The Effect of Audio-Visual Integration on Attentional Blink

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Abstract

Attentional Blink (AB) refers to the phenomenon where individuals exhibit diminished recognition ability for stimuli presented within a short temporal window when confronted with a rapid serial stream of stimuli. The occurrence of attentional blink can readily lead to the loss of subsequent information processing, representing a manifestation of attention’ s limitations along the temporal dimension. Numerous studies have demonstrated that when individuals interact with complex information environments, they identify objects or stimuli capable of simultaneously conveying information through both visual and auditory channels more rapidly and accurately. Existing research indicates that audiovisual integration not only facilitates the orienting and search efficiency of spatial attention, but also elicits sensory facilitation effects in long-term attentional processes. The present study investigates whether audiovisual integration can modulate the limiting effects imposed by attentional blink; if such modulation exists, how varying degrees of integration strength influence attentional blink, and how this regulatory efficacy might be further optimized. In Experiment 1, employing the RSVP paradigm, we examined the impact of audiovisual integration on attentional blink by comparing blink effects across different auditory conditions. The results revealed that recognition accuracy significantly improved when the ignored sound synchronized with the target within the blink window, demonstrating that audiovisual integration can attenuate attentional blink, and that this effect was not attributable to auditory salience. Based on the biased competition model, Experiment 2 investigated how different levels of integration modulate attentional blink by adding an auditory task to distribute attention across both visual and auditory channels. The findings demonstrated that recognition accuracy was even more substantially enhanced when the attended sound synchronized with the target in the blink window, proving that strengthened audiovisual integration effects can more markedly reduce attentional blink. Concurrently, this also illustrates that audiovisual integration can

modulate the attentional blink phenomenon to varying degrees.

Full Text

The Effect of Audiovisual Integration on Attentional Blink

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Abstract: Attentional Blink (AB) refers to the phenomenon where individuals exhibit diminished recognition ability for stimuli appearing within a short time window when confronted with a rapid stream of successive stimuli. This phenomenon can easily lead to loss of subsequent information processing and represents a fundamental limitation of attention in the temporal dimension. Numerous studies have shown that when individuals exchange information with complex environments, they can identify objects or stimuli that present information simultaneously through both visual and auditory channels more quickly and accurately. Existing research indicates that audiovisual integration not only facilitates spatial attention orientation and search efficiency but also elicits sensory facilitation effects during sustained attention. The present study investigates whether audiovisual integration can modulate the limitations imposed by attentional blink; if such an effect exists, how the strength of integration influences attentional blink, and how this modulatory effect can be optimized.

In Experiment 1, we employed the RSVP paradigm to explore the effect of audiovisual integration on attentional blink by comparing blink magnitude across different sound conditions. The results demonstrated that recognition accuracy significantly improved when the ignored sound synchronized with the target in the blink window, proving that audiovisual integration can reduce attentional blink and that this effect is not attributable to auditory salience. Based on the biased competition model, Experiment 2 investigated how different integration levels modulate the blink by adding an auditory task to distribute attention across both modalities. The findings revealed that when the attended sound synchronized with the target in the blink window, recognition accuracy improved even more substantially, demonstrating that enhanced audiovisual integration effects can more significantly reduce attentional blink. These results also illustrate that audiovisual integration can modulate attentional blink phenomena to varying degrees.

Keywords: attentional blink; multisensory integration; audiovisual integration; modality-specific attention; bimodal divided attention

1. Introduction

During sustained attentional processing, individuals exhibit diminished recognition ability for stimuli appearing within a short timeframe when confronted with a continuous stream of stimuli. Raymond et al. (1992) named this temporal processing limitation "Attentional Blink" (AB). When different types of stimuli appear consecutively at the same location, if the second target (Target2, T2) appears within a short temporal window after the first target (Target1, T1)—known as Target Onset Asynchrony (TOA), typically 200-500 ms—participants' accuracy in identifying T2 decreases significantly (Barry et al., 2015; Broadbent & Broadbent, 1987; Chun & Potter, 1995; Dux & Marois, 2009; Pomerleau et al., 2014; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1997; Weichselgarner, 1987; Chen & Wang, 2012). This time window is termed the attentional blink window (Zeng & Liu, 2015; Chen et al., 2014). In summary, attentional blink can be understood as a functional blindness phenomenon occurring in short temporal processes of attention (Martens & Wyble, 2010; Zhang & Wang, 2009), reflecting a fundamental cognitive limitation in the dynamic temporal dimension of attention (Isaak, Shapiro, & Martin, 1999; Potter, Staub, & Connor, 2002). Specifically, the perceptual system can only process a limited amount of information continuously within a given time period (Marois & Ivanoff, 2005), and it represents a characteristic phenomenon for measuring how attentional resources are allocated across temporal stimulus sequences (Wu & Gao, 2013).

Researchers typically employ the Rapid Serial Visual Presentation (RSVP) paradigm to investigate the temporal characteristics of attention—specifically, the attentional blink effect (Chen & Wang, 2012; Dux & Marois, 2009; Russo, Kates, & Wyble, 2017; Dong, 2017). Initially introduced by Lawrence et al. (1971) to study human processing capacity for serial stimuli, this method was later developed and adapted by Jane E. Raymond et al. (1992). In a classic attentional blink experiment, participants first fixate on a central fixation point, after which a stream of single Arabic digit stimuli containing two English letters is presented at a rate of 10 items per second at the screen center. Participants must identify the two letters (target stimuli, recorded sequentially as T1 and T2) in order from the digit stream. Behavioral results primarily examine the probability of correctly judging T2 given correct T1 identification, recorded as T2/T1. The proximity of T2 to T1 is called Lag, which represents T2' s relative position after T1 (MacLean & Arnell, 2012). Experimental results show that T2 recognition accuracy first decreases then rises to stability as Lag increases, with a significant decline in T2 recognition accuracy within the 200-500 ms window after T1.

