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Common intentional binding effects across diverse sensory modalities in touch-free voluntary actions

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ABSTRACT

The intentional binding effect refers to the phenomenon where the perceived temporal interval between a voluntary action and its sensory consequence is subjectively compressed. Prior research revealed the importance of tactile feedback from the keyboard on this effect. Here we examined the necessity of such tactile feedback by utilizing a touch-free key-press device without haptic feedback, and explored how initial/outcome sensory modalities (visual/auditory/tactile) and their consistency influence the intentional binding effect. Participants estimated three delay lengths (250, 550, or 850 ms) between the initial and outcome stimuli. Results showed that regardless of the combinations of sensory modalities between the initial and the outcome stimuli (i.e., modal consistency), the intentional binding effect was only observed in the 250 ms delay condition. This findings indicate a stable intentional binding effect both within and across sensory modalities, supporting the existence of a shared mechanism underlying the binding effect in touch-free voluntary actions.

1. Introduction

Human beings interact with external world through voluntary actions. The sense of agency (SoA) is the subjective experience of controlling one's voluntary actions and ensuing action consequences, which arises during the interaction between actions and external world (Gallagher, 2000; Haggard, 2017; Wen et al., 2015). According to the classical comparator model (Blakemore et al., 1998, 2002), the generation of SoA is based on the sensorimotor predictions that emphasize the roles of internal signals and the comparison between predicted and actual outcomes. When an agent performs a goal-directed action, the brain generates not only the motor command but also an efference copy of the motor command. This efference copy is utilized to predict potential action outcomes which

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subsequently are compared with the actual outcomes. SoA arises when the predicted outcomes and the actual ones match. Any minor spatio-temporal discrepancies will contribute to a mismatch and further weaken or eliminate SoA (Blakemore et al., 1999; Shergill et al., 2013). In contrast, the apparent mental causation theory emphasizes external, contextual cues, i.e., the causal relationship between a performed action and its outcome (Wegner & Wheatley, 1999). The agent retrospectively makes causal inference according to the priority (actions occur before the outcomes), consistency (actions are in accordance with the outcomes), and exclusivity (there are no other alternative causes for the outcomes) principles (Wegner, 2003; Wegner et al., 2004). Unlike these models that tend to emphasize either internal or external factors, the cue integration theory proposes that SoA is generated by optimally weighing a combination of internal, sensorimotor cues and external, contextual, inferential cues according to their availability and reliability (Synofzik et al., 2013; Moore et al., 2009). In most cases, reliable internal sensorimotor cues, such as action intention (Moore & Fletcher, 2012) and proprioception (Synofzik et al., 2009), weigh intrinsically over external cues and dominate SoA. However, when the reliability of internal motoric signals decreases, external cues becomes relatively reliable and plays a leading role in the generation of SoA (Moore & Haggard, 2008; Moore et al., 2009). In this study, we examined the cue integration theory by removing the internal cues generated from the tactile feedback of voluntary actions. Although voluntary actions were accompanied by other internal cues, such as proprioception, we assumed that removing tactile feedback would significantly reduce the weight of internal cues in voluntary actions. This means the agent would rely more on external cues (e.g., action-outcome delays and outcome modalities), which would create a greater impact on SoA.

The intentional binding effect is a well-established measure of SoA, which refers to the phenomenon that the temporal interval between a voluntary action and its subsequent consequence will be subjectively compressed (Capozzi et al., 2016; Cavazzana et al., 2014; Haggard et al., 2002; Ruess et al., 2018; Sidarus & Haggard, 2016; Yabe & Goodale, 2015). Studies adopted the interval estimation paradigm have shown the impact of various factors on the intentional binding effect, such as properties of voluntary actions (Zhao et al., 2013; Zhao et al., 2016), action-outcome intervals (Moore et al., 2009; Humphreys & Buehner, 2009; Kühn et al., 2013; Wen et al., 2015), and outcome modalities (Cravo et al., 2013; Engbert et al., 2007; Engbert et al., 2008; Imaizumi & Tanno, 2019; Tanaka et al., 2019; Wen et al., 2015). A study conducted by Zhao et al. (2013) investigated whether different types of voluntary actions (key-press versus key-release) would induce different intentional binding effects. The key-press action was accompanied by instant tactile feedback from the keyboard, while the key-release action was not. Results showed that the time window for the occurrence of intentional binding effect was narrower for key-release actions than for key-press actions, with ranges of 150–250 ms and 150–1050 ms, respectively. It indicates the importance of instant tactile feedback of voluntary actions for the intentional binding effect (Buehner, 2012). This finding was then confirmed by a further study which confined the temporal intervals to 240–280 ms and 440–480 ms (Zhao et al., 2016). They found an intentional binding effect for voluntary key-press actions but not for key-release actions in Experiment 1. Furthermore, in Experiment 3, they employed a novel laser induction apparatus, which allowed participants to make key-press/key-release actions without touching the keyboard, thus removing the influence of instant tactile sensory feedback. However, the experiment only included voluntary key-press/key-release actions and compared the reported intervals between these two conditions. Since the intentional binding effect is assessed by the disparity in the mean reported interval between voluntary and involuntary/baseline conditions, their experiment was unable to verify the presence of this binding effect. To overcome the limitation, the primary aim of the present study was to explore whether the intentional binding effect could be detected in voluntary actions without tactile sensory feedback (i.e., weakened internal cues that only retained the proprioception from the key-press actions). Moreover, if the intentional binding effect could be observed in touch-free voluntary actions, we aimed to further examine whether it would diminish or disappear at long delay durations, similar to Zhao et al.'s (2013) finding. Specifically, we investigated how the absence of reliable internal cues, manifested by the lack of immediate tactile sensory feedback from the keyboard during voluntary key-press actions, influenced the intentional binding effect, and how external cues, e.g., action-outcome delays, modulated this effect.

