

# Early Perceptual Locus of Suppression During the Attentional Blink

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The attentional blink (AB) demonstrates that recognizing the second of two targets (T1 and T2) is difficult when they appear in close succession in a rapid serial visual presentation (RSVP) stream. The AB has been widely accepted as a suppression of T2 processing at the postperceptual stage. The current event-related potential study updates this view by demonstrating the existence of an early perceptual locus of suppression during the AB. Using line drawings of real-life objects as RSVP items, we required participants in Experiment 1 to either discriminate the exact identities or simply classify the object categories of T1 and T2, and in Experiment 2, we instructed participants to discriminate either T1 and T2 identities (dual-target task) or only T2 identity (single-target task) to invalidate the temporal expectation as an alternative account. The results of Experiments 1 and 2 showed that the T2-elicited first positive peak (P1) component was consistently decreased at Lag 3 whenever a dual-target, but not single-target, task was required, and the magnitude of this P1 suppression was significantly predictive of the behavioral AB magnitude in each dual-target task. When the RSVP items were substituted by classic but size-matched alphanumeric characters in Experiment 3, no P1 suppression was evident as expected, ruling out the large stimulus size as an alternative interpretation. These findings provide the strongest evidence to date that the AB can begin to suppress T2 processing at a very early perceptual stage, at least when observers encounter RSVP items of real-life objects, which calls for more flexible cognitive models for the AB.

## Public Significance Statement

The attentional blink (AB), a striking phenomenon illustrating the limitation of attention in the temporal dimension, has been an enduring research focus in cognitive psychology. The mainstream view has been that the AB represents an inhibition operating only at the postperceptual stage of processing. However, the three event-related potential experiments in humans reported here challenge this view by showing that, whenever images of real-life objects were used as stimulus materials, the P1 component, an event-related potential index of visual sensory processing, was consistently decreased during the AB, which further predicted the behavioral AB magnitude. These findings offer the strongest evidence to date that the AB can begin to operate at a very early perceptual stage of processing, at least when observers encounter visual stimuli representing real-life objects, which updates our understanding of how fast time-based attentional selection can operate.

**Keywords:** attentional blink, perceptual, postperceptual, event-related potentials, P1

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Song Zhao and Jimei Xie contributed equally to the study and are co-first authors. All experimental stimuli, data, and analysis scripts that support the current findings are openly available in the Open Science Framework at <https://osf.io/59rtg/>. The ideas and results of Experiments 1 and 2 were presented at the 25th National Academic Conference of Psychology in China in 2023.

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Our attention system has a remarkable ability to selectively process important information in the rapidly changing world. However, the attentional blink (AB) phenomenon demonstrates that this ability is rather limited in the temporal dimension (Raymond et al., 1992). In a rapid serial visual presentation (RSVP) task, the AB demonstrates that the detection of the second of two target stimuli (T1 and T2) embedded among distracting stimuli is often impaired if T2 follows T1 within a short period of 200–500 ms as compared to a longer interval (Raymond et al., 1992). The AB phenomenon can occur not only when stimuli are the typically used simple alphanumeric characters and words (Chun & Potter, 1995; Luck et al., 1996; Raymond et al., 1992) but also when they are more naturalistic stimuli, such as pictures of common objects and faces (Einhäuser et al., 2007; Evans & Treisman, 2005; Landau & Bentin, 2008). Thus, the robustness of the AB makes it one of the most intensively investigated focuses in cognitive neuroscience (for reviews, see Dux & Marois, 2009; Martens & Wyble, 2010; Zivony & Lamy, 2022).

What stages of processing are impaired during the AB interval, preventing us from reporting T2? The pioneering study (Raymond et al., 1992) proposed that the AB reflects an early attentional gating mechanism by which the processing of stimuli closely following T1 is inhibited at an early perceptual stage, for the purpose of fully encoding the features of T1. Accordingly, when T2 is presented at a short lag after T1, the early gating mechanism would inevitably impair T2 processing, leading to the AB phenomenon. However, in the past 25 years, research recording high temporal-precision event-related potentials (ERPs) elicited by T2 has refuted this theory by showing that the first positive peak (P1) and the first negative peak (N1) components reflecting early perceptual processing were intact during the AB interval (Batterink et al., 2012; Koivisto & Revonsuo, 2008; Kranczoch et al., 2007; Lasaponara et al., 2015; Sergent et al., 2005; Vogel et al., 1998; Weller et al., 2019). Moreover, even the N400 (the negative peak around 400 ms) component related to high-level semantic analysis was sometimes spared during the AB (Sy et al., 2013; Vachon & Jolicoeur, 2011; Vogel et al., 1998; but see Batterink et al., 2010; Giesbrecht et al., 2007). In contrast, the late third positive peak (P3) component associated with working memory encoding was consistently found to be reduced or delayed during the AB (for a recent review, see Zivony & Lamy, 2022). Based on these electrophysiological findings, almost all later theories of the AB converge on the currently widely accepted view that the AB reflects a postperceptual suppression, occurring after the perceptual processing of T2 is completed (Chun & Potter, 1995; Jolicoeur, 1998, 1999; Olivers & Meeter, 2008; Shapiro et al., 1994; Taatgen et al., 2009; Wyble et al., 2009).

However, closer inspection of the existing studies reporting intact P1 and N1 during the AB reveals that all of them used alphanumeric characters or words in their RSVP tasks (Batterink et al., 2012; Koivisto & Revonsuo, 2008; Kranczoch et al., 2007; Lasaponara et al., 2015; Sergent et al., 2005; Vogel et al., 1998), except the more recent one wherein pictures of real-life objects were used (Weller et al., 2019). Importantly, although the main effect of T1-to-T2 lag (short vs. long) on the T2-elicited P1 amplitude did not reach significance in this study, it interacted significantly with another factor, suggesting that the P1 was actually impaired in a subcondition during the AB (see Figure 4 of Weller et al., 2019). Moreover, several studies focusing on facial processing and/or conscious awareness have observed that the N170 (the negative

peak around 170 ms; a face-specific N1 subcomponent) elicited by a facial T2 was smaller during the blink (Darque et al., 2012; Eiserbeck et al., 2022; Luo et al., 2010, 2013), although these observations were not discussed in detail with respect to the locus of the AB. Therefore, it seems that the stage at which the AB *begins to suppress* T2 processing (postperceptual vs. perceptual) may depend on the type of stimulus materials used (alphanumeric characters or words vs. real-life objects or faces). However, as shown above, the existing ERP findings in favor of the presence of an early AB locus are mainly by-products of other findings; thus, the reliability of these preliminary results needs further investigation. Specifically, it remains to be determined whether the T2-elicited P1 and/or N1 components would be suppressed during the AB whenever more naturalistic stimuli are utilized as the RSVP items.

The present study addressed this issue by recording ERPs to RSVP items of real-life objects (Experiments 1 and 2) and alphanumeric characters (Experiment 3). In Experiment 1, participants were required to either discriminate the exact identities of T1 and T2 (e.g., which of the following options was T2?) or simply classify the object categories of T1 and T2 regardless of within-category identity (e.g., was T2 a dog, car, or drum?), with T2 being presented at either Lag 3 or Lag 8 after T1. Experiment 1 found that the T2-elicited P1 component was consistently decreased at Lag 3 relative to Lag 8 regardless of task demand (discrimination or classification). In parallel, the magnitude of the P1 suppression was predictive of the behavioral AB magnitude irrespective of task demand. Experiment 2 further revealed that this P1 suppression and its predictive role in impaired T2 performance held true when both T1 and T2 identities needed to be discriminated (dual-target task) but not when only T2 identity needed to be discriminated (single-target task), thereby invalidating the temporal expectation as an alternative account. When the RSVP items of real-life objects were replaced by equal-sized alphanumeric characters in Experiment 3, no P1 suppression was evident in any task as expected, thereby ruling out the large stimulus size as an alternative interpretation. Collectively, these findings provide the strongest evidence to date that the AB can begin at an early perceptual level whenever observers are encountering RSVP items of real-life objects, which calls for more flexible cognitive models for the AB.

## Method

### Participants

A total of 98 paid volunteers from Soochow University participated in the study. Among them, 36 participated in Experiment 1 (19 male and 17 female participants, age range = 18–25 years,  $M_{\text{age}} = 21.2$  years), 31 participated in Experiment 2 (13 male and 18 female participants, age range = 18–25 years,  $M_{\text{age}} = 20.3$  years), and 31 participated in Experiment 3 (13 male and 18 female participants, age range = 18–27 years,  $M_{\text{age}} = 21.10$  years). Each of them participated in only one experiment. Participants were asked for their gender, but they were also given the options of “none of the above” and “prefer not to say.” In all experiments, these options were not selected. No information regarding race and ethnicity were collected. The minimal sample size per experiment was set a priori to 30, which was comparable to (or even larger than) those used in previous studies where early ERP effects were observed during the AB (Darque et al., 2012; Eiserbeck et al., 2022; Luo et al., 2010, 2013; Weller et al.,

2019). All participants were healthy, right-handed, and had normal or corrected-to-normal vision. They were naive as to the hypothesis of the study. In agreement with the Declaration of Helsinki, written informed consent as approved by the institutional review board of Soochow University (protocol code: SUDA20210808H01, date of approval: August 08, 2021) was obtained from all subjects before their participation.

### Stimuli, Apparatuses, and Tasks

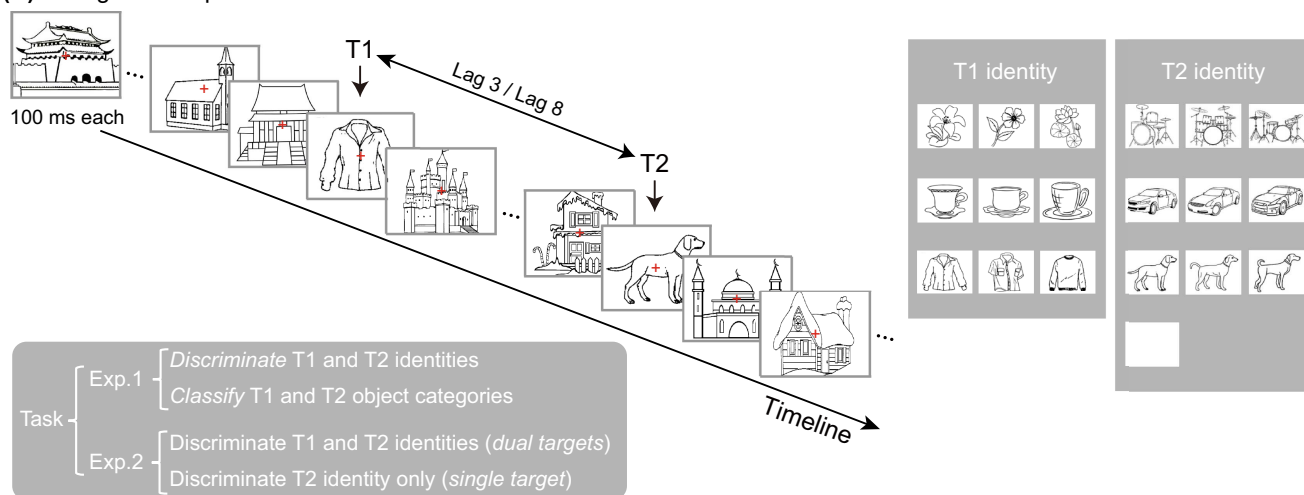
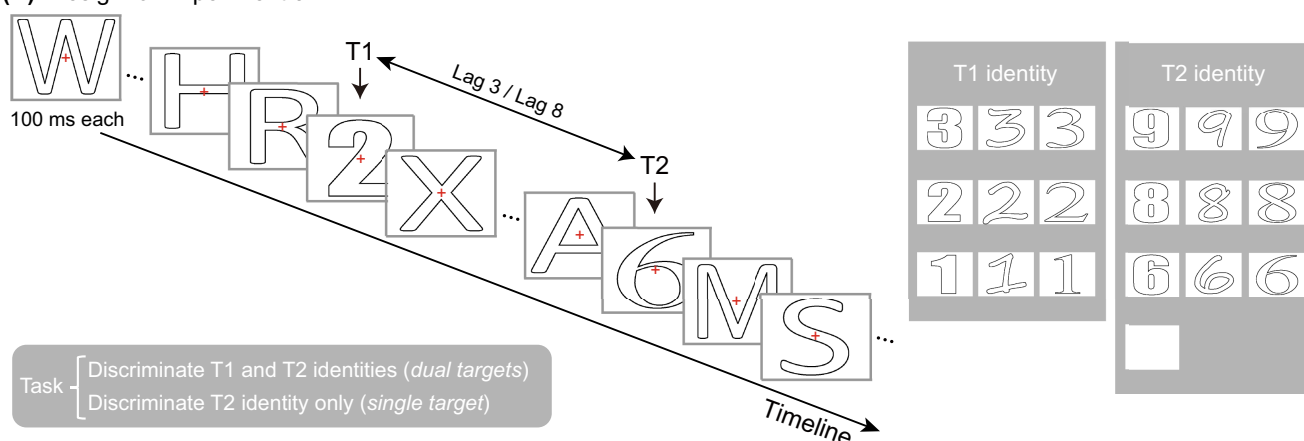
Experiment 1 was performed in a dark and sound-attenuated chamber. The stimulus presentation was scripted using the software Presentation (Version 18.0, NeuroBehavioral Systems, Inc.). Visual stimuli were presented on a 27-in. liquid crystal display monitor (ASUS PG279Q, resolution of  $1920 \times 1,080$ , refresh rate at 120 Hz) on which the background color was set to gray (red green blue: 128, 128, 128). Subjects sat in front of the monitor with a viewing distance of approximately 80 cm and were required to maintain their eyes fixed on a red cross (red green blue: 255, 0, 0;  $0.3^\circ \times 0.3^\circ$  of visual angle), which was displayed at the center of the screen throughout each RSVP stream. Stimulus materials consisted of 48 black and white line drawings of *real-life objects* (each  $5.6^\circ \times 4.5^\circ$  in visual angle), including 30 unique drawings of houses used as distractors, nine unique drawings (three articles of clothing, three cups, and three flowers) used as the first target (T1; see Figure 1A, right), and nine unique drawings (three dogs, three cars, and three drums) used as the second target (T2; see Figure 1A, right). The drawings for T1 and T2 were from two nonoverlapping sets to avoid the priming effect (Koelewijn et al., 2008) or the repetition blindness effect (Kanwisher, 1987). All of these line drawings were taken from recent studies in which dual-target RSVP tasks were used (Zhao et al., 2022; Zhao, Feng, Huang, et al., 2021; Zhao, Feng, Liao, et al., 2021).

