 was close to T1 (i.e., at lag −1) and when T2 was presented within the AB period. However, when T1 report was not required (i.e., in the single task), T2 performance did not vary according to T2 lag (i.e., no AB effect), although the presence of D1 did affect the accuracy of T2 report (i.e., D1 effect). Moreover, when the two tasks were compared directly, we found that, for D1 at lag −1, T2 performance was more severely impaired across T2 lag conditions in the dual task than in the single task.

The larger negative impact of D1 on T2 performance in the dual task than in the single task, appearing most obviously when D1 was at lag −1, demonstrated that T1 processing does not disrupt the negative attentional set induced by D1. Rather, T1 competes with items nearby, including D1, for limited resources and enhances the inhibition induced by D1 against the properties defining D1. This enhancement of inhibition could be a mechanism that protects T1 processing from distractor interference (Olivers & Watson, 2006; Raymond et al., 1992). A consequence of this enhancement is that the negative attentional set against the category represented by D1 is strengthened, and T2 performance is further impaired during the AB. The fact that increasing the temporal distance between D1 and T1 reduces or even eliminates the detrimental effect of D1 on T2 performance is consistent with this idea.

E 3

Experiment 3 sought to examine whether the load of T1 processing affects the D1 effect on T2 performance by manipulating the difficulty of T1 processing. In Experiment 2, different demands on T1 processing might have elicited different top-down task sets for the two test sessions, and this might reduce the comparability between the dual and single tasks. Additionally, the visual similarity between D1 and T1 (e.g., digit and letter) might have also strengthened the competition between them, and this competition could have been differentially affected by different task demands. In this experiment, T1 report was required throughout the test, while the difficulty of T1 processing was manipulated by using upright or rotated Chinese characters as T1 (see Fig. 5). The main reason for us to use Chinese characters instead of letters was that a Chinese character would have greater dissimilarity from the digit D1 than from a letter T1. This would make the character, whether rotated or not, perceptually distinct and reduce its perceptual competition with D1. Thus, the strength of competition between D1 and T1 and the difficulty of T1 processing could be decoupled. According to the TLC model, the more difficult the T1 processing, the stronger the disruption of central control, the easier the change of input filter configuration by post-T1 items, and the larger the AB effect. By the same logic, the stronger the disruption of central control, the weaker the functioning of the negative attentional set, and the smaller the D1 effect. Alternatively, if the negative attentional set elicited by D1 is independent of the AB mechanism activated by T1 processing, when D1 and T1 are distinct, the D1 effect might not be affected by the T1 manipulation.

Because to our participants Chinese characters are meaningful and visually salient in the alphanumeric RSVP stream, we blurred characters to increase the difficulty of T1 processing. This served as the T1 baseline condition. To further increase the difficulty of T1 processing, we rotated the blurred Chinese characters upside-down (i.e., 180°). We expected that the processing of the rotated characters would consume more resources and lead to a more severe AB effect (cf. Taatgen et al., 2009). The empirical question was whether the D1 effect on T2 performance would vary accordingly.

Method

Participants A group of 22 right-handed Hangzhou Normal University students (19–22 years of age, mean = 20.6) were paid for their participation in the experiment. None of them had been tested in the previous experiments.

Design and procedure This experiment had a 2 (T1 type:

T2 performance T2 performance, given correct report of T1, was analyzed similarly. The main effect of T1 type was significant, $F(1, 21) = 40.79$, $p < .001$, with T2 T1 performance being higher following upright T1 (65.7%) than following rotated T1 (57.7%). The main effect of D1 condition was significant, $F(1, 21) = 79.82$, $p < .001$, with a higher T2 accuracy in the D1-absent (69.6%) than the D1-present (53.7%) condition. The main effect of T2 lag was significant, $F(2, 42) = 5.38$, $p < .01$, reflecting an AB effect shown in Fig. 6b. Importantly, the interaction between T1 type and D1 condition was not significant, $F < 1$, indicating that more difficult T1 processing had no discernible impact on the D1 effect. This is inconsistent with the predictions of the TLC model.