The binding effect has been observed across diverse action-outcome modalities in previous studies. Some reseachers utilized auditory stimuli as action outcomes (Humphreys & Buehner, 2009; Imaizumi & Tanno, 2019), while others used visual (Cravo et al., 2013; Imaizumi & Tanno, 2019; Wen et al., 2015) or somatic outcomes (Engbert et al., 2008). Comparisons among these modalities have yielded inconsistent findings. Engbert et al. (2008) reported comparable intentional binding effects for auditory, visual, and somatic outcomes, while Imaizumi and Tanno (2019) identified a weaker effect in visual outcomes compared to auditory outcomes. Additionally, a robust and long-lasting auditory intentional binding has been observed with action-outcome intervals of less than 900 ms (Imaizumi & Tanno, 2019) and up to 4 s (Humphreys & Buehner, 2009). In contrast, Cravo et al. (2013) found the visual binding effect occurred within a narrower action-outcome interval range of 250–350 ms. Furthermore, Imaizumi and Tanno (2019) indicated that the auditory intentional binding effect diminished with increased action-outcome delays, and evidence suggested that an increased visual intentional binding effect was positively correlated with a longer action-outcome interval (Wen et al., 2015). Given these observations, no consensus has been reached regarding the influence of outcome modalities and action-outcome delays. The prevailing understanding is that the intentional binding effect for visual and somatic outcomes is not as robust as that observed for auditory ones (Tanaka et al., 2019). Based on these findings, the current study intended to examine whether the binding effect was influenced by specific modality of action outcomes (external cues) when internal cues such as instant tactile sensory feedback became unreliable.

The final purpose of this study was to investigate the role of internal prospective cues (i.e., the congruency of action and outcome modalities, which was manipulated by anticipation) on the intentional binding effect. To the best of our knowledge, no prior studies have employed the interval estimation paradigm to investigate whether the consistency of sensory modalities between the initial stimulus (S1) and the outcome stimulus (S2) can influence the binding effect. Here, the initial stimulus (S1) refers to the stimulus presented at the beginning of the trial, which disappears either immediately when the voluntary action is initiated (Action condition) or after a random period of presentation (No-Action or Baseline condition). In contrast, the outcome stimulus (S2) refers to the stimulus presented after the initial stimulus (S1) disappears for a variety of temporal delays (i.e., the temporal interval between the disappearance of S1 and the appearance of S2). For example, in an experiment conducted by Cravo et al. (2013), participants assessed the temporal interval between the disappearance of a fixation cross (S1) and the appearance of a disk (S2). The disappearance of the cross (S1) can be induced by either an action (button press, voluntary conditions) or no action (involuntary conditions), with the temporal intervals between S1 and S2 systematically manipulated. Results indicated that temporal estimations were shorter under voluntary conditions than under involuntary conditions, and temporal judgments increased for longer intervals. Imaizumi and Tanno (2019) used a low tone (S1) and a high tone (S2) as auditory stimuli in the first experiment and substituted them with a gray circle (S1) and a blue circle (S2) as visual stimuli in the second experiment. However, this study only compared the role of outcome modalities between the two experiments on the binding effect, maintaining the identical sensory modalities of S1 and S2 in both experiments. It was found that a robust auditory intentional binding decreased for longer outcome delays, while weak visual intentional binding only existed in small delay conditions (i.e., 100 ms and 300 ms). Given participants' preconceptions regarding the consistency of modalities between S1 and S2, the experimental context, and the instructed task (Synofzik et al., 2008), the present study employed visual, auditory, and tactile initial and outcome stimuli to evaluate how sensory modality consistency (internal cues) would modulate the intentional binding effect. To address this issue, we compared the magnitudes of the intentional binding effect when the sensory modalities of S1 and S2 were identical or different.

In summary, the present study employed the interval estimation paradigm to investigate two key aspects of the intentional binding effect. Firstly, by isolating the potential influence of tactile sensory feedback from the intentionality of voluntary actions, the study aimed to explore whether the binding effect existed for voluntary touch-free key-press actions and whether it decreased for longer delay durations. Here, the tactile feedback refers to the haptic feeling of touching or contacting the keyboard surface. Secondly, the study sought to compare the results across different initial (S1) and outcome (S2) modalities to assess the impact of the sensory modality and sensory modality consistency on the intentional binding effect. Since no prior studies have systematically examined the integrated roles of voluntary actions without tactile sensory feedback, delay duration, sensory modality, and sensory modality congruency upon the binding effect, this research would largely provide a promising exploratory basis for understanding the intentional binding effect within the framework of cue integration theory. Specifically, tactile sensory feedback was absent when performing voluntary actions (i.e., internal cues became unreliable), whether and how various cues (i.e., external cues: action-outcome delays and outcome modalities; internal cues: sensory modality congruency) affected the intentional binding effect deserve our further investigation.