At the beginning of each trial in Experiment 1, the red fixation appeared in the middle of the screen and lasted for 1,000 ms, which was immediately followed by an RSVP stream presented also at the center of the screen (Figure 1A, left). Each RSVP stream was comprised of 17 distinct line drawings, including two targets (T1 and T2) and 15 distractors selected randomly (without repetition) from the 30 drawings of houses. Each line drawing was presented for 100 ms with no interstimulus interval, yielding a presentation rate of 10 Hz. T1 could be one of the nine drawings (i.e., three articles of clothing, three cups, and three flowers) with equal probability and appeared randomly and equiprobably in the third, fourth, or fifth position in the RSVP stream. T2 appeared randomly and equiprobably in the third (i.e., at Lag 3; 50% of all trials) or eighth (i.e., at Lag 8; 50% of all trials) position after T1. Meanwhile, T2 could be one of another nine drawings with equal probability (i.e., three dogs, three cars, and three drums; 50% of all trials; T2-present condition) or could be blank (i.e., a white rectangle with the same size as the line drawings; 50% of all trials; T2-absent condition; see Figure 1A, right). The T2-absent condition was used to get rid of the distractor-evoked ERPs and obtain ERPs elicited purely by T2, following the methods of previous studies (Lasaponara et al., 2015; Luo et al., 2010, 2013; Sergent et al., 2005; Vogel et al., 1998; Weller et al., 2019).

In Experiment 1, participants were instructed to recognize the two targets sequentially at the end of each RSVP stream. However, the recognition rule (task demand) varied from block to block.

Specifically, Experiment 1 consisted of two task demands: discrimination and classification, with a block design in which the discrimination and classification blocks accounted for half of all blocks, respectively. The two types of blocks were presented in a pseudorandomized order, in accordance with the way we manipulated top-down attention in our previous studies (Zhao, Feng, Liao, et al., 2021; Zhao, Li, et al., 2021). In the discrimination block, participants were asked to report the exact identities of both T1 and T2 as accurately as possible by pressing buttons on the keyboard's number pad (Buttons 1–9 for T1, Buttons 0–9 for T2) with the right hand, and only if the exact identity of T1 or T2 was correctly recognized would this response be coded as a correct discrimination. In the classification block, participants were required to simply classify the object categories of T1 and T2 regardless of within-category identity by pressing buttons on the keyboard's number pad (Buttons 1, 4, and 7 for T1; Buttons 0, 1, 4, and 7 for T2) with the right hand. There was no time limit for participants to indicate their responses. Note that the options for T1 and T2 and their corresponding button numbers were presented to participants when they made their responses. The button-press for T2 triggered the next trial. Experiment 1 consisted of 24 blocks (12 discrimination blocks and 12 classification blocks) with 63 trials being arranged in each block, resulting in a total of 1,512 trials. Participants were allowed to have a rest between blocks in order to relieve fatigue. Therefore, the design of Experiment 1 generated eight main conditions: T2 Presence (present, absent)  $\times$  Lag (Lag 3, Lag 8)  $\times$  Task Demand (discrimination, classification), with 189 trials in each condition. This experiment was conducted to test whether the AB would suppress T2 processing at the perceptual stage (e.g., indexed by a decreased P1 component) whenever real-life objects are utilized as the RSVP items.

In Experiment 2, the same stimuli, apparatuses, and RSVP streams as Experiment 1 were used, but the recognition rule (task type) was modified. Specifically, Experiment 2 consisted of two task types: dual target and single target, with a block design in which the dual-target and single-target blocks accounted for half of all blocks, respectively. The two types of blocks were presented in a pseudorandomized order based on prior AB studies (Luo et al., 2010, 2013). In the dual-target blocks, participants were required to discriminate sequentially the exact identities of both T1 and T2, which was identical to the discrimination task in Experiment 1. In the single-target blocks, however, participants were asked to discriminate only the exact identity of T2 while ignoring T1. Collectively, Experiment 2 consisted of 12 blocks (six dual-target blocks and six single-target blocks) of 108 trials each, resulting in a total of 1,296 trials. Accordingly, the design of Experiment 2 included eight main conditions: T2 Presence (present, absent)  $\times$  Lag (Lag 3, Lag 8)  $\times$  Task Type (dual target, single target) with 162 trials in each condition. This experiment was conducted to invalidate the “temporal expectation” as a main cause of the current findings. Specifically, as Zivony and Lamy (2022) have put forward, the difference in T2 processing between the short and long lags may result not only from T2 processing being suppressed at the short lag but also from T2 processing being enhanced at the long lag where a higher temporal expectation exists: Because T2 appears later in the long-lag condition than in the short-lag condition, the expectation that it will soon appear is higher in the long-lag condition than in the short-lag condition (see also Kranczioch & Bryant, 2011; Nobre et al., 2007; Zhao, Feng, Huang, et al., 2021). Apparently, the higher

**Figure 1***Illustration of Experimental Designs for Experiments 1–3***(A) Designs for Experiments 1 and 2****(B) Design for Experiment 3**

**Note.** (A) Schematic illustration of the 10-Hz RSVP stream employed in Experiments 1 and 2 where the stimulus materials were line drawings of real-life objects. Each stimulus was presented for 100 ms without interstimulus interval. The second target (T2), which could be either an object drawing or a blank image, was presented in the third (i.e., at Lag 3) or eighth (at Lag 8) position after the first target (T1). In Experiment 1, participants were required to either discriminate the exact identities of T1 and T2 (discrimination task) or simply classify the object categories of T1 and T2 regardless of within-category identity (classification task) without time limit after each RSVP stream. The options for T1 and T2 and their corresponding button numbers were presented to participants when they responded. In Experiment 2, participants were instructed to discriminate either the exact identities of T1 and T2 (dual-target task, same as the discrimination task in Experiment 1) or only the exact identity of T2 (single-target task). (B) Schematic illustration of the pattern-matched RSVP stream employed in Experiment 3 where the stimulus materials were replaced by equal-sized alphanumeric characters. The task for participants in Experiment 3 was the same as in Experiment 2. Exp. = experiment; RSVP = rapid serial visual presentation; + = fixation cross. Line drawings shown in Figure 1A: Adapted from “Neural Basis of Semantically Dependent and Independent Cross-Modal Boosts on the Attentional Blink,” by S. Zhao, C. Feng, X. Huang, Y. Wang, and W. Feng, 2021, *Cerebral Cortex*, 31(4), p. 2293 (<https://doi.org/10.1093/cercor/bhaa362>). Copyright 2021 by Oxford University Press. Adapted with permission. See the online article for the color version of this figure.

temporal expectation may assist participants in better preparing for the long-lag T2 when it has not yet arrived, leading to enhanced T2 processing at the long lag. So, given that the temporal expectation should influence T2 processing regardless of whether T1 needs to be discriminated (Zivony & Lamy, 2022), if a smaller early ERP component (e.g., P1) at Lag 3 than at Lag 8 is found only in the dual-target task but not in the single-target task, then this early ERP suppression can be attributed solely to the AB with confidence.

In Experiment 3, the general design was identical to Experiment 2 but with the following two exceptions. First, the stimulus materials were replaced by 41 black and white line drawings of *alphanumeric characters* (each also  $5.6^\circ \times 4.5^\circ$  in visual angle). Among them, 23 drawings of uppercase letters (A–Z, with the exception of B, G, and I; using Calibri font) were used as distractors (see Figure 1B, left), nine drawings of numbers (1, 2, and 3, with each having three distinct fonts: Impact, Segoe Print, and Times New Roman) were



used as T1 (see Figure 1B, right), and the remaining nine drawings of numbers (6, 8, and 9, with each having the aforementioned three distinct fonts) were used as T2 (see Figure 1B, right). Note that similar to Experiment 2, each RSVP stream also consisted of 17 items (T1, T2, and 15 distractors), and only if the exact identity of T1 or T2 was correctly recognized (e.g., accurately recognizing that T2 was the Number 6 in Times New Roman font, see Figure 1B, left) would this response be treated as a correct discrimination. Second, the six dual-target blocks and six single-target blocks in Experiment 3 were presented in the order either AAA-BBB-BBB-AAA or BBB-AAA-AAA-BBB (counterbalanced across participants) to minimize the possibility that the T1 task requirement in a dual-target block might carry over to its subsequent single-target block, which could lead to an underestimation of the difference in lag effect between the single-target and dual-target tasks. Minimizing such an underestimation was especially important here because Experiment 3 expected to find no AB-induced early ERP suppression, and the between-task difference in lag effect here needed to capture the AB-induced effect (if any) as much as possible. Experiment 3 was conducted to further support the proposal that the stage at which the AB begins to suppress T2 processing (perceptual vs. postperceptual) is dependent on the stimulus type (real-life objects vs. alphanumeric characters). Specifically, since the line drawings of real-life objects used in our Experiments 1 and 2 were substantially larger in size than the typical alphanumeric characters or words used in previous studies where no early ERP suppression during the AB was found (Batterink et al., 2012; Koivisto & Revonsuo, 2008; Kranczioch et al., 2007; Lasaponara et al., 2015; Sergent et al., 2005; Vogel et al., 1998), it seems likely that the AB-induced early ERP suppression in our Experiments 1 and 2 was due merely to the stimulus materials being larger in size, which might have provided for a more sensitive measure of early attentional effect. Therefore, if Experiment 3 still observes no early ERP suppression even when the alphanumeric characters used have become as large as our real-life objects, this alternative account can be ruled out, demonstrating that the occurrence of AB-induced early ERP suppression is contingent on the stimulus type per se.

### Electrophysiological Recording and Preprocessing

The electroencephalogram (EEG) in each experiment was recorded continuously when subjects performed the behavioral task, using a SynAmps2 amplifier (NeuroScan, Inc.) and a custom-built 64-electrode elastic cap. The electrodes on the cap were positioned according to a modified 10–10 system montage (for details, see Zhao et al., 2022). Two additional electrodes, AFz and M1 (left mastoid) served as the ground and reference electrodes during data acquisition, respectively. Horizontal eye movements were detected by a pair of bipolar electrodes positioned at the left and right outer canthi (horizontal electrooculogram). Vertical eye movements and blinks were detected by another pair of bipolar electrodes placed above and below the left eye (vertical electrooculogram). The impedances of all electrodes were kept below 5 k $\Omega$ . The online EEG and electrooculogram signals were filtered by a band-pass filter of 0.05–100 Hz and digitized at a sampling rate of 1,000 Hz. EEG recording was carried out using the software SCAN (Version 4.5, NeuroScan, Inc.).

