Collision Narrows the Temporal Binding Window of Multisensory Integration

Jun Wang[1,2], Jiahao Lu[1,2], Xiahui Zhang[3], Lei Jia[1,2], and Cheng Wang[1,2]

[1] Department of Psychology, Zhejiang Normal University, Jinhua 321004, China

[2] Key Laboratory of Intelligent Education Technology and Application of Zhejiang Province, Zhejiang Normal University, Jinhua 321004, China

[3] Shanghai Zhongshan Junior High School, Hongkou District, Shanghai 200434, China

ABSTRACT

Collision is usually accompanied by a sound (e.g., a car crash) and thus inherently involves multisensory integration. To date, most studies on collision have focused on the visual modality. Here, we combined the classic launching effect paradigm and the simultaneity judgment task to investigate how collision affects multisensory integration. The unity assumption theory predicts that collision should extend the temporal binding window (TBW) of multisensory integration because of causality perception induced by collision. Participants viewed a ball (the launcher) that moves toward a stationary ball (the target) until they collided (perceptual causality condition, PC), or were gapped by a short distance (visual angle: 2.4 °, non-perceptual causality condition, NPC), at which point the launcher stopped and the target started moving along the same path. A pure tone was presented at different stimulus onset asynchronies (-500-500 ms) with respect to the onset of the target moving. Participants were asked to judge whether the tone and the onset of the target moving (Experiment 1A) or the offset of the launcher moving (Experiment 1B) were simultaneous. Results showed that TBW was narrower in the PC than the NPC conditions, which was inconsistent with the unity assumption theory. In Experiment 2, this effect no longer existed when collision was controlled for. We suggest that the attention boost induced by collision rather than perception of causality, might be a key mediating factor for multisensory integration in the context of collision.

KEYWORDS

collision
multisensory integration
causality perception;
simultaneity judgment task
launching effect paradigm

INTRODUCTION

Collision is a natural phenomenon that happens daily. During our lives, we encounter countless collision events, from harmless ones like colliding billiards to dangerous events like car crashes. In psychological laboratories, researchers usually use the launching effect paradigm to create perception of collision (Hubbard, 2013; Michotte, 1963). In this paradigm, an object (the launcher) moves toward a stationary object (the target) until they collide, at which point the launcher stops and the target starts moving along the same path. As reported in Michotte's (1963) classic studies, observers perceive the launcher as being the cause of the target's motion. Thus far, most studies employing the launching effect paradigm focused only on collision in the visual modality (Hubbard, 2013; Michotte, 1963; Mitterer et al., 2010). However, in the real world, collision is usually accompanied by a sound of a clash. To fully make sense of a collision, perceivers need to integrate the visual collision and the sound into a unified percept. This integration process is called multisensory integration and it has been intensively studied (e.g., Powers et al., 2009; Stevenson et al., 2012; Zampini et al., 2005).

We perceive the multisensory world through different sense organs, each of which feeds inputs into our brain. To perceive the world in a meaningful and coherent way, our brain needs to determine which of the multiple sensory signals belong to the same source and then integrate them. A key clue we heavily rely on to achieve this goal is temporal proximity: integration is maximal when signals from different modalities are perceived as coming simultaneously (Lewald et al., 2001; Noppeney & Lee, 2018). One adaptive capacity of our brain is that it does not require perfect simultaneity, but can tolerate a certain degree of asynchrony to integrate multisensory inputs. This range of cross-modal asynchrony is usually called the temporal binding window (TBW). Researchers have used tools such as the simultaneity judgment task to assess the TBW of multisensory integration (Stevenson, Siemann, et al., 2014; Zampini et al., 2005). Only when asynchrony is within the TBW do cross-modal signals (relative to single-modality signals) result in enhanced neural or behavioral responses (Diederich & Colonius, 2004; Lewkowicz, 1996; Meredith et al., 1987). The width of the TBW is

Corresponding author: Cheng Wang, Department of Psychology, Zhejiang Normal University, #688 Yingbin Rd, Jinhua City, Zhejiang Province, China.
Email: wangc_psych@zjnu.edu.cn

DOI • 10.5709/acp-0345-9

regarded as a proxy for temporal precision of multisensory integration, with narrower TBWs representing higher precision (Stevenson et al., 2012; Zhou et al., 2021). Previous studies have revealed that the TBW of multisensory integration could be modulated by various top-down factors (for reviews, see Choi et al., 2018; Stevenson, Wallace, et al., 2014). In particular, attention has been found to enhance multisensory integration (Tang et al., 2016; Talsma et al., 2010; Talsma & Woldorff, 2005) and attention deficits could lead to reduced temporal precision of multisensory integration (Chan et al., 2015).

Collision inherently involves multisensory integration and induces a perception of causality. Previous work has demonstrated a link between multisensory percepts and causality perception. Using an action-effect task, Kawabe et al. (2013) reported that cross-modal delay between a key press (tactile action) and its visual effect hindered the action-effect causality perception. Furthermore, Schutz and Kubovy (2009) reported that the duration of the action gesture (e.g., beating on a drum) altered the perceived duration of the percussive sound produced by the gesture. This can be explained by the unity assumption theory (also called the causal inference model, Chen & Spence, 2017; Körding et al., 2007; Welch & Warren, 1980) which states that multisensory integration happens only when observers infer that two or more unisensory stimuli originate from the same cause or event. Schutz and Kubovy (2009) further explained that percussive sounds after visual gestures were inferred by the observers to be caused by the visual gesture, and hence be integrated with, and affected by, the visual impact. Another demonstration of the link between multisensory percepts and causality perception is the stream-bounce illusion, in which two identical disks approaching each other on a collision course can be seen as "bouncing off" (i.e., collision) or "streaming through" each other (Grove et al., 2016; Sekuler et al., 1997). However, a brief sound presented around the moment of coincidence would bias the percept toward "bouncing off." This bias indicates that the perceptual system infers, using prior experience, that the sound is caused by a collision (Grove et al., 2016; Zeljko & Grove, 2021). These studies suggest that multisensory percepts would affect the perceived causal relationship between cross-modal stimuli.