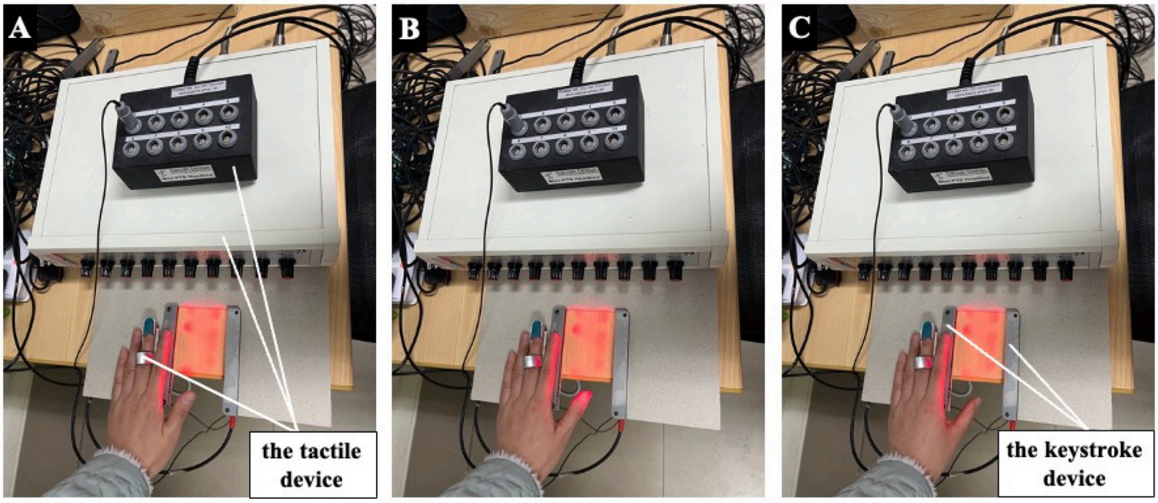

Fig. 1. The set-up of the novel keystroke device and the tactile stimulator system. The keystroke device consists of laser emission/receiver units (the gray columns on either side of the red laser beams in the figure), a circuit board system, and a USB power interface. During operation, 32 parallel laser beams were generated by the laser emission unit (the left gray column which was covered by the participant's left hand) and received by the laser receiver unit (the right gray column). The distance between the two laser units (left versus right) was 6.3 cm. (A) The thumb is positioned above the horizontal plane of the keystroke device, in preparation for a key-press action. (B) The thumb is performing a key-press action by moving down to the same horizontal plane as the keystroke device (i.e., the thumb is within the range of laser beams emitted by the laser emission unit), which is shown by the red light on the thumb in the picture. This causes the laser receiver unit to not detect the signal of laser beams, which indicates the occurrence of the touch-free key-press action. (C) The thumb moves under the horizontal plane of the keystroke device, signaling the end of the key-press action. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Experimental design

Three experiments were conducted, all employing the interval estimation paradigm and adopting a 2 Action Type (active and passive) × 3 Outcome Modality (visual, auditory, and tactile) × 3 Delay Duration (250, 550, and 850 ms) within-subject design. Participants were required to report temporal intervals between the offset of a visual, auditory, or tactile initial stimulus (S1) and the onset of an outcome stimulus (S2, in visual, auditory, or tactile modality). The three delay durations were carefully chosen to ensure that participants could perceive the variations of the interval between S1 and S2 and to avoid response sets (Engbert et al., 2007). The three experiments followed identical procedures except that the initial stimulus (S1) was visual in Experiment 1, auditory in Experiment 2, and tactile in Experiment 3. This variation in initial stimulus modality was added as a between-subject factor in further analysis, resulting in a four-factorial mixed design. The dependent variables of the experiment were perceived intervals and intentional binding scores across all three experiments. The calculation method is elaborated in 2.1.4 Statistical Analysis.

2.1.1. Participants

The sample size was determined using *MorePower* 6.0.4 (Campbell & Thompson, 2012). Given the lack of similar prior research, we assumed a medium effect size (Cohen's $f = 0.25$, $\alpha = 0.05$) with 80 % power and calculated the sample size for the four-way repeated-measures analysis of variance (rANOVA). Our main interest was the effect of the two-way interaction between Action Type and Delay Duration on the perceived intervals, which required a total of 81 participants across the three experiments.

We recruited 41 participants in Experiment 1 and 40 participants each in Experiments 2 and 3. After removing outliers (see 2.1.4 Statistical Analysis for details), there remained 36 qualified participants (17 males, 20.11 ± 2.21 years) in Experiment 1, 36 participants (18 males, 20.78 ± 1.99 years) in Experiment 2, and 36 participants (18 males, 20.75 ± 1.89 years) in Experiment 3.

All participants were right-handed with normal or corrected-to-normal vision and hearing. Participants all signed informed consent before the experiment and received monetary compensation for their participation. The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

2.1.2. Apparatus and stimuli

The apparatus used in the three Experiments were identical. The keystroke device was a touch-free, infrared grating multi-function reaction time recorder system created by our group (Patent No. ZL 2019 2 1272662.9, see Fig. 1). It allowed the key-press action to occur without producing timely tactile feedback, i.e., the haptic feeling of touching or contacting the keyboard surface. Each touch-free key-press action was made by the thumb's vertical movement through the empty space between two laser units recorded by the device.

The computer program controlling the Experiments was carried out in MATLAB R2020a (The MathWorks Inc., USA). Visual stimuli were presented on an XG2730 series 27-inch screen (2560 pixels × 1440 pixels, 120 Hz refresh rate) with a Windows 10 operating system. Auditory stimuli were presented through Beats Solo3 Wireless headphones (used as a wired headset via the connecting cable). Tactile stimuli (i.e., vibrations) were produced by a mPTS 10-channel Piezo-Tactile Stimulator System, a tactile device, which was placed on the participant's left middle finger (see Fig. 1). The device converted auditory signals into vibrations.