Research demonstrates that attentional blink magnitude varies across experiments and can be enhanced, reduced, or even eliminated by manipulating certain factors. Multiple factors influence the blink phenomenon, including both participant characteristics and experimental settings. Cindy et al. (2001) applied the classic attentional blink paradigm to different age groups, finding that older adults exhibit more pronounced attentional blink with age and reduced perceptual sensitivity (Van et al., 2009). In studies of special populations, Wang et al. (2019) found that deaf individuals show more significant attentional blink effects than hearing individuals under equivalent conditions. Amirault et al. (2009) also found that individuals with autism are more prone to attentional blink than normal controls. Populations with executive dysfunction, attention deficits, and related organic lesions—such as schizophrenia patients (Mathis et al., 2012), ADHD patients (Cheng & Liu, 2017), dyslexia patients (Wang, 2019), and depression patients (Li, Wang, & Gao, 2006)—all exhibit greater impairments in temporal attention persistence (Chen et al., 2014). Furthermore, researchers have identified approximately 5% of individuals in the population who show minimal or no blink phenomenon, termed "non-blinkers" (Martens & Johnson, 2005; Martens, Munneke, Smid & Johnson, 2006). Individual differences also constitute an important factor affecting attentional blink, which is closely related to working memory capacity (Nieuwenstein & Potter, 2006). Specifically, larger working memory capacity is associated with reduced attentional blink (Colzato, Spape, Pannebakker & Hommel, 2008), whereas severe memory load exacerbates attentional blink (Akyurek, Hommel & Jolicoeur, 2007; Akyurek, Leszczynski & Anna, 2010). Many studies also highlight the influence of current emotional states: positive emotions are more likely to capture attention and reduce attentional blink when resources compete during sustained attention (Olivers & Nieuwenhuis, 2005; Vermeulen, 2010), while negative emotions tend to induce larger attentional blink effects (MacLean, Arnell & Busseri, 2010; Smith, Most, Newsome & Zald, 2006). Research also indicates that individuals in high-anxiety states exhibit more pronounced attentional blink phenomena (Van Dam, Earleywine & Altarriba, 2012).

Beyond participant state characteristics, experimental task design and stimulus presentation parameters also significantly affect blink magnitude. Arnell and Jolicoeur (1999) manipulated the temporal interval between adjacent stimuli (Stimulus Onset Asynchrony, SOA) and found that lengthening SOA alleviated attentional blink due to reduced interference. Based on previous research, it is clear that controlling both SOA and single stimulus presentation duration can influence attentional blink. Summarizing the temporal parameters of stimulus presentation reveals that within the blink window, when SOA is held constant, the blink effect decreases as stimulus presentation duration increases; when presentation duration is fixed, the blink effect decreases as SOA increases. Additionally, research indicates that during stimulus material selection, attribute differences between target stimuli and surrounding distractors create varying blink magnitudes (Maki, Bussard, Lopez, & Digby, 2003), and when both belong to the same category, semantic concepts also affect blink size (Dux & Coltheart, 2005). Wang (2008) concluded that greater similarity between distractors and targets makes individuals more prone to attentional blink. Regarding attributes of targets within the blink window, Choi and Chang et al. (2012) modified the traditional paradigm by highlighting T2' s color and found that salient color marking of subsequent targets could reduce attentional blink. Subsequently, Luo and Zhao (2014) manipulated both color attribute consistency and category attribute consistency between the two targets in an RSVP paradigm and found that both attributes influence attentional blink. Moreover, increasing the intensity of T2’ s physical attributes can also affect attentional blink magnitude (Joo & Chong, 2013; Landau & Bentin, 2008). However, target attribute manipulation is not limited to the physical level but can extend to more ecologically meaningful modality attributes. Oliver and Van der Burg (2008) found that presenting T2 simultaneously through both visual and auditory channels also reduced attentional blink (Kranczioch & Thorne, 2015; Schneider, 2013). Similar findings exist at other sensory levels: Robinson, Mattingley and Judith (2013) manipulated target attributes across visual and olfactory channels and found that simultaneous presentation in both modalities improved target recognition, demonstrating that target modality attributes can influence attentional blink. Han and Zhao (2013) summarized that in RSVP paradigms, target stimuli with salient task-irrelevant attributes can capture substantial attention and cause temporal fluctuations in attention through data-driven processing.

When individuals exchange information with the external environment, the human brain perceives information input from multiple sensory channels more acutely (Chen, Pan, & Wang et al., 2016; Ernst & Bülthoff, 2004; Frassinetti et al., 2002; Frens et al., 1995). To accomplish information search tasks more accurately in complex environments, individuals can integrate information from different sensory channels into a coherent, meaningful representation (Koelewijn, Bronkhorst, & Theeuwes, 2010). This brain function for processing information across sensory systems is called Multisensory Integration (MSI, Beauchamp et al., 2004; Lewkowicz & Ghazanfar, 2009; Talsma et al., 2010), which involves the interaction and integration of information from different sensory channels into a unified, coherent, stable, and meaningful perceptual process (Ernst & Bülthoff, 2004; Jong et al., 2009; Spence, 2007; Stein & Stanford, 2008; Tang, Wu, & Shen, 2016; Wen et al., 2009). Multisensory integration can reduce perceptual system noise and lower perceptual thresholds by fitting information from each channel (Lovelace, Stein, & Wallace, 2003), enabling individuals to better perceive stimulus information. Behaviorally, this manifests as more accurate and faster judgments for stimuli containing multichannel information (Sun et al., 2011).