In offline preprocessing, the continuous EEG signals were first down-sampled to 500 Hz, and then low-pass filtered (half-amplitude

cutoff: 33.75 Hz, transition band width: 7.5 Hz) using a zero-phase shifted (two-pass forward and reverse), Hamming-windowed sinc finite impulse response filter to attenuate high-frequency noise triggered by muscle activities or external electrical sources. The filtered EEG data were rereferenced to the average of the left and right mastoid (M1 and M2) electrodes, and then segmented into 800-ms epochs time-locked to T2 onset with a 200-ms pre-T2 baseline. In terms of artifact correction, the independent component analysis was applied to these EEG epochs to identify and remove independent components (ICs) corresponding to common EEG artifacts such as horizontal eye movements and eye blinks (Delorme & Makeig, 2004). On average,  $2.90 \pm 0.26$  ( $M \pm SE$ ) ICs were removed in Experiment 1,  $2.41 \pm 0.74$  ICs were removed in Experiment 2, and  $1.61 \pm 0.18$  ICs were removed in Experiment 3. After the independent component analysis, epochs were first baseline-corrected (–100 to 0 ms), and automatic artifact rejection was then performed for the time range of –100 to 500 ms based on a threshold of  $\pm 75$   $\mu V$  to discard epochs contaminated by residual artifacts. Furthermore, based on previous EEG/ERP studies using dual-target RSVP tasks (Kranczioch et al., 2007; Maier & Abdel Rahman, 2018; Vogel et al., 1998; Zhao et al., 2022), only trials (epochs) on which T1 was correctly discriminated or classified were further analyzed, resulting, on average, in  $88.25 \pm 0.71\%$  ( $M \pm SE$ ) and  $93.37 \pm 0.55\%$  of the epochs left in the discrimination and classification conditions in Experiment 1,  $88.19 \pm 0.73\%$  and  $97.96 \pm 0.37\%$  of the epochs left in the dual-target and single-target conditions in Experiment 2, and  $79.85 \pm 1.39\%$  and  $94.71 \pm 1.26\%$  of the epochs left in the dual-target and single-target conditions in Experiment 3, respectively. The remaining valid epochs in each condition were then averaged separately to obtain corresponding ERP waveforms.

### Data Analysis

On the basis of the fact that voltage fields are additive linearly, to isolate ERPs elicited purely by T2, time-locked ERPs on T2-absent trials were first subtracted from ERPs on T2-present trials. This operation was conducted separately for each of the four subconditions in Experiment 1 divided according to task demand (discrimination, classification) and lag (Lag 3, Lag 8) and for each of the four subconditions in Experiments 2 and 3 divided according to task type (dual target, single target) and lag (Lag 3, Lag 8). These subtractions would cancel out the systematic ERPs elicited by the pre-T2 and post-T2 distractors, as well as the inherent but T2-unrelated ERP difference between Lag 3 and Lag 8 conditions caused by the preceding T1-evoked ERPs being still on their way at Lag 3 but almost finished at Lag 8 (cf. Lasaponara et al., 2015; Luo et al., 2010, 2013; Sergent et al., 2005; Vogel et al., 1998; Weller et al., 2019).<sup>1</sup> All subsequent analyses were based on the above operations.

The P1 and N1 components, which have been considered to reflect sensory/perceptual processing (e.g., Luck et al., 2000; Mangun, 1995; Vogel & Luck, 2000), were measured as the mean amplitudes over a posterior region of interest consisting of eight

<sup>1</sup> Despite being effective in theory, these subtractions may not operate perfectly in practice given that the distribution of the randomly selected pre- and post-T2 distractors on T2-present trials may not be identical to that on T2-absent trials. However, the baselines of our extracted T2-elicited ERPs were consistently flat across Experiments 1–3 (see Figures 3 and 4), suggesting that ERPs elicited by the pre-T2 and post-T2 distractors were balanced out appropriately, if not fully, in the present study.

bilaterally parieto-occipital electrodes (P5, P6, P7, P8, PO5, PO6, PO7, and PO8) either within the time windows of 140–170 ms and 210–240 ms after T2 onset (for Experiments 1 and 2) or within 116–146 ms and 200–230 ms (for Experiment 3), respectively. Meanwhile, the P3 component was also measured given that it has been consistently found inhibited during the AB (e.g., Akyürek et al., 2010; Craston et al., 2009; Dell'Acqua et al., 2015; Kranczioch et al., 2003; Sessa et al., 2007; Vogel et al., 1998). It was quantified as the mean amplitude within the time window of 400–500 ms over a central–parietal region of interest comprised of six adjacent electrode sites (CPz, CP1, CP2, Pz, parietal 1, and parietal 2). Notably, the above measurement parameters were chosen in an unbiased, condition-blind manner as recommended in recent ERP literature: the collapsed localizer (e.g., Feldmann-Wüstefeld et al., 2020; Luck & Gaspelin, 2017; Wang et al., 2019; also termed “the aggregate grand average of grand averages”; Brooks et al., 2017), given that the asymmetry in the number of trials between conditions was small here. That is, ERP waveforms were first collapsed across all conditions to be compared, and the time windows and electrodes where each corresponding ERP component had its greatest amplitude in the collapsed waveform were then chosen for the measurement of the noncollapsed data. In addition, the widths of the chosen windows were also comparable to those used in previous studies (Anllo-Vento & Hillyard, 1996; Batterink et al., 2012; Donohue et al., 2011; Feng et al., 2014; Zhao, Feng, Liao, et al., 2021; Zhao, Li, et al., 2021).

In Experiment 1, to examine whether early perceptual processing of T2 would be suppressed during the AB interval whenever images of real-life objects are utilized, separate two-way repeated-measures analyses of variance (ANOVAs) with factors of task demand (discrimination, classification) and T1-to-T2 lag (Lag 3, Lag 8) were first conducted on the mean amplitudes of P1 and N1 components. The same two-way ANOVA was also performed on the P3 amplitude to test the influence of AB on postperceptual processing of T2. To check whether the behavioral AB effect was successfully induced in the present study, the outcome of T2 response (accurate/inaccurate) was analyzed on a single-trial level using a logistic mixed-effects model (Jaeger, 2008) with fixed effects of task demand, lag, and their interaction. Following previous studies (Barr et al., 2013; Falandays et al., 2020), the maximal random-effects structure that achieved convergence was used, with redundant random effects removed backward. We did not analyze T2 accuracy in terms of the percentage of accurate T2 responses using the two-way ANOVA above, because an ANOVA like that can lead to a spurious two-way interaction if the percentages are close to ceiling in some conditions but not in other conditions (for details, see Jaeger, 2008). Note that to better understand the AB effects in different task demand conditions, no matter whether the two-way interactions were significant or not, planned comparisons were further performed between Lag 3 versus Lag 8 trials separately for the discrimination and classification conditions.

Moreover, to investigate whether the identified AB-induced ERP amplitude decreases (if there were) would further account for the impaired T2 performance during the AB, Pearson correlation analyses were conducted between the magnitudes of the two separately for the discrimination and classification tasks. The magnitude of ERP amplitude decrease during the AB was computed

for each participant as the ERP amplitude difference between Lag 8 and Lag 3 conditions, and similarly, the magnitude of impaired T2 performance during the AB was calculated for each participant as the difference in T2 accuracy between Lag 8 and Lag 3 conditions. Given the well-known close relationship between the AB and postperceptual processing (Zivony & Lamy, 2022), at least a significant positive correlation between the magnitudes of P3 amplitude decrease and T2 accuracy decrease during the AB was expected. If the above neural–behavioral correlations were found not only for the P3 but also for the P1 and/or N1 components in either task demand condition, a partial correlation analysis would be further conducted to see whether the late P3 amplitude decrease could still explain the variance of the behavioral AB magnitude after controlling the early P1 and/or N1 amplitude decreases, because in this case the P3 amplitude decrease might merely be a downstream effect of the preceding ERP amplitude decreases.

In Experiments 2 and 3, the general analytic procedures for behavioral and ERP data (including the neural–behavioral correlation analyses that were limited to the identified AB-induced ERP decreases) were identical to those used in Experiment 1 but with the following exception. That is, only when the 2 (lag: Lag 3, Lag 8)  $\times$  2 (task type: dual target, single target) two-way interaction was significant would the differences between Lag 3 and Lag 8 conditions be further analyzed separately for the dual-target and single-target tasks. This is because such a significant two-way interaction would suggest that the lag effect was present only in the dual-target task but not in the single-target task or that it was present in both tasks but substantially larger in the dual-target than single-target task, with the former indicating that the temporal expectation was entirely unable, and the latter indicating that it was insufficient, to account for the lag effect in the dual-target task. Instead, the absence of such a two-way interaction along with a significant main effect of lag would suggest that the lag effect in the dual-target task was merely a result of the temporal expectation, rendering further comparisons under each task type unnecessary.

Last, given the inherent difficulty in supporting the null hypothesis in conventional statistical tests, the Bayesian repeated-measures ANOVAs, paired-samples *t* tests, or correlation analyses were further conducted in case of nonsignificant results (i.e.,  $p > .05$ ), using a scale *r* (Cauchy scale) value of 0.707. A Bayes factor ( $BF_{10}$ ) below 0.333 was considered as substantial evidence for the absence of an effect (Dienes, 2014; Wagenmakers et al., 2018).

## Transparency and Openness

We reported how we determined our sample size, all data exclusions, manipulations, and measures in the study, and we followed Journal Article Reporting Standards (Kazak, 2018). All experimental stimuli, data, and analysis scripts are openly available at the Open Science Framework at <https://osf.io/59rtg/>, and a citation of these materials is included in our reference list (see Zhao et al., 2024). EEG/ERP data were analyzed using MATLAB, Version 2017a (The MathWorks, Inc.) and the toolbox EEGLAB, Version 2021.1 (Delorme & Makeig, 2004). Behavioral data in terms of the binomial T2 accuracy were analyzed using R, Version 4.4.0 (R Core Team, 2024) and the package lme4, Version 1.1-35.3 (Bates et al., 2015). This study's design and its analysis were not preregistered.

## Results

### Behavioral Results

In Experiment 1, the outcome of T2 response (accurate/inaccurate) was analyzed using a logistic mixed-effects model with fixed effects of lag (Lag 3, Lag 8), task demand (discrimination, classification), and their interaction. The maximal random-effects structure that reached convergence consisted of a random intercept for participants and by-participant random slopes for lag and task demand. The results showed a highly significant main effect of task demand ( $b = 2.883$ ,  $SE = 0.198$ ,  $z = 14.308$ ,  $p < .001$ ) such that there were overall fewer accurate T2 responses in the discrimination task than in the classification task (see Figure 2A for illustration of the percentage of accurate T2 responses<sup>2</sup>). This is expected because the criterion of defining an accurate T2 response in the discrimination task was inherently much stricter than that in the classification task (see the Method section). Importantly, the main effect of lag was also significant ( $b = 1.050$ ,  $SE = 0.144$ ,  $z = 7.275$ ,  $p < .001$ ), whereas the Task Demand  $\times$  Lag interaction was not significant ( $b = -0.001$ ,  $SE = 0.105$ ,  $z = -0.008$ ,  $p = .993$ ). Planned further comparisons showed that the effect of lag was significant in each task demand condition (discrimination:  $b = -1.050$ ,  $SE = 0.080$ ,  $z = -13.134$ ,  $p < .001$ ; classification:  $b = -1.050$ ,  $SE = 0.118$ ,  $z = -8.905$ ,  $p < .001$ ), which was manifested as fewer accurate T2 responses at Lag 3 than at Lag 8 in both the discrimination task (percentage of accurate T2 responses: Lag 3 =  $54.6 \pm 2.9\%$ ; Lag 8 =  $74.9 \pm 2.5\%$ ; Figure 2A, left) and the classification task (Lag 3 =  $92.4 \pm 1.5\%$ ; Lag 8 =  $96.8 \pm 1.0\%$ ; Figure 2A, right). These findings demonstrate that the behavioral AB effect (Raymond et al., 1992) was robust not only when subjects had to discriminate the exact identities of T1 and T2 but also when they simply classified the object categories of T1 and T2.