The initial stimulus (S1) in Experiment 1 was a 2° × 2° white fixation cross presented on the center of a black screen. S1 in

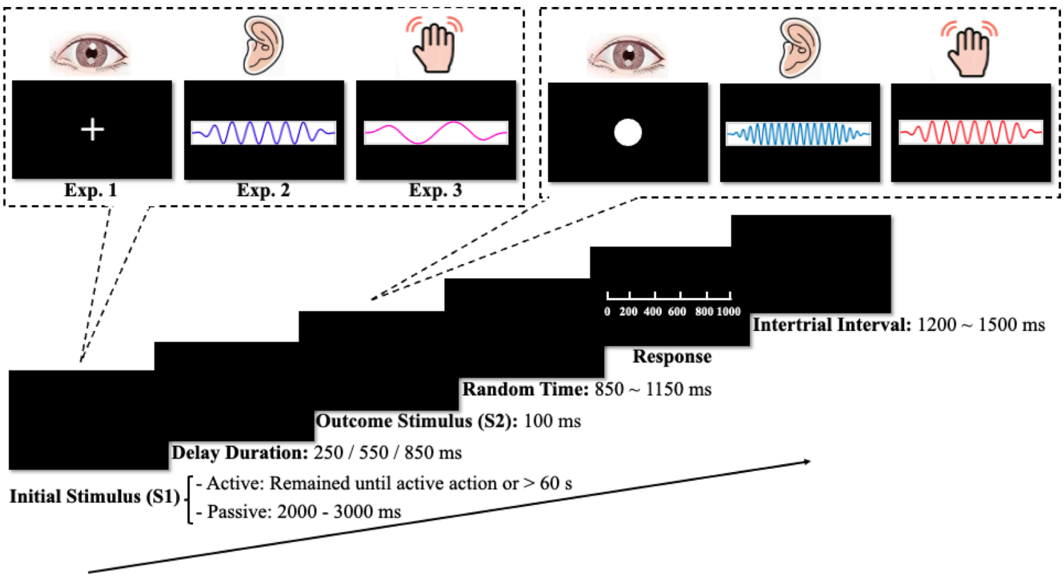

Fig. 2. Trial procedure in Experiments 1, 2, and 3. Detailed descriptions are provided in the text.

Experiment 2 was a sinusoidal tone with a frequency of 200 Hz. S1 in Experiment 3 was tactile vibration converted from a 50 Hz sinusoidal tone by the Tactile Stimulator System. In Experiments 2 and 3, the maximum duration of S1 was 60 s. The outcome stimuli (S2), identical in all three experiments, were a $2^\circ \times 2^\circ$ white disc presented for 100 ms on the center of the screen on a black background (visual), a 100 ms sinusoidal tone with a frequency of 500 Hz (auditory), and a 100 ms tactile vibration converted from a 250 Hz sinusoidal tone (tactile).

2.1.3. Experimental tasks and procedure

Each experiment had 6 blocks based on the 2 Action Type (active and passive) × 3 Outcome Modality (visual, auditory, and tactile) conditions. The order of the 6 blocks was presented at random. The 3 Delay Duration conditions (250, 550, and 850 ms) were run within each block, the order of which was also presented at random.

All experiments began sequentially with a familiarization task, a short training, and a formal experimental session. The familiarization task containing only 3 trials for each of the 6 blocks (2 Action Type × 3 Outcome Modality) aimed to familiarize participants with the procedures and tasks of the experimental session. The 3 Delay Duration was tested once in each block. Succeeding each block was a self-paced break. The formal experiment consisted of 6 blocks containing 45 trials each, which amounted to a total of 270 experimental trials. Each Delay Duration was tested in 15 trials within each block.

At the beginning of each block, instructions were displayed on the screen. Participants were informed about whether the task in the block required a keypress (Action Type: active) or a brief period of waiting (Action Type: passive), and whether the outcome stimulus (S2) at the end of each trial would be a visual, an auditory, or a tactile stimulation (i.e., Outcome Modality).

Fig. 2 illustrates the procedure for a single, typical trial. The experiment began with an initial stimulus (S1), which could be a fixation cross (Experiment 1), a tone (Experiment 2), or a tactile stimulation (Experiment 3). The stimulus would persist until the participant pressed a button (Action Type: active) with the keystroke device or for a random duration ranging from 2000 ms to 3000 ms (Action Type: passive) in the absence of participant action. If the participant in the active condition did not press a key within 60 s, S1 would automatically terminate.

A Delay Duration succeeded the offset of the initial stimulus (S1) and preceded the onset of the outcome stimulus (S2), lasting for 250, 550, or 850 ms. Based on the condition of the block, S2 could be a disc, a tone, or a tactile stimulation, which was then presented for 100 ms and followed by a random, blank time interval varying from 850 ms to 1150 ms. Afterwards, a continuous time scale showing a measurement between 0 and 1000 ms was presented on the screen. Participants were required to judge the time interval between the offset of S1 and the onset of S2 by adjusting the bar on the scale to indicate their response and pressing the Enter key to confirm their decision. The bar on the scale would only appear after participants moved the bar's terminus by dragging the mouse (the bar's starting position was zero). A new trial would begin after a random time interval (1200–1500 ms).