Meredith, Nemitz and Stein (1987) noted that under certain conditions, multisensory suppression effects can occur, where monitoring multiple sensory channels at single or dual locations is slower than monitoring a single channel (Santangelo, Fagioli, & Macaluso, 2010). However, most current integration research focuses on explaining and exploring facilitation effects. Multisensory Performance Improvement Effects refer to the phenomenon where replacing multiple modality-consistent information sources with a single source reduces cognitive load caused by processing redundant information, thereby facilitating information processing across multiple channels, such as the Redundant Signal Effect (RSM, Miller, 1982). Early explanations for this effect included two competing hypothetical models (Miller, 1986). The Independent Activation Model (also called the Race Model) posited that multichannel information is processed in separate channels, with the first channel to complete processing triggering a response and thus improving reaction speed (Raab, 1962). In contrast, the Co-activation Model proposed that information from multiple channels converges and fuses into common perceptual information at a specific stage, increasing stimulus intensity and resulting in more efficient responses (Giray & Ulrich, 1993; Gondan et al., 2005; Miller, 1982). However, due to the complexity and uncertainty of real-world information, this facilitation phenomenon in the human brain may exist both between different channels and within the same channel across different pieces of information (Knill & Saunders, 2003; Van der Kooij et al., 1999), making it difficult to programmatically calculate optimal integration patterns.

Later researchers proposed the Bayesian decision model, which better explains integration facilitation effects—the human brain' s perception of environmental stimuli is purposeful, and its processing tends to follow a principle of maximizing benefits (Ermst & Bulthoff, 2004; Yuille & Bulthoff, 1993; Liu, Zhang, Wang, & Zhang, 2008). In terms of real-world applicability, the Redundant Signal Effect has received more attention from researchers compared to other forms of multisensory integration.

In daily life, it is evident that multisensory integration influences attention orientation, concentration, and arousal levels, while active attentional control can conversely regulate the degree of multisensory integration. Both attention and sensory integration facilitate efficient information processing, exhibit multistage complexity, and involve intricate interactive mechanisms (Peng, Chang, Ren, Wang, & Tang, 2018). While multisensory integration improves attentional resource utilization, autonomous processing that violates principles can also produce detrimental attentional effects. From the perspective of multisensory illusions, several common illusion phenomena serve as examples. The McGurk effect is a common illusion in human speech perception; when visual and auditory source information conflict, visual information can interfere with auditory detection under certain conditions (Luo, Kang, & Zhou, 2018), preventing focused attention input. The ventriloquism effect is a typical example of visual dominance influencing auditory detection, causing attentional orientation biases toward auditory information sources (Kitagawa & Ichihara, 2002). The double-flash illusion is an integration illusion where audition dominates vision, causing attention to prioritize auditory information and creating biases in visual information processing that impair accurate visual judgments (Yu, Wang, & Zhang, 2017).

Although multisensory integration can create obstructive illusions under certain conditions, it generally facilitates attentional processing. Analyzing the most common audiovisual integration facilitation phenomenon reveals that audiovisual integration can capture attention and improve attentional orientation and search efficiency through both top-down and bottom-up driven mechanisms (Tang, Wu, & Shen, 2016). Matusz and Eimer (2011) manipulated the modality attributes of cue stimuli in a spatial cue-target paradigm and found that audiovisual cues captured more attentional resources, enabling more accurate prediction of subsequent targets and improving attentional orientation, demonstrating that audiovisual integration can modulate and influence attentional orientation (Krause et al., 2012; Mahoney et al., 2012; Mast et al., 2015). Van der Burg et al. (2008) manipulated target modality attributes in an audiovisual search paradigm and found that task-irrelevant sounds accompanying target stimuli significantly improved search speed, showing that audiovisual integration can also affect attentional search efficiency (Pluta et al., 2011; Van der Burg et al., 2011). This effect is not limited to selective attention; audiovisual integration can also influence sustained attention. Researchers using the classic RSVP paradigm found that synchronously presenting auditory stimuli when T2 appeared alleviated the traditional attentional blink phenomenon (Olivers & Van der Burg, 2008), demonstrating that audiovisual integration can facilitate recognition efficiency during sustained attention (Kranczioch & Thorne, 2013; Kranczioch & Thorne, 2015).

Multisensory integration can affect attention under specific conditions, and numerous studies also indicate that attention reciprocally influences multisensory integration (Talsma & Woldorff, 2005). Active attentional regulation affecting multisensory integration can be broadly categorized into two approaches: modulating integration strength through spatial attentional orienting and modality-selective attention (Tang, Wu, & Shen, 2016). Spence (2001) found that when attention was actively allocated to a spatial discrimination task, participants judged audiovisual targets at attended locations more rapidly, indicating that spatially-based active attention can influence multisensory integration (Fairhall & Macaluso, 2009; Li, Wu, & Touge, 2010). When attention is focused on a specific modality, perception of information in that modality is enhanced. Talsma, Doty and Woldorff (2007) found that when participants directed attention to both auditory and visual channels, their responses to audiovisual stimuli were more accurate than when attending to a single channel, demonstrating that controlling attentional modality can also influence multisensory integration. Wilschut, Theeuwes and Olivers (2011) subsequently noted that at the cognitive processing level, the attention system comprises two major components: orienting (spatial dimension) and modality selection (modality dimension). Subsequent research has confirmed that attention can be directed not only to spatial locations but also to sensory modalities (Talsma & Durk, 2015). Based on modality-selective attention, Yu et al. (2017) used the sound-induced flash illusion paradigm to investigate how different attention allocation methods affect the illusion, finding that attention directed to different modalities influences integration effects and consequently affects the flash illusion. Tang et al. (2019) used a spatial cue-target paradigm to examine how attention directed to different modalities affects spatial orienting to audiovisual targets. Results showed that compared to attending only the visual channel, bimodal attention reduced the amount of inhibition of return produced by audiovisual targets, indicating stronger audiovisual integration ability and demonstrating that controlling attentional modality can regulate audiovisual integration quantity and consequently affect attentional phenomena (Gu, 2016; Tang, Sun, & Peng, 2020). Thus, controlling modality attention to regulate multisensory integration and influence attentional phenomena has been confirmed at both attentional orienting and discrimination levels. In summary, individuals can actively control attention to influence multisensory integration effects under specific conditions.