In Experiment 2, the binomial T2 accuracy was also analyzed using a logistic mixed-effects model, with fixed effects of lag (Lag 3, Lag 8), task type (dual-target, single-target), and their interaction. The maximal random-effects structure that reached convergence included a random intercept for participants and by-participant random slopes for task type and lag. The results showed highly significant main effects of lag ( $b = 1.939$ ,  $SE = 0.126$ ,  $z = 15.448$ ,  $p < .001$ ) and task type ( $b = 1.910$ ,  $SE = 0.120$ ,  $z = 15.872$ ,  $p < .001$ ). More importantly, the two-way interaction was also highly significant ( $b = -0.777$ ,  $SE = 0.073$ ,  $z = -10.591$ ,  $p < .001$ ). Specific comparisons revealed that the effect of lag was significant in the dual-target task ( $b = -1.162$ ,  $SE = 0.073$ ,  $z = -15.842$ ,  $p < .001$ ), with much fewer accurate T2 responses at Lag 3 relative to Lag 8 (percentage of accurate T2 responses: Lag 3 =  $55.8\% \pm 3.2\%$ ; Lag 8 =  $77.5\% \pm 2.7\%$ ; Figure 2B, left). Meanwhile, different from the assumption of this experiment, fewer accurate T2 responses at Lag 3 relative to Lag 8 were also found in the single-target task ( $b = -0.385$ ,  $SE = 0.076$ ,  $z = -5.073$ ,  $p < .001$ ; Lag 3 =  $77.5\% \pm 2.3\%$ ; Lag 8 =  $82.2\% \pm 2.2\%$ ; Figure 2B, right), indicative of the existence of the temporal expectation effect (Zivony & Lamy, 2022). However, the highly significant two-way interaction and the percentages of accurate T2 responses provided above indicate that the lag effect on T2 accuracy in the crucial dual-target task was approximately five times as large as that in the single-target task, demonstrating that the former originated *mainly* from the AB suppressing T2 at Lag 3 rather than the temporal expectation facilitating T2 at Lag 8.

When the RSVP items were replaced by alphanumeric characters in Experiment 3, the same pattern of behavioral results was found as in Experiment 2. The binomial T2 accuracy was again analyzed using the logistic mixed-effects model with fixed effects of lag, task type, and their interaction. The maximal converging random-effects structure included a random intercept for participants and by-participant random slopes for task type and lag. The results revealed that the two main effects (lag:  $b = 2.333$ ,  $SE = 0.149$ ,  $z = 15.639$ ,  $p < .001$ ; task type:  $b = 2.797$ ,  $SE = 0.153$ ,  $z = 18.257$ ,  $p < .001$ ) and the two-way interaction ( $b = -0.910$ ,  $SE = 0.083$ ,  $z = -10.978$ ,  $p < .001$ ) were all significant. Specific comparisons showed that accurate T2 responses were fewer at Lag 3 than at Lag 8 not only in the dual-target task ( $b = -1.423$ ,  $SE = 0.100$ ,  $z = -14.284$ ,  $p < .001$ ; percentage of accurate T2 responses: Lag 3 =  $49.4\% \pm 3.2\%$ ; Lag 8 =  $77.5\% \pm 2.3\%$ ; Figure 2C, left) but also in the single-target task ( $b = -0.513$ ,  $SE = 0.107$ ,  $z = -4.817$ ,  $p < .001$ ; Lag 3 =  $83.9\% \pm 1.8\%$ ; Lag 8 =  $89.0\% \pm 1.6\%$ ; Figure 2C, right), suggesting the presence of the temporal expectation. Nevertheless, the highly significant two-way interaction, as well as the fact that the lag effect's magnitude (quantified based on the percentage of accurate T2 responses) in the dual-target task, was approximately five times as large as that in the single-target task, demonstrates again that the behavioral lag effect in the crucial dual-target task was *primarily* a consequence of the AB.

### ERP Results

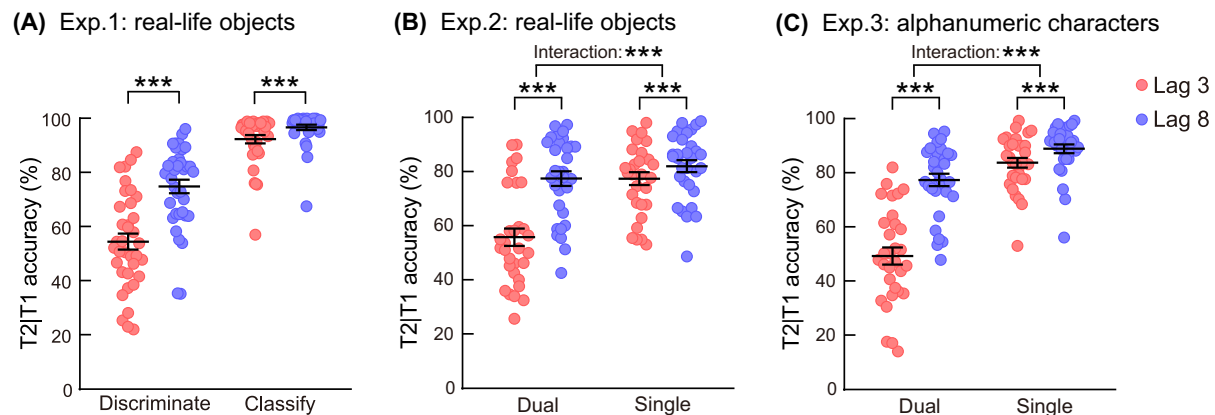
#### *Experiments 1 and 2: Both P3 and P1 Amplitudes Are Consistently Suppressed During the AB When the Stimulus Materials Are Real-Life Objects*

To reveal the impact of AB on early sensory processing of T2 and the role of task demand, the Task Demand  $\times$  Lag ANOVA was first performed on the mean amplitudes of T2-elicited *P1 component* in Experiment 1 (see Figure 3A). The results revealed significant main effects of task demand and lag, task demand:  $F(1, 35) = 10.973$ ,  $p = .002$ ,  $\text{adj } \eta_p^2 = .217^3$ ; lag:  $F(1, 35) = 22.480$ ,  $p < .001$ ,  $\text{adj } \eta_p^2 = .374$ , indicating that the P1 amplitude was overall smaller in the discrimination task than in the classification task and was overall smaller at Lag 3 than at Lag 8. The two-way interaction was not significant,  $F(1, 35) = 0.648$ ,  $p = .426$ ,  $\text{adj } \eta_p^2 = -.010$ ,  $\text{BF}_{10} = 0.297$ , with Bayes factor providing substantial evidence for the nonsignificant interaction. Further planned comparisons by paired  $t$  tests showed that the P1 amplitudes were significantly smaller at Lag 3 than at Lag 8 not only in the discrimination task,  $t(35) = -3.856$ ,  $p < .001$ ,  $d = -0.643$ ; Lag 3 =  $1.90 \pm 0.23 \mu\text{V}$  ( $M \pm SE$ ); Lag 8 =  $2.79 \pm 0.24 \mu\text{V}$ , but also in the classification task,  $t(35) = -3.644$ ,  $p = .001$ ,  $d = -0.608$ ; Lag 3 =  $2.37 \pm 0.18 \mu\text{V}$ ; Lag 8 =  $3.05 \pm 0.22 \mu\text{V}$ . These direct comparisons demonstrate that when real-life objects are used as the RSVP items, the early sensory

<sup>2</sup> We still visualized T2 accuracy in the form of the percentage of accurate T2 responses in our Figure 2 in order to comply with the existing AB literature (for similar conducts, see Eiserbeck et al., 2022; Maier & Abdel Rahman, 2018).

<sup>3</sup> For all ANOVA results in the present study, we reported the "adj  $\eta_p^2$ " (adjusted partial  $\eta$  squared) introduced by Mordkoff (2019) rather than the traditional  $\eta_p^2$ , because the former can correct for the positive bias (i.e., overestimation of the true effect size) of the latter.



**Figure 2***Lag Effects on T2 Performance in Experiments 1–3*

**Note.** Mean percentages of accurate T2 responses (given T1 accurate) are shown as functions of lag (Lag 3, Lag 8) and task demand (discrimination, classification) in Experiment 1 (A), and as functions of lag (Lag 3, Lag 8) and task type (dual target, single target) in Experiment 2 (B) and Experiment 3 (C). In all graphs, single-subject data are depicted by red scatter dots for Lag 3 conditions and by blue scatter dots for Lag 8 conditions, group-averaged data are marked by black symbols, and error bars represent  $\pm 1$  SE. In Experiment 1, significantly lower T2 accuracy at Lag 3 than at Lag 8—a typical manifestation of the AB—was found in both the discrimination and classification tasks. Experiment 2 further showed that the lag effect on T2 accuracy in the dual-target task was much larger than that in the single-target task (despite both being significant), indicating that the former stemmed *mainly* from the AB impairing T2 at Lag 3 rather than the temporal expectation facilitating T2 at Lag 8 when real-life objects were used as the RSVP items. When the RSVP items were replaced by size-matched alphanumeric characters in Experiment 3, the same pattern of behavioral results was found as in Experiment 2. Exp. = experiment; T1 = first target; T2 = second target; RSVP = rapid serial visual presentation; SE = standard error; AB = attentional blink. See the online article for the color version of this figure. \*\*\*  $p < .001$ .

processing indexed by the P1 component is substantially suppressed during the AB regardless of task demand.

To examine whether the robust P1 lag effect observed in Experiment 1 can be accounted for by the temporal expectation, the Task Type  $\times$  Lag ANOVA was performed on the mean amplitudes of T2-elicited P1 component in Experiment 2 (see Figure 3B). The results showed significant main effects of task type,  $F(1, 30) = 12.652, p = .001, \text{adj } \eta_p^2 = .277$ , and lag,  $F(1, 30) = 7.694, p = .009, \text{adj } \eta_p^2 = .181$ , indicating that the P1 amplitude was overall smaller in the dual-target task than in the single-target task and was overall smaller at Lag 3 than at Lag 8. Importantly, the two-way interaction was significant,  $F(1, 30) = 4.730, p = .038, \text{adj } \eta_p^2 = .111$ , indicating that the P1 amplitude was affected by lag differently in the dual-target and single-target tasks. Further analyses of the interaction by paired  $t$  tests revealed that the P1 amplitude at Lag 3 ( $2.22 \pm 0.30 \mu\text{V}$ ) was significantly smaller than that at Lag 8 ( $2.94 \pm 0.28 \mu\text{V}$ ) only in the dual-target task,  $t(30) = -3.723, p = .001, d = -0.669$ , but not in the single-target task,  $t(30) = -1.131, p = .267, d = -0.203, \text{BF}_{10} = 0.343$ ; Lag 3 =  $3.03 \pm 0.26 \mu\text{V}$ ; Lag 8 =  $3.27 \pm 0.22 \mu\text{V}$ , with the Bayes factor providing marginally substantial evidence for the null hypothesis. These findings demonstrate that the P1 lag effect in our dual-target task cannot be accounted for by the temporal expectation enlarging the P1 amplitude at Lag 8; instead, this effect resulted *exclusively* from the P1 amplitude at Lag 3 being suppressed by the AB.