The short training session aimed to familiarize participants with different time intervals within 1000 ms. It consisted of a single block of 20 trials. Each trial began with a 1-s screen informing the participant of the duration of the following white disc. Specifically, the first trial displayed the words "100 ms" for 1 s, and the subsequent disc was presented in the center of the screen for 100 ms. For the first ten trials, the duration of the disc started at 100 ms (i.e., the 1st trial) and increased in steps of 100 ms on each subsequent trial. Inversely, for the last ten trials, the duration of the disc started at 1000 ms (i.e., the 11th trial) and decreased in steps of 100 ms on each subsequent trial. Each trial ended with a blank screen which would remain blank until the participant pressed the Enter key to begin the next trial.

2.1.4. Statistical analysis

We defined outliers as trials where the perceived intervals were three standard deviations away from the mean of each condition (18 conditions in total: 2 Action Type × 3 Outcome Modality × 3 Delay Duration; see Barlas, 2019), $M_{\text{excluded}} = 0.42$ % of all trials in Experiment 1, $M_{\text{excluded}} = 0.38$ % of all trials in Experiment 2, and $M_{\text{excluded}} = 0.23$ % of all trials in Experiment 3.

Data met one of the following criteria were excluded: (1) The proportion of outlier trials was more than 20 % of all trials in one participant; (2) Participants failed to follow the experimental instructions; (3) Participants failed to demonstrate a monotonically increasing trend in the estimations of 250, 550, and 850 ms (Barlas, 2019). Perceived intervals and actual delays for each participant were subjected to linear trend analysis (coefficients: −3, 0, 3 for 250, 550, and 850 ms, respectively). Five participants in Experiment 1, four in Experiment 2, and four in Experiment 3 were excluded based on these criteria. The remaining experimental data were analyzed using *SPSS* 26.0 (IBMCorp., Armonk, N.Y., USA) and the significance level was set to 0.05. The Greenhouse-Geisser correction was applied when the Mauchly's sphericity test for ANOVA was violated. Bonferroni correction was applied for multiple comparisons in post-hoc analysis for ANOVA.

To examine whether the intentional binding effect occurred (i.e., shorter perceived intervals under active conditions compared with passive conditions), a 3 (Initial Modality: visual, auditory, and tactile; between-subject factor) × 2 (Action Type: active and passive; within-subject factor) × 3 (Outcome Modality: visual, auditory, and tactile; within-subject factor) × 3 (Delay Duration: 250, 550, and 850 ms; within-subject factor) rANOVA was carried out on the perceived intervals (i.e., the temporal intervals between the offset of S1 and the onset of S2). Furthermore, to check whether the binding effect would decrease for longer delay durations if the intentional binding effect existed, the interaction between the Action Type and the Delay Duration in the aforementioned four-factorial rANOVA is our most concerned focus.

To identify the impact of Outcome Modality and the Consistency of Sensory Modality on the magnitude of the intentional binding effect, we employed the intentional binding scores as an index of the degree of intentional binding. The intentional binding scores were calculated by subtracting the mean perceived intervals in the passive Action Type from those in the active Action Type separately for each corresponding condition (Barlas, 2019; Imaizumi & Tanno, 2019; Poonian & Cunnington, 2013). A negative binding score implies shorter interval estimation under the active Action Type compared to the passive Action Type, which indicates the existence of intentional binding effect. A 3 (Initial Modality: visual, auditory, and tactile; between-subject factor) × 3 (Outcome Modality: visual, auditory, and tactile; within-subject factor) × 3 (Delay Duration: 250, 550, and 850 ms; within-subject factor) rANOVA was then carried out on the intentional binding scores to examine the influence of Outcome Modality.

The sensory modalities for the initial and outcome stimuli were either identical (e.g., both visual) or different (e.g., visual for one but auditory for the other) in our experiment. To assess whether the consistency of the initial and outcome sensory modalities affected intentional binding, we conducted a 2 (Consistency of Sensory Modality: consistent and inconsistent; within-subject factor) × 3 (Delay Duration: 250, 550, and 850 ms; within-subject factor) × 3 (Initial Modality: visual, auditory, and tactile; between-subject factor) rANOVA on the recalculated intentional binding scores.

Finally, to assess the evidence for and against H_0 if null effects were found in the traditional frequentist statistical analyses, we calculated Bayes Factors (BF) for rANOVA, using JASP 0.17.3 (JASP Team, 2023) with default priors on the parameters. We reported effects in favor of the null hypothesis (BF_{01}) and interpreted the strength of evidence as anecdotal ($1 < BF < 3$), moderate ($3 < BF < 10$), strong ($10 < BF < 30$), very strong ($30 < BF < 100$), or extreme ($100 < BF$; Lee & Wagenmakers, 2014). As there were four experimental factors in our current study, the Bayesian model averaging (BMA; Heck & Bockting, 2021; Hinne et al., 2020; Wagenmakers et al., 2018) was adopted for coping with many candidate models in the Bayesian analysis (reported as BF_{excl}).

3. Results

The descriptive statistics of perceived intervals under different conditions in Experiments 1, 2, and 3 are shown in Table 1. A four-way rANOVA was conducted on the perceived intervals, which showed no significant main effect for Action Type, $F(1, 105) = 0.90$, $p = 0.344$, $\eta_p^2 = 0.01$, or Initial Modality/Experiment, $F(2, 105) = 1.05$, $p = 0.353$, $\eta_p^2 = 0.02$, while significant main effects was observed for Outcome Modality, $F(1.79, 188.13) = 8.66$, $p < 0.001$, $\eta_p^2 = 0.08$, and Delay Duration, $F(1.14, 119.92) = 972.42$, $p < 0.001$, $\eta_p^2 = 0.90$. The significant main effects were qualified by significant two-way and three-way interactions. Significant two-way interactions were found between Action Type and Delay Duration, $F(1.52, 159.20) = 33.05$, $p < 0.001$, $\eta_p^2 = 0.24$, and between Outcome Modality and Delay Duration, $F(3.18, 333.56) = 2.99$, $p = 0.029$, $\eta_p^2 = 0.03$. The other two-way interactions were all non-significant, indicated by $ps > 0.05$. The three-way interaction among Initial Modality (Experiment), Outcome Modality, and Delay Duration was significant, $F(6.35, 333.56) = 3.13$, $p = 0.005$, $\eta_p^2 = 0.06$. All other three-way and four-way interaction results were not significant, indicated by $ps > 0.05$.