In the present study, we combined two classic experimental paradigms (the launch effect paradigm and the audiovisual simultaneity judgment task) to examine how collision affected multisensory integration. In Experiment 1, the participants viewed a ball (the launcher) that moved toward a stationary ball (the target) until they were adjacent, at which point the launcher stopped and the target started moving along the same path. Then, a pure tone was presented at different stimulus onset asynchronies (SOAs, −500–500 ms) with respect to the onset of the target moving. In the condition of perceptual causality (PC), the launcher collided with the target, while in the condition of non-perceptual causality (NPC), the launcher did not contact the target. The participants were asked to judge whether the tone and the onset of target movement were simultaneous. According to the unity assumption, as the sound was presented with the collision in the PC condition, observers would perceive the sound and the target movement as originating from the same cause (i.e., the collision), leading to a unitary multisensory percept of the collision, whereas in the NPC condition, no such unitary percept would be formed because the two balls did not contact. Because the brain can tolerate a certain degree of audiovisual asynchrony to ensure multisensory integration (Morein-Zamir et al., 2003; Spence & Squire, 2003), the tone and the onset of target movement separated with same SOA would be more likely to be perceived as being simultaneous in the PC than the NPC condition, resulting in longer TBW for simultaneity judgment in the PC condition. As perception of causality was manipulated via collision (two balls contacted or not), the two conditions in Experiment 1 differed with respect to not only the perception of causality but also the presence of collision. In Experiment 2, we designed the experiment such that the collision happened in both conditions while the perception of causality existed only in the PC condition, and tested how this manipulation would change the results.

EXPERIMENT 1

Experiment 1 tested how collision affected multisensory integration. We used the launching effect paradigm to create a perception of collision in combination with the audiovisual simultaneity task that was used to probe the TBW of multisensory integration (see Figure 1). In Experiment 1A, the participants were asked to judge whether the onset of The target moving and the tone were simultaneous; and in Experiment 1B, the task was to judge whether the offset of the launcher moving and the tone were simultaneous. Because the offset of the launcher moving and the onset of the target moving were at the same time, we expected the results of Experiments 1A and 1B to be similar.

Methods

PARTICIPANTS

We conducted an a priori power analysis using G*Power (Faul et al., 2007) to determine the necessary sample size. This analysis (two dependent means, Cohen's $d = 0.5$, $\alpha = 0.05$, power = 0.8, two-tailed) gave a minimum sample size of 34 participants. Experiments 1A (10 males, M_{age} 22.24±1.65 years) and 1B (11 males, M_{age} 21.97±1.91 years) each recruited 34 participants. For each experiment, we collected data until 34 participants met our inclusion criteria. Four and six participants were replaced in Experiments 1A and 1B, respectively, following the exclusion criteria described in the Data Analysis section. All participants had normal hearing and normal or corrected-to- normal vision, and none reported any personal history of neurological or psychiatric disorders. All participants gave written informed consent before the experiment and received monetary compensation. This study was approved by the research ethics committee of Zhejiang Normal University.

STIMULI AND PROCEDURE

Participants viewed two types of launch movies: PC and NPC (see Figure 1). In both conditions, the movies began with a black ball (the launcher) moving to the right towards a stationary white ball (the target). In the PC condition, immediately after the launcher contacted the target, the launcher stopped moving and the target began moving with the same direction and speed. In the NPC condition, the launcher

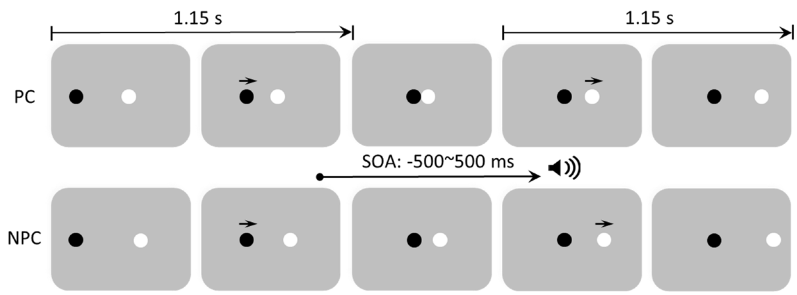

FIGURE 1.

Schematic of the procedure in Experiment 1. Participants viewed a ball (the launcher) that moved toward a stationary ball (the target) until they were adjacent, at which point the launcher stopped and the target started moving along the same path. In the PC condition, the launcher contacted the target, while in the NPC condition, the launcher did not contact the target. A tone was presented at different stimulus onset asynchronies (SOAs, −500–500 ms) with respect to the onset of target moving (which was at the same time as the offset of launcher moving). The participants were asked to judge whether the tone was simultaneous with the onset of the target moving (Experiment 1A) or the offset of the launcher moving (Experiment 1B). PC = perceptual causality; NPC = non-perceptual causality.

stopped moving before contacting (with a gap of 2.4 °) the target, which started moving when the launcher stopped. For both conditions, a pure tone (50 ms duration, 500 Hz, ramped on and off for 10 ms each) were presented via a stereo speaker (Lenovo L1525) at different SOAs (ranging from -500 to 500 ms in steps of 100 ms) with respect to the onset of the target moving. Participants were asked to judge, by pressing "1" or "2" on the keyboard, whether the tone was simultaneous or non-simultaneous with the onset of the target moving (Experiment 1A) or the offset of the launcher moving (Experiment 1B). The visual stimuli were presented on a LCD screen with 60 Hz refresh rate, 1920 × 1080 resolution, positioned about 60 cm from The participants. Both balls (subtending 2.2 °) moved at a constant speed of 4.7 °/s. All stimuli were generated and presented using the software Presentation (Neurobehavioral Systems Inc., Albany, NY, USA).