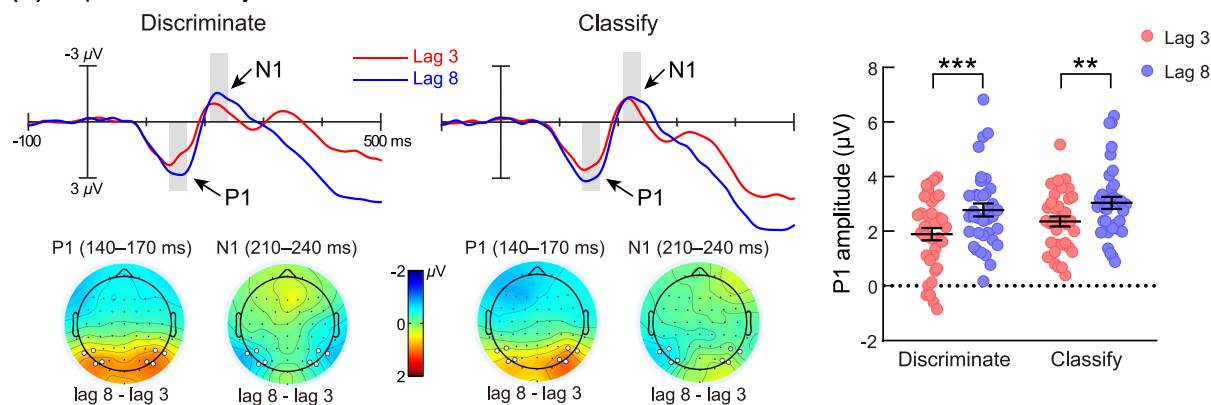
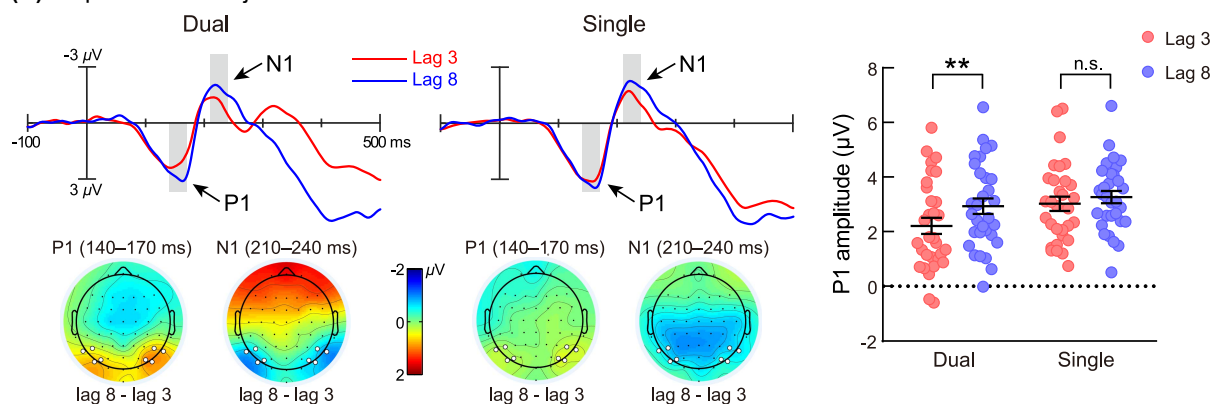
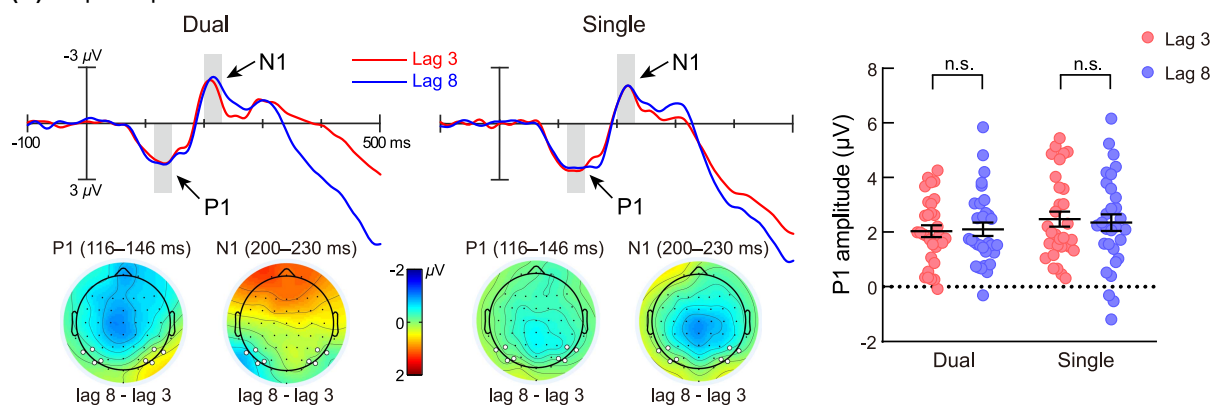
For Experiment 1, the same Task Demand  $\times$  Lag ANOVA was also operated on the mean amplitudes of the subsequent N1 component (see Figure 3A). There was a significant main effect of lag, with the N1 amplitude being overall smaller at Lag 3 than at Lag 8,  $F(1, 35) = 6.158, p = .018, \text{adj } \eta_p^2 = .126$ , but the main effect

of task demand was nonsignificant,  $F(1, 35) = 0.013, p = .912, \text{adj } \eta_p^2 = -.028, \text{BF}_{10} = 0.174$ . The two-way interaction was nonsignificant,  $F(1, 35) = 1.905, p = .176, \text{adj } \eta_p^2 = .025, \text{BF}_{10} = 0.440$ , but the Bayes factor provided relatively weak evidence for the nonsignificant interaction. Further paired  $t$  tests yielded that the N1 amplitude at Lag 3 ( $-0.84 \pm 0.24 \mu\text{V}$ ) was significantly lower than that at Lag 8 ( $-1.41 \pm 0.32 \mu\text{V}$ ) only in the discrimination task,  $t(35) = 2.341, p = .025, d = 0.390$ , but not in the classification task,  $t(35) = 1.684, p = .101, d = 0.281, \text{BF}_{10} = 0.644$ ; Lag 3 =  $-0.99 \pm 0.31 \mu\text{V}$ ; Lag 8 =  $-1.24 \pm 0.34 \mu\text{V}$ . These results suggest that the N1 lag effect is contingent on task demand.

For Experiment 2, the Task Type  $\times$  Lag ANOVA operated on the N1 amplitudes (see Figure 3B), showing a significant main effect of lag,  $F(1, 30) = 18.273, p < .001, \text{adj } \eta_p^2 = .361$ , with the N1 amplitude being overall smaller at Lag 3 than at Lag 8. However, neither the main effect of task type,  $F(1, 30) = 4.103, p = .052, \text{adj } \eta_p^2 = .095, \text{BF}_{10} = 1.211$ , nor the two-way interaction,  $F(1, 30) = 0.185, p = .670, \text{adj } \eta_p^2 = -.022, \text{BF}_{10} = 0.293$ , was significant, and the Bayes factor of the two-way interaction showed substantial evidence for the null hypothesis. This nonsignificant two-way interaction indicates that the N1 lag effect in the dual-target task (Lag 3 =  $-1.09 \pm 0.28 \mu\text{V}$ ; Lag 8 =  $-1.83 \pm 0.39 \mu\text{V}$ ) was equivalent to that in the single-target task (Lag 3 =  $-1.48 \pm 0.39 \mu\text{V}$ ; Lag 8 =  $-2.11 \pm 0.38 \mu\text{V}$ ). Given that any lag effect in a single-target task represents the influence of the temporal expectation (Zivony & Lamy, 2022), the current findings suggest that the N1 lag effect observed in our dual-target task was more likely to be a consequence of the temporal expectation rather than the AB.

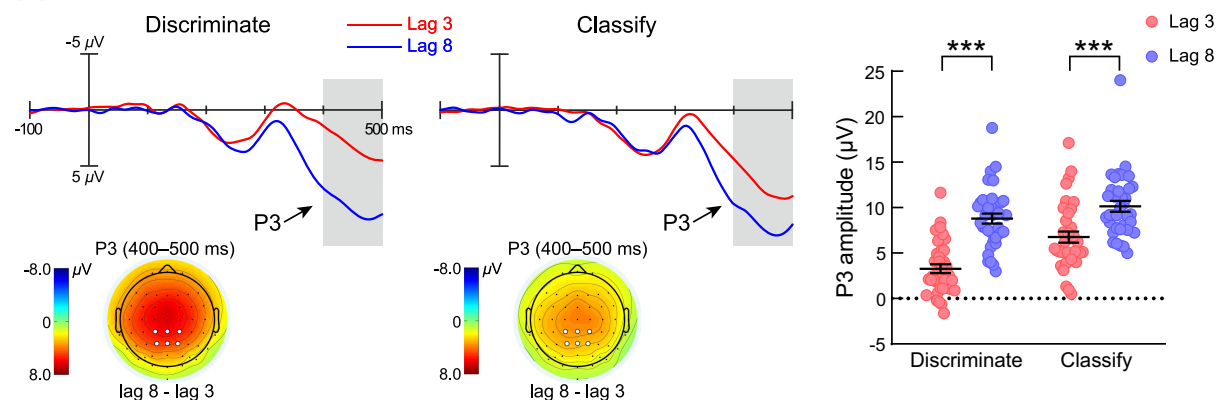
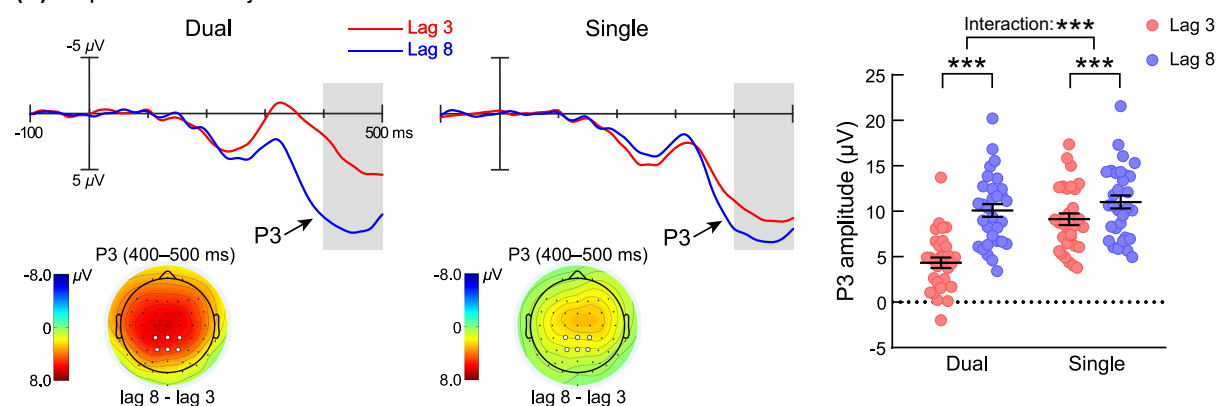
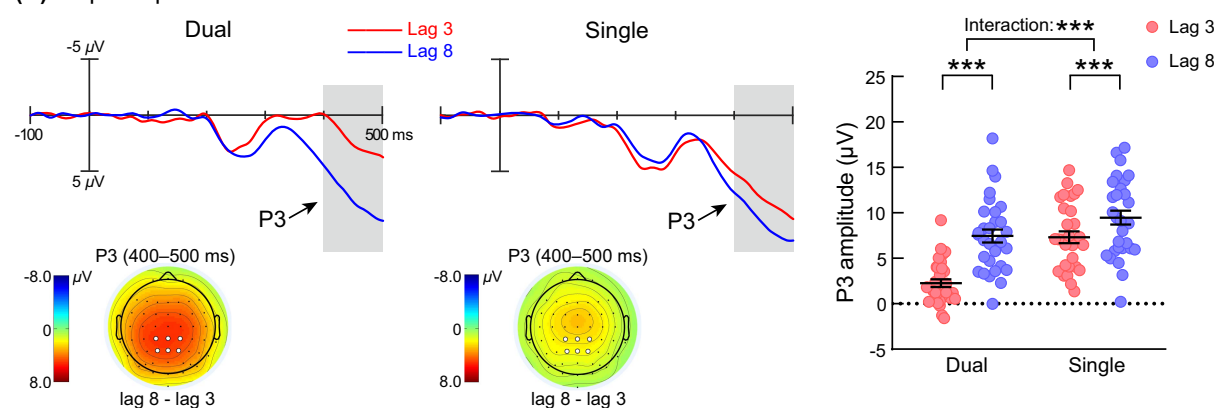
For the purpose of comparison, the above analysis procedure was also conducted for the late P3 component. In Experiment 1 (see Figure 4A), the two main effects were significant, task demand:



**Figure 3***Lag Effects on T2-Elicited P1 and N1 Components in Experiments 1–3***(A) Exp.1: real-life objects****(B) Exp.2: real-life objects****(C) Exp.3: alphanumeric characters**

**Note.** Extracted ERP waveforms (averaged over the posterior ROI) elicited purely by T2s at Lag 3 and Lag 8 and scalp topographies of the Lag 8 – Lag 3 difference amplitudes during the P1 and N1 components are shown separately for the discrimination and classification tasks in Experiment 1 (A) and for the dual-target and single-target tasks in Experiment 2 (B) and Experiment 3 (C). The shaded areas on waveforms and white dots on scalp topographies depict the time windows (140–170 ms and 210–240 ms for Experiments 1 and 2, 116–146 ms and 200–230 ms for Experiment 3) and posterior ROI where the P1 and N1 mean amplitudes were quantified. The computed P1 mean amplitudes are also shown as functions of task demand and lag in Experiment 1 (A) and as functions of task type and lag in Experiments 2 and 3 (B and C), with single-subject data being depicted by scatter dots and grand-averaged data being marked by black symbols. Error bars represent  $\pm 1$  SE. In Experiment 1, the P1 was reduced at Lag 3 relative to Lag 8 regardless of task demand, whereas the N1 was reduced at Lag 3 only in the discrimination task. In Experiment 2, although the N1 lag effect was independent of task type, the P1 lag effect was significant only in the dual-target task, demonstrating that the P1 lag effect originated *exclusively* from the P1 at Lag 3 being suppressed by the AB when real-life objects were used as the RSVP items. In contrast, when the RSVP items were replaced by size-matched alphanumeric characters in Experiment 3, neither P1 nor N1 lag effect was evident, suggesting that the AB-induced P1 suppression is contingent on stimulus type. T2 = second target; Exp. = experiment; n.s. = nonsignificant; ERP = event-related potential; ROI = region of interest; SE = standard error; AB = attentional blink; RSVP = rapid serial visual presentation; P1 = the first positive peak; N1 = the first negative peak. See the online article for the color version of this figure.