Because the interaction between Action Type and Delay Duration was our most concerned focus, we next conducted a simple effects analysis on this two-way interaction (see Fig. 3). When the Delay Duration was 250 ms, the perceived intervals were significantly shorter for the active Action Type than for the passive Action Type, $MD = -21.99$, $F(1, 105) = 10.38$, $p = 0.002$, $\eta_p^2 = 0.09$. When the Delay Duration was 550 ms, there was no significant difference for the perceived intervals under these two action types, $MD = 10.37$, $F(1, 105) = 1.87$, $p = 0.175$, $\eta_p^2 = 0.02$. The Bayesian paired sample *t*-test was performed on the perceived intervals, which moderately supported the null hypothesis ($BF_{01} = 3.82$). When the Delay Duration was 850 ms, the perceived intervals were significantly longer for

Table 1
Perceived intervals ($M \pm SD$) as a function of Initial Modality, Action Type, Outcome Modality, and Delay Duration in Experiments 1, 2, and 3. (unit: ms).

Initial Modality	Action Type	Outcome Modality	Delay Duration		
			250 ms	550 ms	850 ms
Visual (Experiment 1)	Active	Visual	189 ± 93	409 ± 153	614 ± 170
		Auditory	198 ± 123	369 ± 148	583 ± 175
		Tactile	231 ± 117	426 ± 150	627 ± 155
	Passive	Visual	224 ± 80	406 ± 131	595 ± 162
		Auditory	230 ± 84	384 ± 108	586 ± 147
		Tactile	266 ± 107	431 ± 115	599 ± 129
Auditory (Experiment 2)	Active	Visual	164 ± 59	365 ± 133	585 ± 178
		Auditory	173 ± 71	376 ± 130	588 ± 191
		Tactile	174 ± 67	406 ± 142	623 ± 190
	Passive	Visual	190 ± 59	355 ± 104	550 ± 153
		Auditory	200 ± 98	373 ± 129	562 ± 181
		Tactile	187 ± 69	379 ± 120	582 ± 184
Tactile (Experiment 3)	Active	Visual	198 ± 85	379 ± 128	598 ± 143
		Auditory	189 ± 80	379 ± 122	568 ± 149
		Tactile	207 ± 69	410 ± 122	607 ± 145
	Passive	Visual	201 ± 70	361 ± 105	552 ± 146
		Auditory	204 ± 87	356 ± 117	530 ± 141
		Tactile	219 ± 67	380 ± 105	565 ± 132

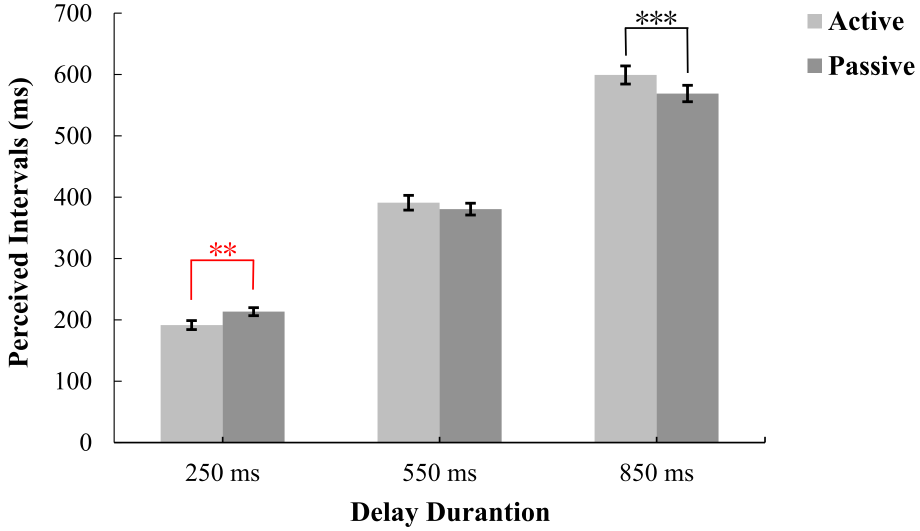

Fig. 3. Perceived intervals as a function of Action Type and Delay Duration. Red lines and asterisks indicate that the intentional binding effect occurs. Note: 1) Error bars represent *SEMs*; 2) **: $p < 0.01$; ***: $p < 0.001$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the active than for the passive condition, $MD = 30.25$, $F(1, 105) = 13.91$, $p < 0.001$, $\eta_p^2 = 0.12$.

To explore the influence of Outcome Modality and the Consistency of Sensory Modality on the intentional binding effect, intentional binding scores were calculated by subtracting the mean perceived intervals in the passive condition from that in the active condition for each Outcome Modality and Delay Duration separately in Experiments 1, 2, and 3. The descriptive statistics of intentional binding scores in Experiments 1, 2, and 3 are shown in Table 2.