The interaction between D1 condition and T2 lag was significant, $F(2, 42) = 4.41$, $p < .05$, with a larger D1 effect inside than outside the AB. The interaction between T1 type and T2 lag was significant, $F(2, 42) = 22.77$, $p < .001$. As depicted in Fig. 6b, the rotated T1 induced a larger AB effect than did the upright T1. The three-way interaction was not significant, $F < 1$, confirming that the rotated T1 did not influence the D1 effect.

Intrusion error rates The intrusion error rates for T2 were entered into a 2 (T1 type) 3 (T2 lag) ANOVA. The main effect of T1 type was not significant, $F(1, 21) = 2.15$, $p > .1$, indicating that the difficulty of T1 processing did not affect the competition between D1 and T2. The main effect of T2 lag was significant, $F(2, 42) = 7.74$, $p < .001$, with the highest intrusion error rate (41.4%) at lag 3, replicating previous experiments.

Discussion

Using a perceptually distinct T1, this experiment replicated the previous finding that presenting D1 before T1 reduced the accuracy of T2 report, and this detrimental D1 effect was larger inside than outside the AB. Moreover, increasing the difficulty of T1 processing increased the AB effect, which is consistent with the TLC model, but did not influence the D1 effect, which is, by contrast, inconsistent with the model.

It is generally assumed that the processing of rotated objects consumes additional resources, and consistent with this, T1 performance was worse when T1 was rotated than when T1 was in the normal position. The more demanding T1 processing generated a larger AB effect, consistent with the TLC model and with many other models of the attentional blink (e.g., the two-stage model; Chun & Potter, 1995). Importantly, this T1 effect did not interact with the D1 effect when T1 and D1 were perceptually distinct. This suggested that the negative attentional set elicited by D1 could be kept throughout the RSVP stream and independent to prevent consolidation of post-T1 distractors from entering into working memory. Clearly, here the AB effect is attributed to temporary inhibitory control rather than to the temporary loss of control. Another computational model (Taatgen et al., 2009), which is based on threaded cognition theory (Salvucci & Taatgen, 2008), proposes that competition for resources between the detection of targets and their consolidation into working memory is not the reason for the AB effect, because these two kinds of processing belong to different cognitive modules and do not share resources. Instead, the detection of T2 is temporarily suspended when another control process is triggered, partially by the detection of a distractor, to protect the consolidation of T1, thereby causing the AB. This additional control process, however, can be prevented from occurring when a concurrent task (e.g., peripheral dot detection) is added, which competes for the same resources with this control processing (e.g., Olivers & Nieuwenhuis, 2005, 2006; Taatgen et al., 2009). Thus, in this approach, the AB is attributed to too much control rather than to a loss of control. Consistent with these two computational models, our findings demonstrate that top-down control is not lost during the AB period.

We agree with the core notion of the threaded-cognition models that the central control system is not a single-task system but has different parallel subsystems. The AB is not the consequence of suspension of top-down control during T1 consolidation, but instead is due to inhibitory control. Indeed, the role of inhibitory control in the AB has also been also demonstrated in a recent bilingual study (Colzato et al., 2008). In Colzato et al.'s study, the bilinguals exhibited stronger inhibition of return (IOR) as well as a more pronounced AB effect than did monolinguals. It was suggested that because bilinguals need inhibitory control to suppress one language while speaking or processing the other, they might have acquired a stronger ability for inhibitory control than monolinguals. The stronger ability of maintaining an inhibitory attentional set has resulted in a stronger AB effect.