The experiment included one within-subject factor, launch type (PC and NPC). There were 25 trials for each combination of SOAs and launch type, resulting in 550 trials in total. These trials were delivered randomly in five separate blocks, with short breaks between blocks. At the beginning of the experiment, participants were presented with 10 practice trials to acquaint them with the task. Before the experiment, a pilot test was conducted, in which participants were presented with 20 movies for each condition but without auditory stimuli, and were asked to judge whether the black ball caused the white ball to move. All participants judged all PC movies as causal, and all NPC movies as noncausal. Participants who judged otherwise were not included in the experiment proper.

DATA ANALYSIS

We computed the TBW as a proxy for multisensory integration. For each participant, the rate of simultaneity judgments was calculated at each SOA for each condition. The observed distribution of responses was fit to two psychometric logistic functions (Treutwein & Strasburger, 1999): one for the negative SOAs (left side) and a second for the positive SOAs (right side). For each side, we located the point on the SOA axis corresponding to the 75% performance on the fitted logistic function (Powers et al., 2009; Stevenson, Siemann, et al., 2014), respectively denoted as the left and right window of the TBW. The total TBW was the sum of the left and right windows. Figure 2, Panel A and Figure 3, Panel A show this process for an example individual. Individual rates at each SOA were averaged across participants, and submitted to the same fitting procedure to produce the grand average fitted curve, as shown in Figure 2, Panel B and Figure 3, Panel B. If any data of a participant were unable to fit ($R^2 < 0.85$) with a logistic function, all data of this participant were discarded. Paired-samples *t* tests were conducted on the total, left, and right windows of the TBW to assess whether perception of collision affected audiovisual integration.

Results and Discussion

EXPERIMENT 1A

In the data of an example participant shown in Figure 2, Panel A, the right side of the distribution of responses was clearly more left-shifted in the PC than the NPC condition, resulting in a decreased TBW in the PC condition. Comparisons of the rates of simultaneity judgments at each SOA (see Figure 2, Panel B) revealed that the rates were significantly lower in the PC than NPC condition at SOAs of −100, 300, 400, and 500 ms ($|t|s > 2.81$, $ps < .022$, Cohen's $ds > 0.481$, *p* values were corrected for multiple comparisons using the false discovery rate approach), but not at other SOAs ($|t|s < 1.54$, $ps > .294$, Cohen's $ds < 0.264$). Individual and mean TBWs for each condition are shown on the violin plots in Figure 2, Panel C. For the right window, window size was significantly smaller in the PC ($M = 252$ ms, $SD = 73$ ms) than NPC ($M = 277$ ms, $SD = 76$ ms) condition, $t(33) = -2.59$, $p = .014$, Cohen's $d = 0.444$. However, for the total window and the left window, window size was comparable in the PC and NPC conditions, $|t|s < 1.44$, $ps > .160$, Cohen's $ds < 0.246$.

EXPERIMENT 1B

In the example participant's data shown in Figure 3, Panel A, the right side of the distribution of responses was clearly more left-shifted in the PC than NPC condition, resulting in a decreased TBW in the PC

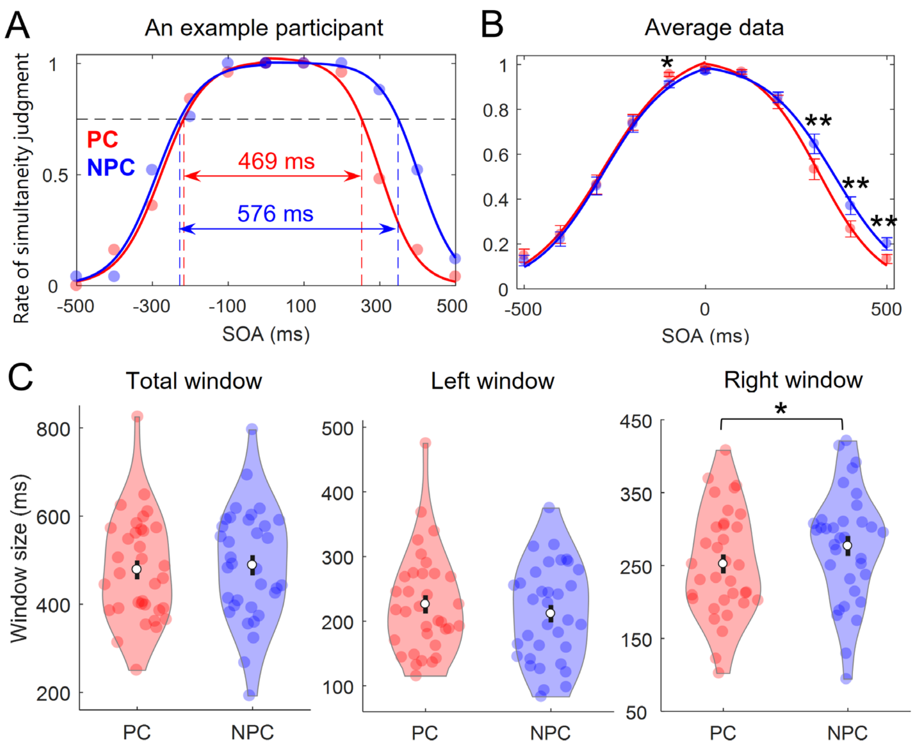

FIGURE 2.