Previous research has confirmed that audiovisual integration can facilitate selective attention performance in the spatial dimension (attentional orienting) (Krause et al., 2012; Mast et al., 2015; Matusz & Eimer, 2011), but exploration of audiovisual integration's effect on divided attention in the temporal dimension (attentional blink) remains largely unexplored. Although Oliver and Van der Burg (2008) investigated this relationship using the RSVP paradigm by manipulating sound presentation location and found that synchronous audiovisual presentation of T2 could reduce attentional blink—attributing this phenomenon to audiovisual enhancement—these studies only considered that audiovisual targets might cause sensory integration and capture more attention, while overlooking that stimulus salience can also promote attentional capture. Research indicates that stimuli sufficiently unique and salient in a particular dimension (Singletons) can significantly capture attention (Becker & Horstmann, 2011; Theeuwes, 2013), and this capture phenomenon exists not only in physical attributes at the visual level, such as stimulus color (Choi & Chang, 2012) or shape (Luo & Zhao, 2014), but also in stimulus information modality attributes. Vroomen and De Gelder (2000) added different synchronous sounds to continuous visual search sequences and found that when a novel, salient feature singleton existed in the auditory channel, this auditory stimulus facilitated visual target recognition in the short sequence, demonstrating that salient feature singletons at the auditory level can significantly capture attention. Therefore, previous research exploring audiovisual integration' s effect on attentional blink did not strictly control for novelty in auditory channel attributes, failing to adequately demonstrate that synchronous sound facilitation of visual search results from enhanced audiovisual integration. In visual attentional blink research, is attentional capture by sounds synchronized with T2 in the blink window purely caused by audiovisual integration? If we can exclude the above factors and confirm that blink reduction is indeed caused by audiovisual integration, will this blink reduction phenomenon be influenced by the magnitude of audiovisual integration? Therefore, this study conducted two experiments to explore the effect of audiovisual integration on attentional blink. Experiment 1 used the traditional RSVP paradigm, manipulating stimulus modality attributes to more thoroughly examine whether audiovisual integration can affect visual attentional blink after excluding sound salience factors, and aimed to replicate previous findings under similar conditions. Experiment 2 built upon Experiment 1 by adding an auditory channel task to control attention allocation across modalities, exploring how different integration strengths affect attentional blink. Based on previous research, we expected to observe the traditional attentional blink phenomenon in this study, and that audiovisual integration could reduce attentional blink effects, with this reduction being independent of sound salience. Additionally, in Experiment 2, we anticipated that distributing attention to both modalities would enhance integration ability, and that audiovisual integration' s attenuating effect on attentional blink would consequently strengthen.

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2. Experiment 1: The Effect of Audiovisual Integration on Attentional Blink Under Visual Modality-Focused Attention

2.1 Method

(1) Participants

Using G*Power 3.1 to calculate required sample size based on statistical power analysis, Experiment 1 required 28 participants. We ultimately recruited 40 undergraduate or graduate students from a university, aged 19-28 years. All participants had normal or corrected-to-normal vision and hearing, were right-handed, in good health with no history of brain injury or mental illness, and had not previously participated in similar psychology experiments. Participants received modest compensation after completing the experiment. Since this experiment aimed to investigate the effect of audiovisual integration on attentional blink under visual focused attention, we excluded 4 participants who showed no attentional blink phenomenon. The final valid sample consisted of 36 participants (18 male, 24 female) with a mean age of 20.83 ± 2.01 years.

(2) Apparatus and Materials

All visual stimuli were presented on a Dell E2316Hf 19-inch monitor with a resolution of 1280$×1024andarefreshrateof60Hz.Participantswerepositionedapproximately80cmfromthescree
192, 192, 192).Theexperimentalprogramwaswrittenanddatawerecollectedusing E−
Prime1.1runningonMicrosoftWindows7.Visualstimuli, referencingOliversandVanderBurg(2008), werepr
Auditory materials were created using Adobe Audition 3.0 as 75 dB pure tones generated from sine waves (1259 Hz), lasting 50 ms and presented synchronously with visual stimuli. Sounds were played through an external speaker (PHILIPS SPA311) placed behind the monitor center. According to participants' verbal reports, they could clearly identify that the sound originated from the central position.

(3) Design and Procedure

This experiment used a 3 (sound condition: no sound vs. single tone at T2 vs. tone throughout) × 3 (Lag condition: Lag1 vs. Lag2 vs. Lag5) within-subjects design. The experiment included 9 conditions: no sound Lag1, no sound Lag2, no sound Lag5, single tone Lag1, single tone Lag2, single tone Lag5, tone throughout Lag1, tone throughout Lag2, and tone throughout Lag5. Each condition comprised 48 trials, totaling 432 trials. Trials were presented in randomized blocks, with block order counterbalanced across participants, and all conditions were fully randomized.

The experimental procedure is illustrated in Figure 1 [Figure 1: see original paper]. Each trial began with a 1000 ms central fixation cross, which participants were instructed to fixate. This was followed by a rapid stream of 23 elements, each consisting of four screens (stimulus presentation 67 ms + blank screen 33 ms + mask 50 ms + blank screen 100 ms). The next stimulus appeared 250 ms after each stimulus presentation. After the RSVP stream, three questions appeared at screen center: Q1: "What was the first letter you saw? Press the corresponding key" ; Q2: "What was the second letter you saw? Press the corresponding key" ; and Q3: "Judge the sound you heard: high tone press 1, low tone press 0, no sound press 9." Participants responded via keypress without time pressure, and response accuracy was recorded. Sound stimuli synchronized with visual stimuli were presented randomly, and participants were instructed to ignore the sounds. Before the experiment, participants adjusted a chinrest and table height to align their gaze with screen center and read standardized instructions. The practice phase included 36 trials covering all experimental conditions (randomly presented). The experimenter accompanied participants during practice to ensure clear understanding and correct task performance. Total experiment duration was approximately 90 minutes (including practice and breaks).

(4) Data Analysis

Data were processed and analyzed using E-Prime 1.1 and Microsoft Office Excel Professional Plus 2016. Statistical analyses were conducted using IBM SPSS Statistics 21 and JASP 0.11.1.0.