Before we fully accept the above arguments, we need to consider two alternative accounts for the D1 effect observed in this study. The first alternative account, which we alluded to in the Discussion of Experiment 1, attributes the effect to the loss of temporal order information in working memory or visual short-term memory (VSTM) for D1 and T2. According to this account, when only T1 and T2 are to be reported in a trial, participants rely on the temporal markers (e.g., automatic time-stamping of objects in VSTM) to distinguish between T1 and T2. When D1 is also presented, the temporal order information may get lost, and participants may confuse D1 with T2, possibly due to the increased memory load. This confusion leads to intrusion errors and an enlarged AB effect, relative to the condition in which D1 is absent. However, as we argued in the Discussion of Experiment 1, this account cannot explain why our intrusion errors showed lag 1 sparing and why the D1 effect in Experiment 2, with the same temporal proximities between D1 and T2, was substantially smaller in the single than in the dual task. Moreover, our previous study (Zhang et al., 2009) found that the presence of D1 evoked an N2 ERP component, and that N2pc to T2 was delayed for D1-present relative to D1-absent trials. This delay was for trials in which T2 was correctly reported—hence, T2 was not confused with D1—indicating that the D1 effect observed here was not simply due to the loss of temporal order information and the confusion between D1 and T2.

The second alternative account assumes that although a negative attentional set could be established by D1, and this attentional set could reduce the activation of representations associated with the items in the same category as D1, the negative attention set itself was lost after the processing of T1. That is, the D1 effects we reported here are the consequences of the *initial* establishment of a negative attentional set by D1, but are not due to a *sustained* negative attentional set during the AB. Representations of members belonging to the D1 category, including T2, are suppressed by the presentation of D1, resulting in the long-lasting impairment of T2 report. We believe that it would be difficult to dissociate the (long-lasting) effect of an initial negative attentional set from the effect of a sustained negative attentional set. One aspect of the present data seems to be inconsistent with this alternative account, which predicts gradual recovery, over time or lag, of the activation of items in the D1 category. If this were so, the representation of T2 should have its lowest activation level at lag 1, and should show the largest D1 effect at this location. However, across the three experiments, the D1 effect at lag 1 was never larger than the effect at lag 3. Although one might argue that the reo-1.2.8(g30(ac7(duproa55.mall8(

remain activated. Consequently, T2 identification should not be impaired, and no AB effect should be observed. Obviously the assumption of no attentional set during the AB period is unfeasible.

When Raymond et al. (1992) originally coined the term "attentional blink," they also proposed a temporary-inhibition account for it. According to this account, the inhibition mechanism was triggered by the T1 processing to inhibit perceptual processing of post-T1 items, including T2. Although this inhibition account was no longer popular after Shapiro and his colleagues proposed an alternative interference theory (Isaak, Shapiro, & Martin, 1999; Shapiro, 1994; Shapiro, Raymond, & Arnell, 1994), the role of inhibition in the AB has been reconsidered recently (e.g., Loach & Mari-Beffa, 2003; Olivers & Meeter, 2008; Olivers & Watson, 2006). Accumulating evidence has suggested that the AB is not a hardwired attentional deficit, but rather accommodates flexible modulations, as demonstrated by various experimental manipulations, such as emotion arousal, concurrent tasks, background stimuli, or even mere instructions (Arend, Johnston, & Shapiro, 2006; Olivers & Nieuwenhuis, 2005, 2006; Shapiro, Caldwell, & Sorensen, 1997). Thus the AB is a window that allows us to probe into the limited capacity and the flexibility of the human brain.

In summary, by embedding a special distractor (D1) in the RSVP stream, this study demonstrates that a negative attentional set against T2, which is in the same semantic category as D1, can be established on a trial-by-trial basis. Importantly, this attentional set, a form of top-down control, has a detrimental impact upon T2 performance on top of the usual AB effect, and this D1 effect remained the same or was augmented when the demand on T1 processing was enhanced. Such findings suggest that top-down control processes are not interrupted during the AB.