Results of Experiment 1A. Panel A: An example participant's rates of simultaneity responses as a function of SOAs (–500–500 ms) in the PC and NPC conditions. Two logistic curves were fit to each participant's distributions of responses to derive an estimation of the temporal binding window (TBW). Panel B: Logistic curves fit to grand mean rates of simultaneity responses. Dots represents mean, and error bars indicate ± SEM. Panel C: Violin plots for the window size of total, left, and right TBWs. Colored dots represent individual data points. White dots represent averages. Error bars indicate ± SEM. PC = perceptual causality; NPC = non-perceptual causality. * $p < .05$; ** $p < .01$.

condition. Comparisons of the rates of simultaneity judgment at each SOA (see Figure 3, Panel B) revealed that the rates were significantly lower in PC than NPC condition at SOAs of 300 and 400 ms ($|t|$s > 3.14, *ps* < .022, Cohen's *ds* > 0.539), but not at other SOAs ($|t|$s < 1.4, *ps* > 0.508, Cohen's *ds* < 0.240). Mean and individual TBWs for each condition are shown in Figure 3, Panel C. For the total window, window size was significantly smaller in the PC (M = 467 ms, SD = 105 ms) than NPC (M = 493 ms, SD = 111 ms) condition, $t(33) = -2.11$, $p = .042$, Cohen's $d = 0.362$. For the right window, window size was also significantly smaller in the PC (M = 222 ms, SD = 69 ms) than NPC (M = 267 ms, SD = 82 ms) conditions, $t(33) = -2.72$, $p = .010$, Cohen's d = 0.466. However, for the left window, window size was comparable in the PC (M = 225 ms, SD = 74 ms) and NPC (M = 227 ms, SD = 69 ms) conditions, $t(33) = -0.30$, $p = .768$, Cohen's $d = 0.051$.

As per our experimental manipulation, perception of causality existed only in the PC condition. This should lead to longer TBWs in the PC than the NPC condition according to the unity assumption theory. However, in both Experiments 1A and 1B, we observed that the TBW (mainly the right window) was shortened in the PC condition relative to the NPC condition, which was at odds with the unity assumption theory. In the current experiments, perception of causality was manipulated via collision. In the PC condition, the two balls collided, while in the NPC condition, the two balls did not contact. Thus, the two conditions differed not only with respect to the perception of causality but also the presence of collision. As the results could not be explained by the difference in perception of causality using the unity assumption theory, it might be that the difference in presence of collision underlies the observed results. To further examine this possibility, in the following experiment, we made the collision happen in both conditions while still keeping perception of causality only in the PC condition. If the presence of collision was the key reason for the shorter TBW, then we would not observe TBW difference between the two conditions.

EXPERIMENT 2

In this experiment, we still used the launch effect paradigm, but with a small modification aiming to make the collision present in both the PC and NPC condition while keeping perception of causality only in the PC condition. Specifically, an intermediary consisting of four connecing balls (PC condition) or of two separated balls (NPC condition) was added, bridging the spatial gap between the stopping position of the launcher and the starting position of the target (see Figure 4, Panel A). As a result, the spatial gap between the launcher and the target were

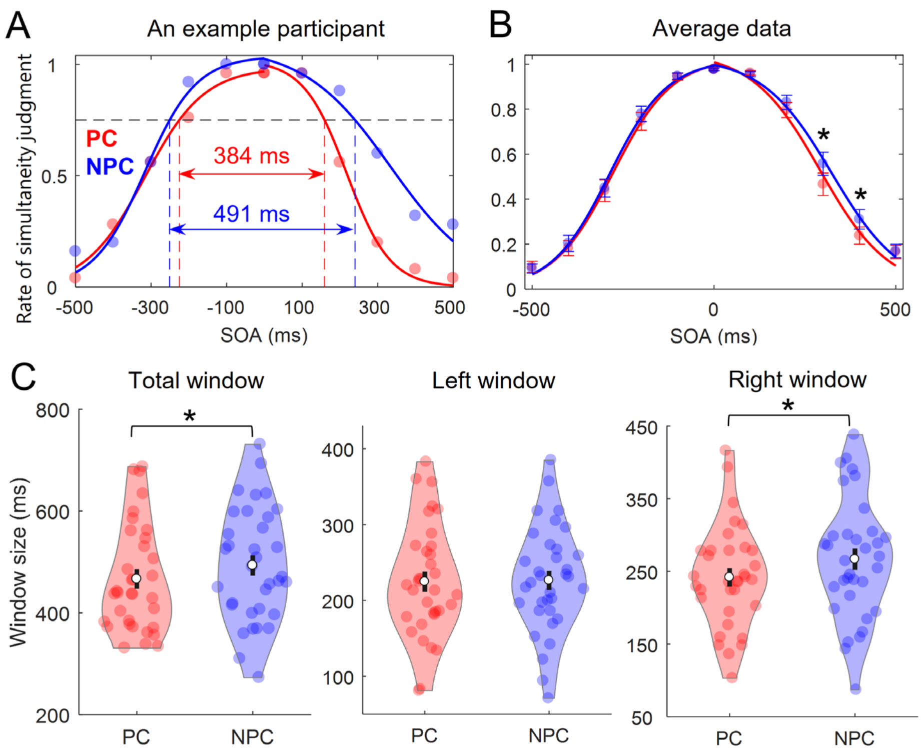

FIGURE 3.

Results of Experiment 1B. Panel A: Example participant's rates of simultaneity responses as a function of SOAs (-500~500 ms) in the PC and NPC conditions. Two logistic curves were fit to each participants' distributions of responses to derive an estimation of the temporal binding window (TBW). Panel B: Logistic curves fit to grand mean rates of simultaneity responses. Dots repr sents mean, and error bars indicate ±SEM. Panel C: Violin plots for the window size of total, left, and right TBWs. Colored dots represent individual data points. White dots represent averages. Error bars indicate ± SEM. PC = perceptual causality; NPC = non-perceptual causality; * $p < .05$.

equal between the two conditions. If the TBW difference observed in Experiment 1 was due to collision, we expected to observe no TBW difference between the two conditions.

Method

PARTICIPANTS

Thirty-four new participants took part in Experiment 2 (13 males, mean age 23.06 ± 2.21 years). This sample size was determined by the same power analysis as used in Experient 1. We collected data until 34 participants met our inclusion criteria. Two participants were replaced following the exclusion criteria described in the Data Analysis section. This study was approved by the research ethics committee of Zhejiang Normal University.