Two dependent variables were analyzed: T1 accuracy (probability of correctly identifying the first target) and T2/T1 accuracy (probability of correctly identifying the second target given correct T1 identification). After calculating T1 and T2/T1 accuracy, we conducted a one-way ANOVA on T1 accuracy with sound condition (no sound vs. single tone at T2 vs. tone throughout) as the factor to examine the main effect of sound condition and compare differences between conditions. For T2/T1 accuracy, we conducted a 3 (sound condition) × 3 (Lag condition) repeated-measures ANOVA to examine main effects and interactions, followed by simple effects analysis to compare differences between sound conditions. Following Martens and Wyble' s (2010) index for measuring AB (accuracy differences between temporal windows), we conducted a one-way ANOVA on AB magnitude across different sound conditions.

2.2 Results and Analysis

Overall T1 accuracy was 88.64%. A one-way ANOVA on T1 accuracy (sound condition: no sound vs. single tone at T2 vs. tone throughout) revealed no significant effect of sound, $F(2, 105) = 0.59$, $p = 0.55$, $p^2 = 0.01$, indicating that task-irrelevant auditory stimuli did not affect accuracy on the first task.

Overall T2/T1 accuracy was 88.29%. A 3 (sound condition) × 3 (Lag condition) repeated-measures ANOVA on T2/T1 accuracy (see Figure 2 [Figure 2:

see original paper]) revealed a significant main effect of sound condition, F(2, 70) = 12.70, $p < 0.001$, $p^2 = 0.27$, indicating that different sound conditions affected T2 judgment accuracy (i.e., attentional blink). Pairwise comparisons showed that T2/T1 accuracy in the no-sound condition (85.35%) was significantly lower than in both the single-tone-at-T2 condition (90.59%) and the tone-throughout condition (88.92%), demonstrating that presenting a sound synchronously with T2 (relative to no sound) improved T2 recognition accuracy and alleviated attentional blink.

The main effect of Lag was significant, F(1.181, 41.350) = 40.73, $p < 0.001$, $p^2 = 0.54$, indicating that different T2-to-T1 lag positions affected T2 judgment accuracy. Pairwise comparisons revealed that T2/T1 accuracy at Lag5 (95.21%) was significantly higher than at Lag2 (91.98%) and Lag1 (77.67%), confirming the classic attentional blink phenomenon in this experiment—T2 judgment accuracy in the RSVP paradigm increased with distance from T1.

The sound × Lag interaction was significant, F(2.812, 98.425) = 23.98, $p < 0.001$, $p^2 = 0.41$, indicating that synchronous T2 sounds and T2 lag position jointly affected T2 judgment accuracy. Simple effects analysis revealed that at Lag1, the sound effect was significant, F(2, 70) = 29.89, $p < 0.001$, $p^2 = 0.46$, with T2/T1 accuracy in the no-sound condition (68.37%) significantly lower than in both sound conditions (82.84% and 81.81%), which did not differ significantly from each other. This indicates that at Lag1, synchronous T2 sounds improved judgment accuracy regardless of sound salience. At Lag2, the sound effect was not significant, F(2, 70) = 1.36, $p = 0.26$, $p^2 = 0.04$, with no significant differences across sound conditions, indicating no statistically significant effect of sound on T2 recognition at Lag2. At Lag5, the sound effect was significant, F(2, 70) = 3.98, $p = 0.02$, $p^2 = 0.09$, with T2/T1 accuracy in the tone-throughout condition (93.81%) significantly lower than in the no-sound condition (96.24%), indicating that non-salient T2-synchronous sounds interfered with T2 recognition at Lag5.

Finally, using the accuracy difference between T1 and T2/T1 at pre- and post-blink windows (AB magnitude) as the dependent variable and sound condition as the independent variable, a one-way ANOVA (see Figure 3 [Figure 3: see original paper]) revealed a significant main effect of sound condition, F(2, 105) = 9.71, $p < 0.001$, $p^2 = 0.16$, indicating that different sound conditions produced different attentional blink magnitudes under selective attention. Multiple comparisons showed that AB in the no-sound condition was significantly larger than in both sound conditions, which did not differ significantly. In short, this demonstrates that sounds synchronized with T2 reduce attentional blink within the blink window, regardless of sound salience.

3. Experiment 2: The Effect of Audiovisual Integration on Attentional Blink Under Bimodal Divided Attention

Experiment 1 demonstrated that audiovisual integration from visual stimuli and task-irrelevant auditory information indeed affects attentional blink. This suggests that audiovisual integration settings and regulation should become a control factor in future research on attentional blink limitations, effectively improving individuals' blind phenomenon in the blink window and achieving better alleviation and control. How can we maximize the use of audiovisual integration function to reduce or even eliminate attentional blink? In other words, will differences in audiovisual integration strength produce varying degrees of impact on attentional blink?

Mudrik, Faivre and Koch (2014) noted that most meaningful sensory integration phenomena require conscious participation, and that unconscious integration can lead to erroneous perception, while attention-induced consciousness can eliminate illusion phenomena (Palmer & Ramsey, 2012). Mittag et al. (2013) indicated that distributing attention across modalities can enhance redundant signal effects. Previous research has also found that divided attention can strengthen audiovisual integration, making audiovisual targets more easily perceived in visual tasks (Van der Burg et al., 2011). Since audiovisual integration can reduce attentional blink, can we further attenuate blink by controlling attentional modality allocation to increase integration capacity? The Biased Competition Model also proposes that attentional bias enhances sensory neural responses to selected information (Mishra, Bavelier, & Gazzaley, 2012). Theoretically, allocating attention to both modalities should further enhance integration' s impact on blink. Therefore, we designed a second experiment that added an auditory task to distribute attention across both modalities, investigating whether increased audiovisual integration strength under these conditions could more effectively reduce attentional blink.