\*\*  $p < .01$ . \*\*\*  $p < .001$ .

**Figure 4***Lag Effects on T2-Elicited P3 Component in Experiments 1–3***(A) Exp. 1: real-life objects****(B) Exp. 2: real-life objects****(C) Exp. 3: alphanumeric characters**

**Note.** Similar to Figure 3 but for ERP waveforms averaged over the central–parietal ROI and scalp topographies during the P3 interval (400–500 ms), as well as the computed P3 mean amplitudes. Experiment 1 (A) found that the P3 was reduced at Lag 3 regardless of task demand. Experiment 2 (B) further showed that the P3 lag effect in the dual-target task was much greater than that in the single-target task (although both were significant), suggesting that the former came *primarily* from the P3 at Lag 3 being impaired by the AB rather than the P3 at Lag 8 being facilitated by the temporal expectation when real-life objects were used. When alphanumeric characters were used in Experiment 3 (C), the same pattern of results was found as in Experiment 2, implying that the AB-induced P3 suppression is independent of stimulus type. Exp. = experiment; T2 = second target; ERP = event-related potential; ROI = region of interest; AB = attentional blink; P3 = the third positive peak. See the online article for the color version of this figure.

\*\*\*  $p < .001$ .

$F(1, 35) = 59.465, p < .001, \text{adj } \eta_p^2 = .613$ ; lag:  $F(1, 35) = 104.735, p < .001, \text{adj } \eta_p^2 = .739$ , indicating that the P3 amplitude was overall smaller in the discrimination task than in the classification task and was overall smaller at Lag 3 than at Lag 8. The Task Demand  $\times$  Lag interaction was also significant,  $F(1, 35) = 28.401, p < .001, \text{adj } \eta_p^2 = .426$ . Further planned contrasts showed that the P3 amplitude at Lag 3 was significantly smaller than that at Lag 8 under both task demands, discrimination:  $t(35) = -10.809, p < .001, d = -1.801$ ; Lag 3 =  $3.27 \pm 0.49 \mu\text{V}$ ; Lag 8 =  $8.79 \pm 0.55 \mu\text{V}$ ; classification:  $t(35) = -7.601, p < .001, d = -1.266$ ; Lag 3 =  $6.75 \pm 0.61 \mu\text{V}$ ; Lag 8 =  $10.14 \pm 0.59 \mu\text{V}$ . Taking the significant two-way interaction into consideration, these results demonstrate that, although the P3 amplitudes are suppressed during the AB interval in both task demand conditions, the suppression is stronger in the discrimination task than in the classification task.

In Experiment 2 (see Figure 4B), all the main effects were significant, task type:  $F(1, 30) = 62.943, p < .001, \text{adj } \eta_p^2 = .668$ ; lag:  $F(1, 30) = 130.674, p < .001, \text{adj } \eta_p^2 = .808$ , indicating that the P3 amplitude was overall smaller in the dual-target task than in the single-target task and was overall smaller at Lag 3 than at Lag 8. Crucially, the Task Type  $\times$  Lag interaction was also highly significant,  $F(1, 30) = 69.139, p < .001, \text{adj } \eta_p^2 = .688$ . Further analyses of the interaction showed that the P3 amplitude at Lag 3 was significantly smaller than that at Lag 8 in both task types, dual-target:  $t(30) = -12.272, p < .001, d = -2.203$ ; Lag 3 =  $4.33 \pm 0.57 \mu\text{V}$ ; Lag 8 =  $10.09 \pm 0.70 \mu\text{V}$ ; single-target:  $t(30) = -5.665, p < .001, d = -1.018$ ; Lag 3 =  $9.13 \pm 0.64 \mu\text{V}$ ; Lag 8 =  $11.02 \pm 0.71 \mu\text{V}$ . However, the highly significant two-way interaction and the descriptive statistics provided above indicate that the P3 lag effect in the crucial dual-target task was approximately 3 times greater as that in the single-target task, demonstrating that the former stemmed more from the AB suppressing the P3 amplitude at Lag 3 than the temporal expectation enlarging the P3 amplitude at Lag 8.

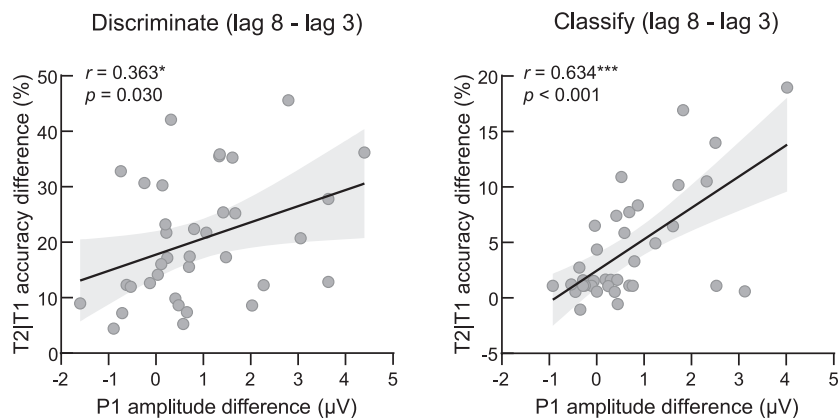
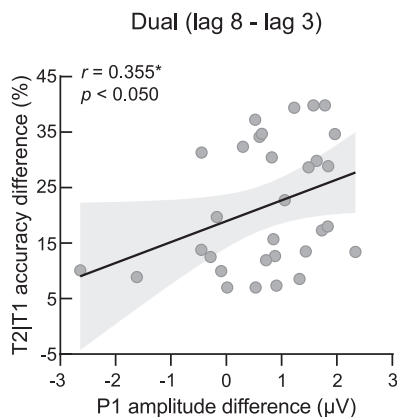
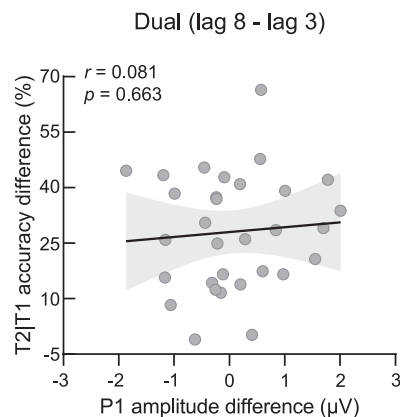
It is noteworthy that the results in Experiment 1's discrimination and classification tasks differed in several aspects. First, the T2-elicited N1 amplitude was smaller at Lag 3 than at Lag 8 only in the discrimination task but not in the classification task. Second, the P3 amplitude was overall greater and impaired by the AB to a lesser extent in the classification task than in the discrimination task. These differences can be attributed to the different processing demands required by the two tasks (see Figure 1A). In the classification task, rough processing of the basic characteristics of T1 and T2 was sufficient to recognize their object categories. In the discrimination task, however, additional processing of the detailed characteristics of T1 and T2 was required to precisely discriminate their exact identities. Accordingly, in contrast to the discrimination task, the classification task's much lower processing demand might have resulted in a situation where, although the early sensory processing of T2 was attenuated by the AB (indexed by P1 suppression), the residual sensory inputs that survived the AB were relatively adequate for participants to roughly recognize T2 category (indexed by intact N1), which in turn increased the probability that it was further encoded in working memory (indexed by smaller P3 suppression). This interpretation is consistent with two prominent proposals: The N1 reflects a goal-directed early discriminative process (Vogel & Luck, 2000), and the P3 suppression during the AB reflects disrupted working memory encoding (Vogel et al., 1998).

Since the dual-target and single-target blocks in Experiment 2 were presented in a pseudorandomized order (cf. Luo et al., 2010, 2013), it is theoretically possible that when a dual-target block happened to be followed by a single-target block, T1 task requirement in the dual-target block might carry over to the subsequent single-target block. However, postexperiment inquiry showed that none of our participants had difficulty in ignoring T1 in the single-target task, even when it was sometimes followed by a dual-target task, suggesting that such an undesired carryover effect seemed less likely to occur actually. Moreover, note that this carryover effect, if any, could only lead to an *underestimation* (rather than overestimation) of the difference in lag effect between the single-target and dual-target tasks. Importantly, the behavioral and main ERP lag effects in the single-target task here were found much smaller than those in the dual-target task. Thus, even if this potential underestimation existed, our core interpretation that the current lag effects in the dual-target task originated mainly from the AB would not be undermined.

### **Experiments 1 and 2: Both P3 and P1 Amplitude Decreases Can Predict the Behavioral AB Magnitude When the Stimulus Materials Are Real-Life Objects**

To investigate whether the aforementioned ERP amplitude decreases are genuinely associated with the impaired T2 accuracy during the AB, Pearson correlation analyses were conducted between the magnitudes of ERP amplitude decreases (calculated as the Lag 8 – Lag 3 amplitude differences over the P1, N1, and P3 intervals) and the magnitude of T2 accuracy decrease (calculated as the Lag 8 – Lag 3 difference in T2 accuracy), separately for each task demand condition in Experiment 1. As expected, it was found that participants who showed larger P3 amplitude decreases during the AB tended to exhibit stronger behavioral AB magnitudes in both the discrimination task,  $r(34) = .536, p = .001$ , and the classification task,  $r(34) = .544, p = .001$ . More importantly, similar correlations were also found between the P1 amplitude decrease and T2 accuracy decrease during the AB in both tasks, discrimination:  $r(34) = .363, p = .030$  (Figure 5A, left); classification:  $r(34) = .634, p < .001$  (Figure 5A, right). However, the correlation between the N1 amplitude decrease and T2 accuracy decrease was far from reliable in the discrimination task,  $r(34) = .205, p = .231, \text{BF}_{10} = 0.414$ , although a significant N1 amplitude decrease during the AB had been found in this task.

Given that the P1 amplitude decrease occurred earlier than the P3 amplitude decrease, it is possible that the variance of the behavioral AB magnitude explained by the late P3 amplitude decrease originated actually from the early P1 amplitude decrease. That is, the P3 amplitude decrease might merely be a downstream effect of the preceding P1 amplitude decrease. On one hand, further Pearson correlation analyses did show that participants with larger P1 amplitude decreases during the AB also exhibited stronger P3 amplitude decreases in each task demand condition, discrimination:  $r(34) = .383, p = .021$ ; classification:  $r(34) = .492, p = .002$ . On the other hand, partial correlation analyses also showed that, for both task demand conditions, the P3 amplitude decreases could still predict the variance of the behavioral AB even when the P1 amplitude decreases were controlled, discrimination:  $r_p(34) = .461, p = .005$ ; classification:  $r_p(34) = .344, p = .043$ . These results demonstrate that the predictive role of the P3 amplitude decrease in

**Figure 5***Relationships Between P1 Suppression and AB Magnitude in Experiments 1–3***(A) Exp.1: real-life objects****(B) Exp.2: real-life objects****(C) Exp.3: alphanumeric characters**

*Note.* Correlations demonstrating the predictive role of P1 amplitude decrease during the AB (quantified as the Lag 8 – Lag 3 amplitude difference) in T2 accuracy decrease during the AB (computed as the Lag 8 – Lag 3 T2 accuracy difference) when real-life objects were used as RSVP items. Scatter plots with fitted lines indicative of the correlation between the P1 amplitude decrease and T2 accuracy decrease are shown separately for the discrimination and classification tasks in Experiment 1 (A), the dual-target task in Experiment 2 (B), and the dual-target task in Experiment 3 (C). The shaded areas depict 95% confidence band for the fitted lines. Note that such correlation was no more significant when the RSVP items were replaced by alphanumeric characters in Experiment 3. Exp. = experiment; T1 = first target; T2 = second target; AB = attentional blink; RSVP = rapid serial visual presentation; P1 = the first positive peak.

\*  $p < .05$ . \*\*\*  $p < .001$ .

the behavioral AB magnitude consisted of a downstream effect of the preceding P1 amplitude decrease and another contribution that was independent of the P1 amplitude decrease.