STIMULI AND PROCEDURE

In the launch movies, an intermediary centered in the screen was added, and remained stationary during the entirety of the movies. At the beginning of each trial, the launcher (the black ball) was stationary on the left side of the screen, and the target (the white ball) sat immediately adjacent to the right edge of the intermediary. The launcher then moved smoothly to the right until it collided with the left edge of the intermediary, at which point the launcher stopped and the target started moving along the same path (see Figure 4, Panel A). The moving speed of both balls (subtending 2.4 °) was 4.7 °/s. In the PC condition, the intermediary was a sequence of four serially connecting brown balls (RGB: 128, 96, 0; each subtending 2.4 °). These four connecting balls were very similar to the solid bar used in a modified launching effect paradigm (Buehner & Humphreys, 2010; Hubbard & Favretto, 2003), which showed that perception of causality still existed when an intermediary bridged the launcher and the target. In the NPC condition, the intermediary was two brown balls separated by a gap of 4.8 ° (see Figure 4, Panel A). This was used to disrupt the sense of causal link between the launcher and the target. Thus, collision happened in both the PC and NPC conditions while perception of causality existed only in the PC condition. For both conditions, a pure tone (50 ms duration, 500 Hz, ramped on and off for 10 ms each) was presented via a stereo speaker at different SOAs (ranged from 0 to 500 ms in steps of 100 ms) after the onset of the target moving. Only positive SOAs were included because the effect of launch type in Experiment 1 was restricted to the right window. Participants were asked to judge, by pressing "1" or "2" on the keyboard, whether the tone was simultaneous or non-simultaneous with the onset of target moving.

The experiment included one within-subject factor of launch type (PC and NPC). There were 25 trials for each combination of SOAs and launch type, resulting in 300 trials in total. These trials were delivered randomly in three separate blocks, with short breaks between blocks. At the beginning of the experiment, participants were presented with 10 practice trials to acquaint them with the task. Before the experiment, a pilot test was conducted in which participants were presented with 20 movies for each condition but without auditory stimuli, and were asked to judge whether the black ball caused the white ball to move. All participants judged all PC movies as causal, and all NPC movies as noncausal. Participants who judged otherwise were not included in the experiment proper.

DATA ANALYSIS

Experiment 2 used the same data analysis method as Experiment 1, except that only the right TBW was calculated, as data were collected only at positive SOAs.

Results and Discussion

Comparisons of the rates of simultaneity judgment at each SOA (see Figure 4, Panel B) revealed that the rates were comparable in the PC and NPC conditions at all SOAs ($|t|$s < 1.57, *ps* > .229, Cohen's *ds* < 0.270. As a result, TBW was also comparable in the PC ($M = 234 \pm 76$ ms) and NPC ($M = 239$ ms, $SD = 73$ ms) conditions, $t(33) = -1.15$, $p = .26$, Cohen's $d = 0.197$ (see Figure 4, Panel C). A Bayesian analysis using the method suggested by Masson (2011) was conducted to test the null hypothesis in the TBW. This analysis revealed a Bayesian factor of 3.99, indicating "substantial" support for the null hypothesis. These results indicated that when visual collision was matched between the two conditions, the TBW difference ceased to exist, suggesting the narrowing effect of launch type observed in Experiment 1 indeed originated from collision.

The effects of launch type on TBW were different between Experiments 1A and 2. To confirm this, we combined the right TBW data collected in Experiments 1A and 2 to conduct an analysis of variance (ANOVA) including the experiment as a between-subjects factor (1A vs. 2) and launch type as a within-subject factor (PC vs. NPC). The results (see Figure 4, Panel D) revealed a significant main effect of launch type, $F(1, 66) = 8.02$, $MSe = 918.36$, p = .006, $\eta_p^2 = 0.108$, and a nonsignificant main effect of experiment, $F(1, 66) = 2.57$, $MSe = 10145.45$, $p =$

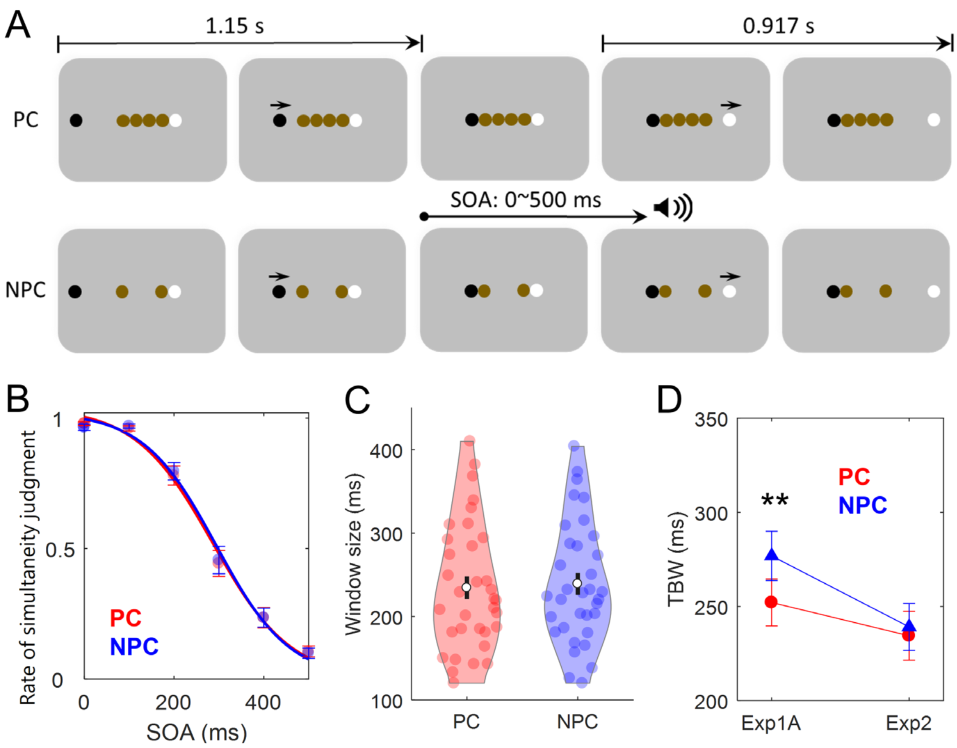

FIGURE 4.