3.1 Method

(1) Participants

Using G*Power 3.1 to calculate required sample size, Experiment 2 required 36 participants. We recruited 39 undergraduate or graduate students from a university, aged 19-28 years. All participants had normal or corrected-to-normal vision and hearing, were right-handed, in good health with no history of brain injury or mental illness, and had not previously participated in similar experiments. Participants received modest compensation after completing the experiment. Since this experiment aimed to investigate the effect of audiovisual integration on attentional blink under bimodal divided attention, we excluded 3 participants who showed no attentional blink phenomenon. The final valid sample consisted of 36 participants (12 male, 24 female) with a mean age of 20.75 ± 2.61 years.

(2) Apparatus and Materials

The apparatus was identical to Experiment 1, and visual and auditory stimuli from Experiment 1 were used with the following modifications. Experiment 2 added another sound: a 75 dB pure tone generated from a sine wave (300 Hz), lasting 50 ms and presented synchronously with visual stimuli through the same external speaker (PHILIPS SPA311) placed behind the monitor center. According to participants' verbal reports, they could clearly identify that the sound originated from the central position. The sound from Experiment 1 was defined as high-pitched, and the new sound added in Experiment 2 was defined as low-pitched.

(3) Design and Procedure

This experiment used a 2 (sound condition: no sound vs. single tone at T2) × 3 (Lag condition: Lag1 vs. Lag2 vs. Lag5) within-subjects design. The experiment included 6 conditions: no sound Lag1, no sound Lag2, no sound Lag5, single tone Lag1, single tone Lag2, and single tone Lag5. Each condition comprised 48 trials, totaling 288 trials. All conditions were presented in fully randomized order.

The experimental procedure is illustrated in Figure 4 [Figure 4: see original paper]. Each trial began with a 1000 ms central fixation cross, which participants were instructed to fixate. This was followed by a rapid stream of 23 elements, each consisting of four screens (stimulus presentation 67 ms + blank screen 33 ms + mask 50 ms + blank screen 100 ms). The next stimulus appeared 250 ms after each stimulus presentation. After the RSVP stream, three questions appeared at screen center: Q1: "What was the first letter you saw? Press the corresponding key" ; Q2: "What was the second letter you saw? Press the corresponding key" ; and Q3: "Judge the sound you heard: high tone press 1, low tone press 0, no sound press 9." Participants responded via keypress without time pressure, and response accuracy was recorded. Sound stimuli synchronized with visual stimuli were presented randomly, and participants were instructed to attend to sound pitch. Before the experiment, participants read standardized instructions. The practice phase included 24 trials covering all experimental conditions (randomly presented). The experimenter accompanied participants during practice to ensure clear understanding and correct task performance. Total experiment duration was approximately 60 minutes (including practice and breaks).

(4) Data Analysis

Data were processed and analyzed using E-Prime 1.1 and Microsoft Office Excel Professional Plus 2016. Statistical analyses were conducted using IBM SPSS Statistics 21 and JASP 0.11.1.0.

Data were first preprocessed by using Q3 responses to exclude trials where participants failed to correctly attend to the auditory task. As in Experiment 1, two dependent variables were analyzed: T1 accuracy and T2/T1 accuracy. After calculating T1 and T2/T1 accuracy, we conducted an independent samples t-test on T1 accuracy (sound condition: no sound vs. single tone at T2) to examine whether different sound conditions were significant. For T2/T1 accuracy, we conducted a 2 (sound condition) × 3 (Lag condition) repeated-measures ANOVA to examine main effects and interactions, followed by simple effects analysis. Following Martens and Wyble' s (2010) index for measuring AB, we conducted a paired samples t-test on AB magnitude across different sound conditions.

Finally, after analyzing both experiments using the same methods, we compared results to investigate differences in how audiovisual integration affects attentional blink under visual focused versus bimodal divided attention. To prevent data instability from affecting results, we conducted Bayesian tests following t-tests in both experiments (Kruschke & Liddell, 2017; Hu et al., 2018; Lü, 2012).

3.2 Results and Analysis

Based on Q3 responses, auditory judgment task accuracy was 96.36%. A paired samples t-test on T1 accuracy (sound condition: no sound vs. single tone at T2) revealed no significant difference between conditions, $t(35) = 0.10$, $p = 0.92$, Cohen' s $d = 0.02$. Specifically, T1 accuracy in the no-sound condition (88.75%) and single-tone-at-T2 condition (88.67%) did not differ significantly, indicating that task-irrelevant sounds did not affect accuracy on the first task.

A 2 (sound condition) × 3 (Lag condition) repeated-measures ANOVA on T2/T1 accuracy (see Figure 5 [Figure 5: see original paper]) revealed a significant main effect of sound condition, $F(1, 35) = 12.06$, $p < 0.001$, $p^2 = 0.26$, indicating that different sound conditions affected T2 recognition accuracy (i.e., attentional blink). Pairwise comparisons showed that accuracy in the single-tone-at-T2 condition (90.17%) was significantly higher than in the no-sound condition (82.93%), demonstrating that presenting a sound synchronously with T2 improved T2 recognition accuracy and alleviated attentional blink.

The main effect of Lag was significant, $F(1.645, 57.560) = 29.37$, $p < 0.001$, $p^2 = 0.46$, indicating that different T2-to-T1 lag positions affected T2 judgment accuracy. Pairwise comparisons revealed that accuracy at Lag1 (78.65%) was significantly lower than at Lag2 (88.87%) and Lag5 (92.21%), confirming the classic attentional blink phenomenon—T2 judgment accuracy in the RSVP paradigm increased with distance from T1.