In order to provide convergent evidence for the predictive roles of the P3 and P1 amplitude decreases in the behavioral AB magnitude found in Experiment 1, similar correlation analyses and partial correlation analysis were also performed for the data in Experiment 2. In the dual-target task, as expected, significant positive correlations were found between the P1 amplitude decrease and behavioral AB magnitude,  $r(29) = .355$ ,  $p < .050$  (Figure 5B), and between the P3 amplitude decrease and behavioral AB magnitude,  $r(29) = .455$ ,  $p = .010$ . In contrast, no significant correlations were

found in the single-target task, P1 and behavior:  $r(29) = -.050$ ,  $p = .791$ ,  $BF_{10} = 0.231$ ; P3 and behavior:  $r(29) = .021$ ,  $p = .910$ ,  $BF_{10} = 0.225$ , which is consistent with the hypothesis that these neural-behavioral associations are specific to the condition in which the AB occurs. Moreover, participants who showed larger P1 amplitude decreases also exhibited stronger P3 amplitude decreases in the dual-target task,  $r(29) = .370$ ,  $p = .040$ , but further partial correlation analysis showed, once again, that the P3 amplitude decrease could still explain the variance of the behavioral AB magnitude even when the P1 amplitude decrease was controlled,  $r_p(29) = .372$ ,  $p = .043$ . Thus, the highly consistent results in Experiments 1 and 2 provide strong evidence that the behavioral AB



originates from not only suppressed postperceptual processing of T2 but also impaired early sensory processing of T2 whenever pictures of real-life objects are used as RSVP items.

### **Experiment 3: Only P3 Amplitude, but Not P1 Amplitude, Is Suppressed During the AB When the Stimulus Materials Are Alphanumeric Characters**

In Experiment 3, the RSVP items of real-life objects used in Experiments 1 and 2 were replaced by size-matched alphanumeric characters (see Figure 1B) to further determine whether the occurrence of P1 suppression during the AB is contingent truly on the stimulus type. The Task Type  $\times$  Lag ANOVA performed on the T2-elicited P1 component (see Figure 3C) showed a significant main effect of task type,  $F(1, 30) = 8.067, p = .008, \text{adj } \eta_p^2 = .189$ , indicating that the P1 amplitude was overall smaller in the dual-target task (Lag 3 =  $2.05 \pm 0.22 \mu\text{V}$ ; Lag 8 =  $2.12 \pm 0.25 \mu\text{V}$ ) than in the single-target task (Lag 3 =  $2.49 \pm 0.28 \mu\text{V}$ ; Lag 8 =  $2.36 \pm 0.31 \mu\text{V}$ ). However, neither the main effect of lag,  $F(1, 30) = 0.065, p = .800, \text{adj } \eta_p^2 = -.027, \text{BF}_{10} = 0.197$ , nor the two-way interaction,  $F(1, 30) = 0.697, p = .410, \text{adj } \eta_p^2 = -.005, \text{BF}_{10} = 0.323$ , was significant, with the corresponding Bayes factors showing substantial evidence for the null hypothesis. These results are consistent with previous studies showing no AB-induced P1 suppression when alphanumeric characters or words were used as the RSVP items (Batterink et al., 2012; Koivisto & Revonsuo, 2008; Kranczioch et al., 2007; Lasaponara et al., 2015; Sergent et al., 2005; Vogel et al., 1998). More importantly, these results showed that the P1 component was intact during the AB even when the alphanumeric characters used here have become as large as the real-life objects used in Experiments 1 and 2, thereby invalidating the large stimulus size as a main cause of the AB-induced P1 suppression observed in Experiments 1 and 2.

Similar to the pattern of the aforementioned P1 results, the Task Type  $\times$  Lag ANOVA performed on the N1 component (see Figure 3C) also did not show a significant main effect of lag,  $F(1, 30) = 0.696, p = .411, \text{adj } \eta_p^2 = -.005, \text{BF}_{10} = 0.264$  or a significant two-way interaction,  $F(1, 30) = 1.108, p = .301, \text{adj } \eta_p^2 = .008, \text{BF}_{10} = 0.260$ , but only showed a marginally significant main effect of task type,  $F(1, 30) = 4.167, p > .050, \text{adj } \eta_p^2 = .097, \text{BF}_{10} = 3.275$ , with the N1 amplitude being overall larger in the dual-target task (Lag 3 =  $-1.99 \pm 0.31 \mu\text{V}$ ; Lag 8 =  $-2.22 \pm 0.30 \mu\text{V}$ ) than in the single-target task (Lag 3 =  $-1.69 \pm 0.25 \mu\text{V}$ ; Lag 8 =  $-1.72 \pm 0.33 \mu\text{V}$ ).

The Task Type  $\times$  Lag ANOVA performed on the P3 component (see Figure 4C) showed the same pattern of results as in Experiment 2. All the main effects were significant, task type:  $F(1, 30) = 64.635, p < .001, \text{adj } \eta_p^2 = .674$ ; lag:  $F(1, 30) = 69.548, p < .001, \text{adj } \eta_p^2 = .690$ , reflected by the P3 amplitude being overall smaller in the dual-target task than in the single-target task and being overall smaller at Lag 3 than at Lag 8. Importantly, the two-way interaction was also significant,  $F(1, 30) = 27.388, p < .001, \text{adj } \eta_p^2 = .462$ . Further analyses of the interaction showed that the P3 amplitude at Lag 3 was significantly smaller than that at Lag 8 in both task types, dual-target:  $t(30) = -8.251, p < .001, d = -1.482$ ; Lag 3 =  $2.27 \pm 0.43 \mu\text{V}$ ; Lag 8 =  $7.45 \pm 0.71 \mu\text{V}$ ; single-target:  $t(30) = -5.396, p < .001, d = -0.970$ ; Lag 3 =  $7.31 \pm 0.66 \mu\text{V}$ ; Lag 8 =  $9.47 \pm 0.76 \mu\text{V}$ . However, the highly significant two-way interaction, as well as the fact that the P3 lag effect's magnitude in the crucial dual-target task,

was approximately three times as large as that in the single-target task, demonstrates again that the former stemmed *more* from the AB suppressing the P3 amplitude at Lag 3 than the temporal expectation enlarging the P3 amplitude at Lag 8.

Last, correlation analyses conducted on the data in the dual-target task of Experiment 3 showed that the P1 amplitude difference between Lag 8 and Lag 3 conditions, which was inherently nonsignificant, was no more predictive of the behavioral AB magnitude,  $r(29) = .081, p = .663, \text{BF}_{10} = 0.224$  (see Figure 5C), with the Bayes factor providing substantial evidence for the null hypothesis. Note that this neural-behavioral correlation analysis was performed even though the P1 lag effect was absent here, because we aimed to furnish complementary evidence that the predictive role of the P1 lag effect is contingent on the P1 lag effect itself being present. In contrast, the magnitude of P3 amplitude decrease could still significantly predict the behavioral AB magnitude,  $r(29) = .483, p = .006$ . Thus, the results of Experiment 3 demonstrate that even when large-size alphanumeric characters are used as the RSVP items, the AB does not suppress T2 processing until the postperceptual stage, in close agreement with previous AB studies using relatively small-size alphanumeric characters or words (e.g., Akyürek et al., 2010; Batterink et al., 2012; Craston et al., 2009; Dell'Acqua et al., 2015; Kranczioch et al., 2003; Meng et al., 2023; Sergent et al., 2005; Sessa et al., 2007; Vogel et al., 1998). More importantly, in conjunction with the results of Experiments 1 and 2, the present study provide direct evidence that the stage at which the AB begins to suppress T2 processing (perceptual vs. postperceptual) is dependent on the stimulus type (real-life objects vs. alphanumeric characters).

## **Discussion**

The current ERP research aimed to determine whether the AB can occur at the perceptual level whenever observers are encountering RSVP items of common objects. By using line drawings of real-life objects as the stimulus materials, Experiment 1 found that, along with the behavioral AB effect manifested as T2 performance being worse at Lag 3 than at Lag 8, the T2-elicited P1 component was decreased at Lag 3 relative to Lag 8 not only when participants were required to discriminate the exact identities of T1 and T2 (discrimination task) but also when they were simply instructed to classify the object categories of T1 and T2 (classification task). Experiment 2 presented the same set of real-life objects and further showed that this P1 lag effect was significant solely when participants needed to discriminate the identities of both T1 and T2 (dual-target task) but not when only the identity of T2 needed discrimination (single-target task), which demonstrates that the P1 lag effect stemmed genuinely and exclusively from the AB suppressing the P1 amplitude at Lag 3 rather than the temporal expectation boosting the P1 amplitude at Lag 8 (cf. Zivony & Lamy, 2022). More importantly, the neural-behavioral associations identified in the dual-target tasks of Experiments 1 and 2 consistently showed that the magnitude of the P1 lag effect could further predict the behavioral AB magnitude. Given that the P1 component is well-established as reflecting an initial sensory process in which the basic visual features (e.g., colors, orientations), but not yet the meaning, of the eliciting stimulus is being extracted (Heinze et al., 1990; Hillyard & Münte, 1984; Luck et al., 1993, 2000; Mangun, 1995), the current findings furnish the strongest

evidence to date that when observers encounter RSVP items of common objects, the AB begins to suppress T2 processing at a very early perceptual stage, before the object category of T2 can be identified by the brain.

Some previous studies have shown evidence in favor of the suppression of *high-level* perceptual processing during the AB. For example, by manipulating the to-be-reported T2 feature, Zivony et al. (2018) found that reporting the high-level features of T2 (identity and semantic category) was more severely impaired by the AB than reporting its low-level feature of color. The authors reasoned that a pure postperceptual account of the AB could not explain this behavioral finding: Had the AB affected T2 processing only at the postperceptual stage, T2 performance should have been equally impaired regardless of the to-be-reported T2 feature (Zivony et al., 2018). Moreover, by manipulating the semantic congruency between T2 and its preceding context word, several investigations reported that the N400, an ERP component particularly sensitive to semantic incongruency (Kutas & Federmeier, 2011), elicited by T2 was decreased during the AB (Batterink et al., 2010; Giesbrecht et al., 2007; Sy et al., 2013; Weller et al., 2019; but see Vachon & Jolicoeur, 2011; Vogel et al., 1998, for an intact N400), indicating that the high-level perceptual processing of T2 can be impaired by the AB, at least under certain conditions. However, the aforementioned studies did not further examine the possibility that the AB may even impair the *low-level* perceptual processing (i.e., the sensory processing) of T2, and this possibility is confirmed by the consistent P1 lag effect and its close association with the behavioral AB magnitude when RSVP items of real-life objects were used. Therefore, these novel findings advance the current understanding of how early the AB can start to suppress T2 processing (for a recent review, see Zivony & Lamy, 2022).

Besides the low-level perceptual locus of the AB, the present results regarding the P3, a late ERP component generally thought to reflect working memory encoding (for a review, see Polich, 2007) further demonstrates that the AB also suppresses T2 processing at the postperceptual stage. Concretely, consistent with previous studies (Akyürek et al., 2010; Craston et al., 2009; Dell'Acqua et al., 2015; Kranczioch et al., 2003; Sessa et al., 2007; Vogel et al., 1998), the T2-elicited P3 amplitude was significantly lower at Lag 3 than at Lag 8 whenever a dual-target task was required (Experiment 1), and this P3 lag effect was much larger in the dual-target task than in the single-target task (Experiment 2), indicating that it stemmed mainly from the AB disrupting T2 processing at Lag 3 rather than the temporal expectation facilitating T2 processing at Lag 8 (cf. Zivony & Lamy, 2022). Also as expected, the magnitude of the P3 lag effect could further predict the behavioral AB magnitude in each dual-target task even when the contribution of the preceding P1 lag effect (which was prominent in Experiments 1 and 2) was controlled, authenticating the proposal that the AB can operate independently at both the perceptual and postperceptual stages of processing. But more than that, the present study also found that the early P1 lag effect, when prominent in Experiments 1 and 2, could reliably predict the late P3 lag effect in each dual-target task to some degree. Although there is no precedent for such interesting correlations in the AB literature (see Roth-Paysen et al., 2022, for the co-occurrence of the P1 and P3 lag effects at most), these correlations strongly suggest that when real-life objects were used as the RSVP items, certain parts of the observed P3 suppression during the AB were *consequences* of the preceding P1 suppression. In other

words, the P3 suppression reported in Experiments 1 and 2 might result not only from the AB limiting working memory encoding *per se* (as mentioned above) but also from the impaired early sensory processing reducing the amount of information that could ultimately get access to working memory. This is in accord with previous studies showing that the P3 amplitude would also decline as the to-be-discriminated stimulus' sensory quality decreased (Cohen et al., 2020; Dehaene et al., 2001). Future AB research should continue to test that inference when both the P1 and P3 lag effects are found.