Author Note This study was supported by grants from the Natural Science Foundation of China (30770712, 30970889, 90920012), the Ministry of Science and Technology of China (973 Program: 2010CB833904), and Zhejiang Provincial Natural Science Foundation of China (Y207628). We thank Haiyang Zhang, Qiuping Cheng, Sinan Yang, and Minglong Jia for their help in running experiments and collecting data. We also thank Fook Chua, Chris Olivers, Albrecht Inhoff, and two anonymous reviewers for their constructive comments and suggestions concerning the earlier versions of the manuscript.

References

Arend, I., Johnston, S., & Shapiro, I. (2006). Task-irrelevant visual motion and flicker attenuate the attentional blink. *Psychonomic Bulletin & Review, 13*(4), 600–607.

Baddeley, A. (1986). *Working memory.* Oxford: Oxford University Press, Clarendon Press.

Botella, J., Arend, I., & Suero, M. (2004). Illusory conjunctions in the time domain and the resulting time-course of the attentional blink. *Spanish Journal of Psychology, 7,* 63–68.

Botella, J., Barriopedro, M. I., & Suero, M. (2001). A model of the formation of illusory conjunctions in the time domain. *Journal of Experimental Psychology. Human Perception and Performance, 27,* 1452–1467.

Broadbent, D. E., & Broadbent, M. H. P. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics, 42,* 105–113. doi:10.3758/BF03210498

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology. Human Perception and Performance, 21,* 109–127. doi:10.1037/0096-1523.21.1.109

Colzato, L. S., Bajo, M. T., van den Wildenberg, W., Paolieri, D., Nieuwenhuis, S., La Heij, W., et al. (2008). How does bilingualism improve executive control? A comparison of active and reactive inhibition mechanisms. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 34,* 302–312.

de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science, 291,* 1803–1806. doi:10.1126/science.1056496

DeSchepper, B., & Treisman, A. (1996). Visual memory for novel shapes: Implicit coding without attention. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 22,* 27–47.

Di Lollo, V., Kawahara, J., Ghorashi, S. M. S., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research, 69,* 191–200.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458. doi:10.1037/0033-295X.96.3.433

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 99,* 225–234.

Grison, S., Tipper, S. P., & Hewitt, O. (2005). Long-term negative priming: Support for retrieval of prior attentional processes. *Quarterly Journal of Experimental Psychology Section, 58A*(7), 1199–1224.

Hopf, J. M., Boelmans, K., Schoenfeld, M. A., Luck, S. J., & Heinze, H. J. (2004). Attention to features precedes attention to locations in visual search: Evidence from electromagnetic brain responses in humans. *Journal of Neuroscience, 24,* 1822–1832.

Houghton, G., Tipper, S. P., Weaver, B., & Shore, D. I. (1996). Inhibition and interference in selective attention: Some tests of a neural network model. *Visual Cognition, 3,* 119–164.

Isaak, M. I., Shapiro, K. L., & Martin, J. (1999). The attentional blink reflects retrieval competition among multiple rapid serial visual presentation items: Tests of an interference model. *Journal of Experimental Psychology. Human Perception and Performance, 25,* 1774–1792.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36,* 138–202. doi:10.1006/cogp.1998.0684

Kawahara, J., Enns, J. T., & Di Lollo, V. (2006a). The attentional blink is not a unitary phenomenon. *Psychological Research, 70,* 405–413.

Kawahara, J., Kumada, T., & Di Lollo, V. (2006b). The attentional blink is governed by a temporary loss of control. *Psychonomic Bulletin & Review, 13,* 886–890.

Kiss, M., Van Velzen, J., & Eimer, M. (2008). The N2pc component and its links to attention shifts and spatially selective visual processing. *Psychophysiology, 45,* 240–249.

Loach, D., & Mari-Beffa, P. (2003). Post-target inhibition: A temporal binding mechanism? *Visual Cognition, 10,* 513–526.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance, 20,* 1000–1014. doi:10.1037/0096-1523.20.5.1000