Procedure and results of Experiment 2. Panel A: Schematic of the procedure in Experiment 2. An intermediary consisting of four connecting balls (PC condition) or of two separated balls (NPC condition) was added, bridging the spatial gap between the final location of the launcher and the initial location of the target. A tone was presented at different stimulus onset asynchronies (SOAs, 0–500 ms) after the onset of target moving. Panel B: Logistic curves fit to grand mean rates of simultaneity response. Dots represents mean, and error bars indicate ± SEM. Panel C: Violin plots for the window size of temporal binding window (TBW). Colored dots represent individual data points. White dots represent averages. Error bars indicate ± SEM. Panel D: Analysis of variance (ANOVA) results using combined data from Experiments 1A and 2. PC = perceptualcausality; NPC = non-perceptual causality;
** *p* < .01.

.114, η_p^2 = 0.037. Importantly, the interaction between experiment and launch type was marginally significant, $F(1, 66) = 3.71$, $MSe = 918.36$, $p = .058$, $\eta_p^2 = 0.053$). A simple effect analysis of this interaction revealed that the effect of launch type was significant in Experiment 1A, $F(1, 66) = 11.33$, $MSe = 918.36$, $p = .001$), but not in Experiment 2, $F(1, 66) = 0.41$, $MSe = 918.36$, $p = .524$. There results were consistent with results of the t tests separately conducted in the two experiments.

The aim of Experiment 2 was to retain the difference in causality perception between the PC and NPC conditions while controlling for collision. To confirm this, and more importantly, to confirm that the difference in causality perception was not weakened due to manipulation of Experiment 2, we collected subjective ratings on causality perception in Experiments 1 and 2. We recruited two independent groups of 20 naive participants (14 males, M_{age} 22.11±1.74 years) to view the launch movies and then give subjective ratings, using a 5-point Likert scale, on causality perceived between the launcher and the target. One group viewed the launch movies used in Experiment 1, and the other group viewed the launch movies used in Experiment 2. Each participant viewed 15 launch movies for each of the PC and NPC conditions. The 5-point scale ranged from 1 (*absolutely noncausal*) to 5 (*absolutely causal*) in steps of 1. The ratings were submitted to an ANOVA including experiment as a between-subjects factor (1A vs. 2) and launch type as a within-subject factor (PC vs. NPC). The results revealed a significant main effect of launch type, $F(1, 38) = 172.42$, $MSe = 0.60$, $p < .001$, $\eta_p^2 = 0.819$. The main effect of experiment, $F(1, 38) = 0.16$, $MSe = 0.648$, $p = .693$, $\eta_p^2 = 0.004$, and the interaction between the two factors, $F(1, 38) = 1.94$, $MSe = 0.60$, p = .172, $\eta_p^2 = 0.049$, were not significant.

We designed Experiment 2 to make the collision happen in both PC and NPC conditions while keeping perception of causality only in the PC condition. The TBW was found to be comparable between the PC and NPC conditions, which was in contrast with the results of Experiments 1A and 1B. Analyzing combined data from Experiment 1A and 2 further confirmed this pattern of results by showing a marginally significant interaction between launch type and experiments. To ensure perception of causality differed between launch types (PC vs. NPC), we collected subjective ratings on causality perception, which were indeed higher for PC than NPC in both experiments. This further confirms that collision could be manipulated independently from perception of causality as we expected in Experiment 2. To sum up, the TBW difference between PC and NPC conditions ceased to exist when collision was controlled for, suggesting that it was collision rather than perception of causality that narrowed TBW in the PC condition.

GENERAL DISCUSSION

Collision is a natural phenomenon that induces perception of causality and inherently involves multisensory integration. The present study combined the classic launching effect paradigm and the simultaneity judgment task to investigate how collision affected multisensory integration. In Experiment 1, two balls collided in the PC condition and induced a perception of causality while no such perception was induced in the NPC condition due to no contact of the balls. According to the unity assumption, the TBW of multisensory integration would be lengthened in the PC condition because observers are more likely to perceive the visual target and the auditory sound as coming from the same event (i.e., collision). However, a shorter TBW was observed in the PC condition, which was at odds with the unity assumption. Experiment 2 showed that this effect ceased to exist when collision was controlled for, suggesting that collision itself rather than causality perception contributed to the shortened TBW.

How did collision narrow the TBW of multisensory integration? Previous research has shown that collision can easily capture attention (Franconeri & Simons, 2003; Lin et al., 2009), and attention facilitates multisensory integration (Talsma et al., 2010). Previous research also showed that individuals with attention deficits exhibited reduced temporal precision in multisensory integration as evidenced by expanded TBW (Chan et al., 2015). In the PC condition of Experiment 1, the collision moment itself attracted relatively more attention, leading to enhanced temporal precision of multisensory integration. As a result, the target onset (Experiment 1A) or the launcher offset (Experiment 1B) were more easily distinguished from the tone, leading to a shorter TBW. In contrast, no such boosted attention was allocated to simultaneity judgments in the NPC condition due to absence of collision. Additionally, one confounding factor of the spatial gap might have also contributed to the observed TBW differences between the PC and NPC conditions. Previous work on the "kappa effect" (Cohen et al., 1953; Price-Williams, 1954) has demonstrated that temporal perception can be distorted by spatial distance. In the NPC condition of Experiment 1, the spatial gap separating the stopping of the launcher and the starting of the target might have distorted the temporal perception of these two time points, making the onset of the target seem closer to the tone. In Experiment 2, both collision and the spatial gap were controlled for, and, as a result, the TBW difference between the two conditions disappeared.