A three-way rANOVA (between-subject factor: Initial Modality/Experiment; within-subject factor: Outcome Modality and Delay Duration) was conducted on the resulting intentional binding scores to investigate the impact of Outcome Modality. The result demonstrated significant main effect for Delay Duration, $F(1.52, 159.20) = 33.05$, $p < 0.001$, $\eta_p^2 = 0.24$, but no significant main effect for Outcome Modality, $F(2, 210) = 1.00$, $p = 0.370$, $\eta_p^2 = 0.01$, or Initial Modality/Experiment, $F(2, 105) = 1.41$, $p = 0.248$, $\eta_p^2 = 0.03$. No significant two-way interactions were found between Outcome Modality and Delay Duration, $F(3.27, 343.41) = 0.29$, $p = 0.848$, $\eta_p^2 < 0.01$. The other two-way and three-way interaction results were all non-significant, indicated by *ps* > 0.05.

To assess the evidence for and against the null effects for Outcome Modality, a three-way rANOVA Bayesian analysis was performed on the same scores. The results revealed a strong evidence in favor of the null effects for Outcome Modality ($BF_{excl} = 11.49$), extreme evidence in favor of the null effects for the interaction between Outcome Modality and Delay Duration ($BF_{excl} = 200.95$), and extreme evidence in favor of the null effects for the interaction among Outcome Modality, Delay Duration, and Initial Modality/Experiment ($BF_{excl} = 155.60$).

Finally, we also analyzed whether the intentional binding effect was affected by the consistency of both the Initial Modality and the Outcome Modality (i.e., the Consistency of Sensory Modality). A three-way rANOVA (between-subject factor: Initial Modality/

Table 2
Intentional binding scores ($M \pm SD$) as a function of Initial Modality, Outcome Modality, and Delay Duration in Experiments 1, 2, and 3. (unit: ms).

Initial Modality	Outcome Modality	Delay Duration		
		250 ms	550 ms	850 ms
Visual (Experiment 1)	Visual	−35 ± 84	4 ± 85	19 ± 112
	Auditory	−32 ± 112	−15 ± 101	−2 ± 135
	Tactile	−35 ± 125	−5 ± 134	29 ± 127
Auditory (Experiment 2)	Visual	−25 ± 61	10 ± 93	35 ± 131
	Auditory	−27 ± 74	2 ± 87	25 ± 125
	Tactile	−12 ± 77	26 ± 103	41 ± 113
Tactile (Experiment 3)	Visual	−3 ± 78	19 ± 102	46 ± 102
	Auditory	−15 ± 81	23 ± 92	38 ± 88
	Tactile	−12 ± 81	30 ± 111	42 ± 98

Experiment; within-subject factor: the Consistency of Sensory Modality and Delay Duration) was conducted on the intentional binding scores. Results showed that there was no significant main effect for the Consistency of Sensory Modality, $F(1, 105) = 0.03$, $p = 0.856$, $\eta_p^2 < 0.001$, or Initial Modality/Experiment, $F(2, 105) = 1.38$, $p = 0.256$, $\eta_p^2 = 0.03$, while significant main effect was observed for Delay Duration, $F(1.54, 161.94) = 30.34$, $p < 0.001$, $\eta_p^2 = 0.22$. No significant two-way interactions were found between the Consistency of Sensory Modality and Delay Duration, $F(1.80, 189.01) = 0.20$, $p = 0.799$, $\eta_p^2 < 0.01$. The other two-way and three-way interaction results were all non-significant, indicated by $ps > 0.05$.

To quantify the relative strength of our experimental data in favor of the null effects for the Consistency of Sensory Modality, a three-way rANOVA Bayesian analysis was performed on the intentional binding scores. The results showed that there was moderate evidence supporting the null hypothesis for the Consistency of Sensory Modality ($BF_{\text{excl}} = 6.21$), but strong evidence for the interaction between this and Delay Duration ($BF_{\text{excl}} = 25.02$), and very strong evidence for the interactions among all three variables ($BF_{\text{excl}} = 41.96$).

4. Discussion

This study investigated how an agent's active or passive action affected the judgments of temporal intervals between the disappearance of a visual/auditory/tactile initial stimulus (S1) and the appearance of a visual/auditory/tactile outcome stimulus (S2) when the tactile feedback from the keypress was absent. Our main results revealed that perceived action-outcome intervals were shorter for the active touch-free action than for the passive action when the actual delay duration was 250 ms, regardless of whether S1 was presented visually (Experiment 1), acoustically (Experiment 2), or tactually (Experiment 3). However, this difference disappeared when the delay duration was 550 ms and reversed when the delay duration was 850 ms. These results indicate that when we removed the instant tactile feedback, the typical intentional binding effect of voluntary actions only existed when the delay duration was 250 ms, and it decreased and was eliminated for longer delay durations (i.e., 550 ms and 850 ms). This aligns with the findings of Zhao et al. (2013), who identified that the intentional binding effect for voluntary key-release actions emerged exclusively within a brief delay of 150 ms or 250 ms. Notably, the lack of tactile feedback for key-release actions in their study could be comparable to the key-press action using the touch-free keystroke device in the present study. Both studies demonstrate that voluntary actions without tactile sensory feedback can still induce the binding effect. This indicates that tactile sensory feedback is not mandatory for the binding effect to occur, emphasizing the essential role of action intention in generating this effect. However, Zhao et al. (2016) reported that tactile sensory feedback was crucial to the difference in the mean reported intervals between voluntary key-press and key-release actions. Our findings do not conflict with Zhao et al.'s (2016) study, as their study only compared conditions of voluntary key-press and key-release actions without directly confirming the occurrence of the binding effect. Therefore, their study does not conclusively testify that haptic feedback is essential for intentional binding effects to occur. In comparison, our results provide an extended, complementary illustration of the conditions that give rise to this binding effect.