The sound × Lag interaction was significant, $F(1.678, 58.745) = 11.52$, $p < 0.001$, $p^2 = 0.25$, indicating that synchronous T2 sounds and T2 lag position interactively affected T2 recognition accuracy. Simple effects analysis revealed that at Lag1, the sound effect was significant, $F(1, 35) = 15.78$, $p < 0.001$, $p^2 = 0.31$, with accuracy in the no-sound condition (71.36%) significantly lower than in the single-tone-at-T2 condition (85.94%), indicating that synchronous T2 sounds improved judgment accuracy at Lag1. At Lag2, the sound effect was also significant, $F(1, 35) = 7.37$, $p = 0.01$, $p^2 = 0.18$, with accuracy in the single-tone-at-T2 condition (92.10%) significantly higher than in the no-sound condition (85.94%), indicating that synchronous T2 sounds also significantly improved judgment accuracy at Lag2. At Lag5, the sound effect was not significant, $F(1, 35) = 0.10$, $p = 0.75$, $p^2 = 0.00$, with no significant difference between sound conditions, indicating that synchronous T2 sounds did not affect T2 judgment accuracy at Lag5.

As in Experiment 1, we conducted a paired samples t-test on AB magnitude (accuracy difference between T1 and T2/T1 at Lag) with sound condition as the independent variable (see Figure 6 [Figure 6: see original paper]). Results showed that under divided attention conditions, different sound conditions produced different attentional blink magnitudes, $t(1,35) = 4.13$, $p < 0.001$, Cohen' s $d = 0.69$, 95% CI = [7.46, 21.86]. In short, this demonstrates that sounds synchronized with T2 alleviate attentional blink within the blink window.

Comparative analysis of T2/T1 at Lag1 and T1 accuracy across conditions in both experiments (see Figure 7 [Figure 7: see original paper]) revealed that in Experiment 1, a paired samples t-test between T1 and T2/T1 at Lag1 showed $t(1,35) = 2.55$, $p = 0.02$, Cohen' s $d = 0.43$, 95% CI = [1.20, 10.52], indicating that attentional blink was reduced but not eliminated when ignoring sounds under single-tone-at-T2 conditions. To exclude potential effects of individual differences or data instability, Bayesian analysis confirmed BF10 3.0, more rigorously demonstrating a significant difference between the two data sets. In Experiment 2, the same analysis between T1 and T2/T1 at Lag1 showed $t(1,35) = 1.643$, $p = 0.11$, Cohen' s $d = 0.27$, indicating that attentional blink disappeared when actively attending to sounds under single-tone-at-T2 conditions.

4. Discussion

This study used two experiments to examine the effect of audiovisual integration on attentional blink and, by controlling attention allocation and orientation, identified methods that more significantly alleviate attentional blink. Both experiments employed the classic RSVP paradigm, controlling the modality of information presented in the stimulus stream and requiring participants to accurately complete target identification tasks according to instructions. Experiment 1' s results demonstrated, after excluding sound salience as a confounding factor, that audiovisual integration can reduce attentional blink. Specifically, when the second target to be identified was synchronized with a sound stimulus, the accuracy reduction caused by blink significantly improved, and the same phenomenon occurred when every visual stimulus was accompanied by a sound. Based on multiple interactions between attention and multisensory integration (Tang, Wu, & Shen, 2016) and the biased competition model (Mishra, Bavelier, & Gazzaley, 2012), Experiment 2 manipulated attentional focus versus division by adding an auditory channel task. Results showed that when auditory channel information was actively processed, enhanced audiovisual integration effects more obviously reduced attentional blink, with no statistically significant difference in accuracy between the two targets—indicating that when attention was distributed across both modalities, increased audiovisual integration modulation more significantly reduced this limitation in continuous attention.

Through Experiment 1’ s data analysis, we first observed the traditional visual attentional blink phenomenon under no-sound conditions: when T2 appeared within 250 ms after T1, participants’ T2 recognition accuracy significantly decreased, consistent with numerous previous visual attentional blink studies (Chen & Wang, 2012; Dux & Marois, 2009; Stein, Peelen, Funk & Seidl, 2010). Under single-tone-at-T2 conditions, we observed similar phenomena to previous studies: within the original blink window, synchronizing T2 presentation with a sound improved recognition accuracy (Kranczioch & Thorne, 2015; Olivers & Van der Burg, 2008; Yasuhiro, Jiro, & Katsumi, 2014). Since novelty in stimulus modality attributes may also cause attentional capture (Robinson, Mattingley, & Judith, 2013), this study designed a tone-throughout condition. Results showed that both tone-throughout and single-tone-at-T2 conditions produced significantly higher accuracy for audiovisual targets in the original blink window compared to the no-sound condition, with no significant difference between the two sound conditions. This demonstrates that regardless of sound salience, synchronizing sound with visual stimuli improves visual target recognition efficiency, more fully indicating that audiovisual integration indeed affects attentional blink. This also verifies that audiovisual integration can enhance stimulus salience (Stein et al., 1996), triggering bottom-up stimulus-driven processing (Matusz & Eimer, 2011) that captures attention even when attentional resources are relatively insufficient, thereby alleviating the efficiency reduction caused by attentional blink.

Notably, in this experiment, opposite accuracy changes occurred between no-sound and tone-throughout conditions at Lag1 versus Lag5. This may be due to task settings. Compared to the no-sound condition, the tone-throughout condition at Lag1 showed increased accuracy due to audiovisual integration, consistent with previous research and theoretical explanations (Olivers & Van der Burg, 2008; Yasuhiro, Jiro, & Katsumi, 2014). The reversal at Lag5 may be because as the distance between targets increased, the interference effect of intermediate distractors also increased (Zhang & Wang, 2009), causing participants to form integrated elements before T2 that also intensified attentional investment, reducing recognition ability for subsequent targets.

In Experiment 2, statistical analysis also revealed the traditional attentional blink phenomenon under no-sound conditions. Under bimodal divided attention control, the single-tone-at-T2 condition also showed improved accuracy for audiovisual targets in the blink window, with no statistically significant difference in recognition accuracy between the two targets—indicating that when attention was divided across modalities, audiovisual integration’ s modulatory effect on attentional blink strengthened. Many previous studies have also shown interactive relationships between audiovisual integration and attention (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Experiment 2’ s results support and enrich this complex interactive processing mechanism, confirming that integration affects not only selective attention but also applies to divided attention research. In the RSVP paradigm, the rapid presentation of numerous stimuli creates high competition levels between stimuli, and when this competitive relationship is strong, attention affects audiovisual integration (Van Ee, Van Boxtel, Parker, & Alais, 2009). Previous conclusions from bimodal attention research indicate that when targets possess both visual and auditory attributes, audiovisual integration forms and increases perceptual saliency for target judgment, making the target more prominent in visual tasks (Van der Burg et al., 2011). Therefore, when attention is distributed across both modalities, integration caused by audiovisual targets increases, manifesting in the experiment as significantly reduced or eliminated attentional blink.