The TBW of multisensory integration includes both the left and right sides of the window, and the effects on the TBW are usually symmetrically found for both sides of the window (Foss-Feig et al., 2010; Liu et al., 2021; Zampini et al., 2005). However, in both Experiments 1A and 1B, the TBW difference between the PC and NPC conditions was observed only for the right window (i.e., visual collision leading), but not for the left window (auditory tone leading). This is probably because auditory stimulus leading is ecologically implausible in collision events, and multisensory integration occurs only in ecologically valid events (Schutz & Kubovy, 2009; Stekelenburg & Vroomen, 2007). For example, Schutz and Kubovy (2009) reported an audiovisual illusion in which the length of the impact gesture altered the perceived duration of the percussive sound produced by the gesture. Importantly, this cross-modal illusion happened only when the percussive sound (effect) was presented up to 700 ms after the visual impact (cause), but disappeared when the sound preceded the visual impact because the latter scenario was not ecologically plausible. In natural collision events, sound is produced by collision. It is ecologically implausible if the sound precedes collision. Accordingly, this might lead to absence of the TBW difference for the left window in Experiment 1.

The TBW has been used to index the temporal precision of multisensory integration, with narrower TBWs indicating higher precision (Stevenson et al., 2012; Zhou et al., 2021). We observed that collision narrowed the TBW of multisensory integration, indicating that collision improved the temporal precision of multisensory integration. Although inconsistent with the unity assumption theory, this result was not odd. Previous research has demonstrated that the TBW was significantly narrowed by a 5-hour (1 hour per day) perceptual training on multisensory processing (Powers et al., 2009). During our daily life, we encounter countless number of collision events. In each encounter, the audiovisual integration of the visual stimuli and the sound accompanying the collision is employed. With this implicit practice, our ability to integrate multisensory information can be improved, leading to enhanced temporal precision. Moreover, some collision events can be dangerous and even lethal, especially for those accompanied by a loud clash, such as car crashes. In order to discern deadly collisions, we need to be equipped with a specialized ability to integrate cross-modal information in collisions. Hence, efficient multisensory integration is vital for survival when encountering life-threatening collisions.

In conclusion, collision enhances the temporal precision of multisensory integration by narrowing the TBW, and this effect is dependent on the ecological plausibility of the cross-modal information. This finding is inconsistent with the prediction of the unity assumption theory, suggesting that attention boost induced by collision, rather than perception of causality, might be a key mediating factor for multisensory integration in the context of collision.

ACKNOWLEDGEMENTS

This research was supported by the China National Social Science Fund in Education (2018 general project: Neural Mechanisms of Multisensory Integration Dysfunction in Autism and Related Intervention under Multi-Modality Educational Perspective. Grant No. BBA180083).

J. Wang and C. Wang designed the research and wrote the paper; J. Lu, X. Zhang, and L. Jia conducted the experiments and analyzed the data. All authors approved the final version of the manuscript for submission.

The authors declare no competing interests.

DATA AVAILABILITY

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. None of the Experiments described were preregistered.

REFERENCES

Buehner, M. J., & Humphreys, G. R. (2010). Causal contraction: spatial binding in the perception of collision events. *Psychological Science, 21*, 44–48. doi: 10.1177/0956797609354734

Chan, J. S., Kaiser, J., Brandl, M., Matura, S., Prvulovic, D., J. Hogan, M., & J. Naumer, M. (2015). Expanded temporal binding windows in people with mild cognitive Impairment. *Current Alzheimer Research, 12*, 61–68. doi: 10.2174/1567205012666141218124744

Chen, Y.-C., & Spence, C. (2017). Assessing the role of the 'unity assumption' on multisensory integration: A review. *Frontiers in Psychology, 8*, 445. doi: 10.3389/fpsyg.2017.00445

Choi, I., Lee, J.-Y., & Lee, S.-H. (2018). Bottom-up and top-down modulation of multisensory integration. *Current Opinion in Neurobiology, 52*, 115–122. doi: doi: 10.1016/j.conb.2018.05.002

Cohen, J., Hansel, C. E. M., & Sylvester, J. D. (1953). A new phenomenon in time judgment. *Nature, 172*(4385), 901-901. doi: 10.1038/172901a0

Diederich, A., & Colonius, H. (2004). Bimodal and trimodal multisensory enhancement: Effects of stimulus onset and intensity on reaction time. *Perception & Psychophysics, 66*, 1388–1404. doi: 10.3758/BF03195006

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175–191. doi: 10.3758/BF03193146

Foss-Feig, J. H., Kwakye, L. D., Cascio, C. J., Burnette, C. P., Kadivar, H., Stone, W. L., & Wallace, M. T. (2010). An extended multisensory temporal binding window in autism spectrum disorders. *Experimental Brain Research, 203*, 381–389. doi: 10.1007/s00221-010-2240-4

Franconeri, S. L., & Simons, D. J. (2003). Moving and looming stimuli capture attention. *Perception & Psychophysics, 65*, 999–1010. doi: 10.3758/BF03194829

Grove, P. M., Robertson, C., & Harris, L. R. (2016). Disambiguating the stream/bounce illusion with inference. *Multisensory Research, 29*, 453–464. doi: 10.1163/22134808-00002524

Hubbard, T. L. (2013). Phenomenal causality I: Varieties and variables. *Axiomathes, 23*, 1–42. doi: 10.1007/s10516-012-9198-8

Hubbard, T. L., & Favretto, A. (2003). Naïve impetus and Michotte's "tool effect": Evidence from representational momentum. *Psychological Research, 67*, 134–152. doi: 10.1007/s00426-002-0122-5

Kawabe, T., Roseboom, W., & Nishida, S. y. (2013). The sense of agency is action-effect causality perception based on cross-modal grouping. *Proceedings of the Royal Society B: Biological Sciences, 280*, 20130991. doi: 10.1098/rspb.2013.0991