In contrast to the AB-specific P1 and P3 lag effects discussed above, Experiment 2 further found that the lag effect on N1 amplitude in the dual-target task was equivalent to that in the single-target task, which suggests that the N1 lag effects observed in Experiments 1 and 2 where real-life objects were employed might result merely from the temporal expectation enlarging the N1 amplitude at Lag 8, instead of the AB suppressing the N1 amplitude at Lag 3 (cf. Zivony & Lamy, 2022). This interpretation corresponds well to the nonsignificant correlation between the N1 lag effect and the behavioral lag effect reported in Experiment 1, given that the behavioral lag effect was then proven to originate mainly from the AB rather than the temporal expectation in Experiment 2 (see Figure 2B). If that is the case, the finding of a prominent N1 lag effect only under the discrimination task but not under the classification task in Experiment 1 would indicate that the task demand modulates the effect of the temporal expectation, rather than the effect of the AB, on the early discriminative processing of T2. Nevertheless, it should be noted that a previous study found that the N170 (a face-specific N1 subcomponent) elicited by facial T2s was smaller at Lag 3 than at Lag 8 only in the dual-target task but not in the single-target task (Luo et al., 2013; but see Luo et al., 2010, for equivalent N170 lag effects in the dual-target and single-target tasks). Therefore, additional research is required to test whether T2 stimulus type (faces vs. objects) would determine the occurrence of an AB-specific N1 lag effect.

In close agreement with previous *discrete* observations of intact P1 during the AB when alphanumeric characters or words were used as the RSVP items (Batterink et al., 2012; Koivisto & Revonsuo, 2008; Kranczioch et al., 2007; Lasaponara et al., 2015; Sergent et al., 2005; Vogel et al., 1998) and suppressed P1 during the AB when real-life objects or faces were used (Roth-Paysen et al., 2022; Weller et al., 2019), the present study *concurrently* found that the AB-induced P1 suppression was evident when the RSVP items were line drawings of real-life objects (Experiments 1 and 2) but not when they were substituted by alphanumeric characters (Experiment 3). Indeed, only a P3 suppression was found during the AB in the latter case. Importantly, the alphanumeric characters and real-life objects used here were carefully matched in size for the first time in the AB literature, thereby ruling out the large stimulus size as an alternative cause of the P1 suppression. Hence, the present findings provide vital evidence that the stage at which the AB begins to suppress T2 processing (perceptual vs. postperceptual) is contingent on the stimulus type used (real-life objects or faces vs. alphanumeric characters or words). In terms of the underlying reasons, our proposal starts with a long-lasting hypothesis that, by default, pictures of real-life objects (including faces), which have abundant and highly distinctive visual features, inherently involve more elaborate sensory encoding than man-made alphanumeric characters and words that have relatively limited and homogeneous visual

features (Ensor et al., 2019; Mintzer & Snodgrass, 1999; Nelson et al., 1976, 1977; Nelson & Reed, 1976). Indeed, this hypothesis was supported by our post hoc ERP analysis showing that in the baseline condition where no AB would occur (i.e., when T2 was presented at Lag 8 in the single-target task), the T2-elicited P1 component was significantly larger when real-life objects were used (Experiment 2) than when size-matched alphanumeric characters were used (Experiment 3), between-subject  $t$  test:  $t(60) = 2.404, p = .019, d = 0.611$  (see Figure 3B versus Figure 3C). However, the normally more elaborate sensory encoding of pictorial stimuli may instead become redundant during the AB wherein only limited attentional resources are available. Accordingly, when real-life objects or faces are used in a dual-target RSVP task, the AB may need to exert an additional “filter” at the perceptual stage to effectively suppress the elaborate but redundant sensory encoding of the items closely following T1 (for the purpose of ensuring T1 encoding), which inescapably attenuates the early perceptual processing of T2 when it is presented at a short lag after T1. Although this proposal is relatively tentative, it offers a potential resolution, for the first time, to the interpretation of the inconsistent P1 results in the AB literature, which would encourage future studies to examine whether the richness of sensory features in stimulus materials is a key factor that determines the stage at which the AB begins to suppress T2 processing.

Alternatively, an even bolder, sensitivity-related proposal is that the AB may *always* begin to suppress T2 processing at an early perceptual stage, but this early suppression effect is presumably much weaker when alphanumeric characters are used than when real-life objects are used. Consequently, the relatively small, scalp-recorded P1 component might be insufficient to pick up the underlying early suppression effect in the former case but sufficient in the latter case, hence the inconsistent P1 results in the AB literature. This proposal seems partially consistent with previous functional magnetic resonance imaging studies using simple gratings or letters as stimulus materials, which consistently detected that the behavioral AB effects were accompanied by reduced activities in early visual cortex (Hein et al., 2009; Williams et al., 2008). However, these “anatomically early” modulations should be treated with caution because they might also be a consequence of delayed feedback from higher order brain regions, in view of the poor temporal resolution of functional magnetic resonance imaging. Indeed, to probe whether there is a sensitivity issue with relying on the P1 component as a neural measure of early suppression, intracranial EEG recordings may provide a promising solution because they can afford higher signal-to-noise ratio and spatial resolution than scalp ERP recordings. Recent intracranial EEG studies in humans have shown that the T1-elicited alpha- and beta-band oscillations recorded in the ventral striatum (Slagter et al., 2017) and T1-elicited P3 component recorded in the hippocampus (Derner et al., 2023) were associated with T2 performance during the AB, but these studies have not yet revealed whether the T2-elicited P1 component recorded in the visual cortex would be suppressed during the AB—a question that needs to be answered in follow-up studies.

More importantly, the aforementioned two proposals also imply that the AB may have at least two distinct suppressive mechanisms. Specifically, the first is an early suppressive mechanism operating at the sensory stage of processing, similar to the early attentional gating mechanism proposed by Raymond et al. (1992). However,

this early mechanism, in our viewpoint, can be invoked (or can be detected by scalp-recorded ERPs) *only when* the stimulus materials used are rich enough in sensory features, as suggested by the intact versus suppressed P1 amplitude during the AB when characters/words versus objects/faces were used (see above). The second is the widely accepted late suppressive mechanism operating at the postperceptual stage, as initially proposed by Chun and Potter (1995) and then verified by Vogel et al. (1998) and so on. Different from the above early suppressive mechanism, this late mechanism is engaged *regardless of* the richness of sensory features in stimulus materials, as indicated by the P3 suppression being consistently observed during the AB irrespective of stimulus type (characters/words: e.g., Akyürek et al., 2010; Batterink et al., 2012; Craston et al., 2009; Dell’Acqua et al., 2015; Kranczioch et al., 2003; Meng et al., 2023; Sergent et al., 2005; Sessa et al., 2007; Vogel et al., 1998; objects/faces: e.g., Darque et al., 2012; Eiserbeck et al., 2022; Roth-Paysen et al., 2022; Zhao, Feng, Liao, et al., 2021), as well as the current finding that the P3 suppression could still predict the behavioral AB magnitude even when the contribution of the P1 suppression was controlled. Remarkably, the two distinct suppressive mechanisms are conceptually analogous to the “dual-disruption” account of the AB recently proposed by Zivony and Lamy (2022) based on the majority of existing ERP findings in the AB literature, with the main exceptions being that (a) our early suppressive mechanism can operate even earlier than theirs (i.e., during vs. after the sensory processing of T2), and (b) the trigger for their early suppressive mechanism was hypothesized to be the difficulty of T1 task rather than the richness of sensory features in stimulus materials. Interestingly, it can be seen that our early suppressive mechanism and theirs are relatively independent. Therefore, our early suppressive mechanism may well be integrated into the dual-disruption model of Zivony and Lamy (2022) to construct a “triple-disruption” model for the AB, with our early suppressive mechanism being the earliest mechanism in the new model. If validated by future AB studies, such a multiple-mechanism model will set the field free from the traditional assumption(s) that the AB reflects a single suppressive mechanism operating at fixed stages of processing (for similar proposals, see Kranczioch et al., 2007; Wong, 2002; Zivony & Lamy, 2022).

Recently, the AB paradigm has been utilized as a tool to reveal the graded nature of visual consciousness and its electrophysiological correlates (Dellert et al., 2022; Eiserbeck et al., 2022; Roth-Paysen et al., 2022). By requiring participants to rate the degree of T2 subjective awareness (e.g., not seen, slight impression, strong impression, or seen completely) in addition to the classic T2 identification task, these ERP studies consistently showed that during the AB interval, there were considerable proportions of intermediate ratings of T2 awareness, and the visual awareness negativity typically spanning the N1 and N2 time ranges enhanced linearly as the ratings of T2 awareness increased. The present study did not conduct such a response-based analysis of the T2-elicited visual awareness negativity because of the lack of a T2 awareness rating task. Although we can instead compare T2-elicited ERPs between correct versus incorrect responses at Lag 3, this comparison is not equivalent to the contrast between strongly versus weakly aware trials, because, for example, an incorrect response does not necessarily result from one being less aware of T2, which would compromise the purity of the “visual awareness negativity effect.”



Moreover, even if we conduct the correct-versus-incorrect ERP analysis at Lag 3, the effects revealed would not be readily attributed to the AB itself. Specifically, since incorrectly identified T2s during the AB may represent not only blinked T2s but also T2s that participants failed to identify for other AB-unrelated reasons (e.g., general fluctuation of attention), it is crucial to use the correct-versus-incorrect ERP differences outside the AB to estimate the magnitude of these AB-unrelated effects (Roth-Paysen et al., 2022; Zivony & Lamy, 2022). In the present study, unfortunately, there were too few incorrect T2 responses at Lag 8 to allow a reliable correct-versus-incorrect ERP analysis (Experiment 1's discrimination task: 42 trials on average; Experiment 2's dual-target task: 32 trials; Experiment 3's dual-target task: 25 trials), especially when focusing on early ERP effects. Therefore, to examine with confidence whether the current P1 modulation would further underlie T2 accuracy during the AB on a trial-by-trial basis, future investigations intending to conduct the correct-versus-incorrect ERP analysis should arrange more trials, especially at the long lag. Meanwhile, to allow the use of the current paradigms to explore early neural correlates of consciousness, a trial-by-trial T2 awareness rating task should be added. These modifications would help to provide deeper insight into the early locus of suppression during the AB and its linkage with visual consciousness.

### Constraints on Generality

Following the majority of previous ERP studies in the AB literature (for a review, see Zivony & Lamy, 2022), we recruited healthy participants aged 18–27 years in the present study; thus, our findings here should be generalized to typically developing young adults. Further research is needed to elucidate whether the current findings apply to other healthy age groups (e.g., children, adolescents, and older adults) or even clinical populations (e.g., individuals with autism or schizophrenia). Moreover, although the present study only found that the P1 and P3 suppression co-occurred during the AB when *line drawings* of common objects were used as RSVP items, there seems no reason to doubt that the same pattern of results can be replicated when more naturalistic *photographs* of common objects or faces (which have even richer sensory features) are used instead. Nevertheless, further research is still required to test this speculation.

### Conclusion

By systematically analyzing ERPs to line drawings of common objects and alphanumeric characters embedded in RSVP streams across three experiments, the present study found that when common objects were used as stimulus materials, the T2-elicited P1 amplitude was consistently decreased during the AB, which was further predictive of the behavioral AB magnitude. These novel but reliable findings provide the strongest evidence to date that the AB can occur at a very early perceptual level, even before the object category of T2 can be identified by the brain, at least when observers are encountering RSVP items of real-life objects. Thus, we tentatively put forward a multiple-mechanism model for the AB, in which the invocation of the early-perceptual suppressive mechanism (or whether the early-perceptual suppressive mechanism can be detected by scalp-recorded ERPs) is hypothesized to be contingent on the richness of sensory features in stimulus materials,

a factor that needs to be examined further in the future. More broadly, the present study also challenges the traditional but influential view that the earliest locus of *time*-based attentional selection is later than that of *space*-based attentional selection (e.g., Hopfinger et al., 2004; Vogel et al., 1998). Instead, our findings demonstrate that under certain circumstances, the former (indexed by the deceased P1 during the AB) can be as early as the latter (indexed by the deceased P1 at unattended locations: Luck et al., 1993; Luck & Hillyard, 1994; Mangun et al., 1993), thereby updating our understanding of the relationship between the two forms of attentional selection in general.

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