Furthermore, from the perspective of attentional blink theories, this experiment' s results also validate the phenomenon where accuracy in blink window tasks does not decrease but instead increases under divided attention states (Dale & Arnell, 2010). The results also have implications for theoretical explanations of attentional blink. Although attentional blink is a malleable attentional phenomenon (Müsch et al., 2012), its occurrence can be explained from both resource allocation and limited resource perspectives (Luo & Zhao, 2014). Resource depletion theory posits that excessive attentional central resource consumption during T1 processing leaves insufficient resources for T2 processing within a certain window, causing attentional blindness. Such limited resource theories all demonstrate resource trade-offs between T1 and T2 (Zhang & Wang, 2009). In this study, compared to T1, audiovisual T2 triggered audiovisual integration that may have lowered its perceptual threshold, enabling T2 processing even when cognitive resource allocation was insufficient. This can also be understood from a resource competition allocation perspective (Shapiro, Schmitz, et al., 2006): increased T2 intensity occupies more resources and enhances processing capacity. In this experiment, T2' s bimodal attributes enabled integrated processing in central resources, occupying more resources and receiving further processing.

However, this study differs from previous research in that attentional blink was only observed at Lag1. This may be due to cross-cultural sensitivity differences in experimental materials—participants in this study, due to different native language environments, may have allocated more attention to cognitive processing of individual stimuli. According to the overinvestment hypothesis (Olivers & Nieuwenhuis, 2006), resource investment exceeding the resource threshold causes interference processing in subsequent longer temporal windows to not reach consciousness threshold (Arend, Johnston, & Shapiro, 2006), resulting in a shortened attentional blink window. Another possibility is that given individual differences in visual attentional blink (Chen et al., 2014), this experiment used more participants and substantially more trials than previous studies. Fecteau and Munoz (2003) noted that individual behavioral performance in experiments is affected by recent events and tasks, which may cause participants to gradually adapt to the current task as trials increase, leading to shorter attentional blink duration.

Comparative analysis of both experiments revealed that at the point of most pronounced blink (T2 at Lag1), the ability of T2-synchronous sounds to reduce attentional blink differed: compared to visual focused attention conditions (ignoring auditory sounds and attending only to visual letters), bimodal divided attention conditions (actively attending to both visual letters and auditory sounds) produced enhanced audiovisual integration effects that eliminated attentional blink. This difference supports the biased competition model hypothesis (Mishra, Bavelier, & Gazzaley, 2012)—shifting attention to both modalities enhances sensory neural responses to selected channel information (Beck & Kastner, 2009), increasing audiovisual integration effects and making recognition accuracy for both targets equivalent in the blink window, thereby eliminating attentional blink. Moreover, stronger integration ability when attending to both modalities also validates the limited resource shared mechanism across channels —when visual system resources are insufficient, shared perceptual attention resources across modalities can be released to the auditory system for integrated processing (Haroush, Deouell, & Hochstein, 2011). Although both experiments showed similar trends in target judgment accuracy (see Figure 10 [Figure 10: see original paper]), some specific data points still differed. Specifically, Experiment 1 showed accuracy increases at larger Lags compared to Experiment 2. This difference may be due to randomization of experimental conditions. Because Experiment 1 needed to exclude sound salience as an interfering factor, its presentation method was adjusted to a block design, whereas Experiment 2 used the more common fully randomized presentation. As mentioned previously regarding trial history effects (Maljkovic & Nakayama, 1994), Experiment 1 participants became more familiar with the current block' s stimulus presentation pattern, causing accuracy increases and leading to minor differences between experiments.

This study summarized that audiovisual integration can attenuate attentional blink and that controlling attentional modality can affect integration effects to further modulate attentional blink to varying degrees. This finding lays a foundation for subsequent research on how to regulate limitations in sustained temporal attention processing. In summary, this study not only confirms previous conclusions that audiovisual integration can reduce attentional blink but also further explores the interaction between the two under attentional allocation control. This research establishes a solid theoretical foundation for subsequent detailed investigations and provides indispensable theoretical support for exploring attention, cognition, and brain networks. However, the ultimate purpose of any research is to apply theoretical foundations to real-life applications. Based on this study' s findings, the objective laws of how audiovisual integration affects attentional blink have good reference value for many fields. In the 21st century of increasing population aging, these regularities can be used for simulation training to prevent and improve perceptual function decline in older adults and enhance their quality of life. These principles can also be applied to traffic psychology, such as driving safety, ergonomic design of in-vehicle indicator lights, and traffic signal design to maximize driving safety. Moreover, as national education departments continuously promote information technology reform in education, multimedia teaching has been widely introduced into classrooms. Integrating these principles with student attention span development patterns and integration effects into teaching software systems can also improve teaching quality and learning efficiency. On the other hand, the objective laws and alleviation measures discovered in this experiment can also assist in athlete selection and provide scientific basis for perceptual control training settings for special populations with attention deficit disorders. This study also has limitations. Visual attentional blink is a common inhibitory phenomenon of visual selective attention in the temporal dimension, with mechanisms different from previous spatial dimension research. However, the stage at which audiovisual integration occurs in sustained attention remains to be further investigated. Future research could use event-related potential techniques to explore the timing of this phenomenon in detail.

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5. Conclusions

1. Audiovisual integration can modulate attentional blink phenomena.
2. Audiovisual integration can reduce attentional blink under unimodal visual focused attention.
3. Audiovisual integration ability is enhanced under bimodal divided attention, more significantly reducing attentional blink.

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