Körding, K. P., Beierholm, U., Ma, W. J., Quartz, S., Tenenbaum, J. B., & Shams, L. (2007). Causal inference in multisensory perception. *PLoS One, 2*, e943. doi: 10.1371/journal.pone.0000943

Lewald, J., Ehrenstein, W. H., & Guski, R. (2001). Spatio-temporal constraints for auditory–visual integration. *Behavioural Brain Research, 121*, 69–79. doi: 10.1016/S0166-4328(00)00386-7

Lewkowicz, D. J. (1996). Perception of auditory–visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1094–1106. doi: 10.1037/0096-1523.22.5.1094

Lin, J. Y., Murray, S. O., & Boynton, G. M. (2009). Capture of attention to threatening stimuli without perceptual awareness. *Current Biology, 19*, 1118–1122. doi: 10.1016/j.cub.2009.05.021

Liu, M., Liu, C. H., Zheng, S., Zhao, K., & Fu, X. (2021). Reexamining the neural network involved in perception of facial expression: A meta-analysis. *Neuroscience & Biobehavioral Reviews*. doi: 10.1016/j.neubiorev.2021.09.024

Masson, M. J. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior Research Methods, 43*, 679–690. doi: 10.3758/s13428-010-0049-5

Meredith, M., Nemitz, J., & Stein, B. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *The Journal of Neuroscience 7*, 3215–3229. doi: 10.1523/jneurosci.07-10-03215.1987

Michotte, A. (1963). *The perception of causality*. Basic Books.

Mitterer, H., Jesse, A. (2010). Correlation versus causation in multisensory perception. *Psychonomic Bulletin & Review, 17*, 329–334. doi: 10.3758/pbr.17.3.329

Morein-Zamir, S., Soto-Faraco, S., & Kingstone, A. (2003). Auditory capture of vision: examining temporal ventriloquism. *Cognitive Brain Research, 17*, 154–163. doi: 10.1016/S0926-6410(03)00089-2

Noppeney, U., & Lee, H. L. (2018). Causal inference and temporal predictions in audiovisual perception of speech and music. *Annals of the New York Academy of Sciences, 1423*, 102–116. doi: 10.1111/nyas.13615

Powers, A. R., Hillock, A. R., & Wallace, M. T. (2009). Perceptual training narrows the temporal window of multisensory binding. *The Journal of Neuroscience, 29*, 12265–12274. doi: 10.1523/jneurosci.3501-09.2009

Price-Williams, D. R. (1954). The Kappa effect. *Nature, 173*(4399), 363–364. doi: 10.1038/173363a0

Schutz, M., & Kubovy, M. (2009). Causality and cross-modal integration. *Journal of Experimental Psychology: Human Perception and Performance, 35*, 1791–1810. doi: 10.1037/a0016455

Sekuler, R., Sekuler, A. B., & Lau, R. (1997). Sound alters visual motion perception. *Nature, 385*(6614), 308–308. doi: 10.1038/385308a0

Spence, C., & Squire, S. (2003). Multisensory integration: Maintaining the perception of synchrony. *Current Biology, 13*, R519–R521. doi: 10.1016/S0960-9822(03)00445-7

Stekelenburg, J. J., & Vroomen, J. (2007). Neural correlates of multisensory integration of ecologically valid audiovisual events. *Journal of Cognitive Neuroscience, 19*, 1964–1973. doi: 10.1162/jocn.2007.19.12.1964

Stevenson, R. A., Siemann, J. K., Schneider, B. C., Eberly, H. E., Woynaroski, T. G., Camarata, S. M., & Wallace, M. T. (2014). Multisensory temporal integration in autism spectrum disorders. *The Journal of Neuroscience, 34*, 691–697. doi: 10.1523/jneurosci.3615-13.2014

Stevenson, R. A., Wallace, M. T., & Altieri, N. (2014). The interaction between stimulus factors and cognitive factors during multisensory integration of audiovisual speech. *Frontiers in Psychology, 5*, 352. doi: 10.3389/fpsyg.2014.00352

Stevenson, R. A., Zemtsov, R. K., & Wallace, M. T. (2012). Individual differences in the multisensory temporal binding window predict susceptibility to audiovisual illusions. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 1517–1529. doi: 10.1037/a0027339

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences, 14*, 400–410. doi: 10.1016/j.tics.2010.06.008

Talsma, D., & Woldorff, M. G. (2005). Selective attention and multisensory integration: Multiple phases of effects on the evoked brain activity. *Journal of Cognitive Neuroscience, 17*, 1098–1114. doi: 10.1162/0898929054475172

Tang, X., Wu, J., & Shen, Y. (2016). The interactions of multisensory integration with endogenous and exogenous attention. *Neuroscience & Biobehavioral Reviews, 61*, 208–224. doi: 10.1016/j.neubiorev.2015.11.002

Treutwein, B., & Strasburger, H. (1999). Fitting the psychometric function. *Percept Psychophysics, 61*, 87–106.

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin, 88*, 638–667. doi: 10.1037/0033-2909.88.3.638

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005). Audio-visual simultaneity judgments. *Perception & Psychophysics, 67*, 531–544. doi: 10.3758/BF03193329

Zeljko, M., & Grove, P. M. (2021). The effects of recent perceptual history on stream-bounce perception. *Journal of Experimental Psychology: Human Perception and Performance, 47*, 795–809. doi: 10.1037/xhp0000916

Zhou, H.-y., Wang, Y.-m., Zhang, R.-t., Cheung, E. F. C., Pantelis, C., & Chan, R. C. K. (2021). Neural correlates of audiovisual temporal binding window in individuals with schizotypal and autistic traits: Evidence from resting-state functional connectivity. *Autism Research, 14*, 668–680. doi: 10.1002/aur.2456

RECEIVED 26.09.2021 | ACCEPTED 01.02.2022