Another goal of the present study was to examine whether the modality of action outcomes would modulate the binding effect when a voluntary keypress received no tactile feedback. The results of the intentional binding scores showed that all three outcome modalities (visual, auditory, and tactile) produced comparable results, and the results did not interact with the initial modality or the duration of delay. This means the binding effect in the absence of tactile sensory feedback is stable and robust across outcome sensory modalities and different combinations of outcome modalities and delay variations. This finding is congruent with Engbert et al.'s (2008) report that the intentional binding effect for auditory, visual, and somatic outcomes is comparable. However, our results contradict some prior findings. For example, Imaizumi and Tanno (2019) found a weaker intentional binding in visual than in auditory outcomes, and the weaker effect was limited to shorter action-outcome delays (i.e., 100 ms and 300 ms). The reason for this conflicting finding is unclear, as our experimental designs and procedures share many similarities to theirs apart from delay durations and the kind of voluntary actions. The delays were 250, 550, and 850 ms in the present study, but were 100, 300, 500, 700, and 900 ms in theirs; our voluntary actions produced no tactile sensory feedback, whereas their voluntary key-press actions produced this feedback. These may have contributed to the difference between our results and theirs.

The last goal of this study was to evaluate whether the consistency of the sensory modality between initial and outcome stimuli could exert an impact on the intentional binding effect for touch-free voluntary actions. The results of the intentional binding scores indicated that neither the consistency nor its interaction with other variables (Initial Modality or Delay Duration) influenced the intentional binding effect of touch-free voluntary actions. One explanation for this finding might be that in this study, the modalities of initial and outcome stimuli were fixed and paired continually within one experimental block and participants were informed of this in advance. Prenotification before and frequent pairings within each block might prompt participants to develop causal beliefs about S1 and S2, potentially enhancing the subjective temporal proximity between these two stimuli (Lorimer et al., 2020; Vuorre, 2017; Hoerl et al., 2020), thereby inducing the intentional binding. In this study, it may be the causal relationships between initial and outcome stimuli rather than the modality consistency that dominate the intentional binding effect, resulting in comparable binding effects across and within modalities, regardless of the modality types and modality consistency.

Based on the cue integration theory, the present study focused on the impact of internal cues (e.g., Action Type and the Consistency of Sensory Modality) and external cues (e.g., Outcome Modality and Delay Duration) on the intentional binding effect within our specific experimental context. In our experiments, voluntary actions without tactile sensory feedback merely retained the proprioception of the movement while almost all keystrokes are accompanied by both proprioception and instant tactile feedback in reality. Therefore, the reliability of internal cues might be significantly impaired in the case of touch-free voluntary actions. Moreover, with the aforementioned unreliable internal cues, SoA may mainly rely on external cues (i.e., Delay Duration) through an inferential process. Specifically, the temporal contiguity between our action and its outcome gives rise to a causal inference (i.e., action begets result) and simultaneously leads to SoA (i.e., "I produce the result"; Humphreys & Buehner, 2009). In daily life, we expect to receive the feedback immediately after our actions. As the interval between an action and its feedback increases, individuals are less likely to attribute the outcome of the action to their own agency. This may explain why implicit SoA (or the intentional binding effect) for touch-free voluntary key-press actions only appeared at the 250 ms action-outcome delay (i.e., the occurrence time of action and outcome was close enough) but was absent at 550 and 850 ms delays. There are other researchers also indicating that action-outcome delays may strongly affect the intentional binding effect. For example, Ulloa et al. (2019) found the role of gaze direction on the intentional binding was restricted to specific time intervals, 300 ms for the gaze transition or 500 ms for the single static gaze direction. This deserves further investigation to better understand how timing impacts the SoA under different experimental paradigms and contexts. To sum up, based on our experimental context and the cue integration theory, when the reliability of internal cues (i.e., touch-free voluntary action) is weakened, external cues (i.e, Delay Duration) will dominate the intentional binding effect and the Consistency of Sensory Modality and Outcome Modality have non-significant impact on the binding effect.

Certain aspects of this study could be improved in future. Firstly, future research could enhance the ecological validity of stimuli by incorporating emotional faces, emotional sounds, and using virtual reality devices, thereby increasing the applicability of experimental results to real-life scenarios. Secondly, the tactile stimulation system utilized for vibration stimuli was accompanied by acoustic sound. To mitigate its interference with the task, participants were required to wear earplugs during the experiment. However, the actual influence of this acoustic-stimulus-induced vibration stimulus on the perceived intervals may be complex and vary across experiments. For subsequent studies, vibration stimulus parameters can be determined during pre-experiments to strike a balance between the intensity of the vibration stimulus and the accompanying sound.

In conclusion, our findings suggest that the intentional binding effect for voluntary actions without tactile sensory feedback occurs around 250 ms. This effect stably exists even in the absence of tactile sensory feedback and across different sensory modalities (initial modalities and outcome modalities).

5. Ethics approval statement

The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

CRediT authorship contribution statement

Jiajia Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lihan Chen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Jingjin Gu:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Tatia Buidze:** Writing – review & editing, Writing – original draft. **Ke Zhao:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Data curation, Conceptualization. **Chang Hong Liu:** Writing – review & editing, Writing – original draft. **Yuanmeng Zhang:** Writing – review & editing, Writing – original draft. **Jan Gläscher:** Writing – review & editing, Writing – original draft. **Xiaolan Fu:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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