No Evidence in Favour of the Existence of 'Intentional' Binding

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Abstract

Intentional binding refers to the subjective temporal compression between a voluntary action and its subsequent sensory outcome. Despite some studies challenging the link between temporal compression and intentional action, intentional binding is still widely used as an implicit measure for the sense of agency. The debate remains unsettled primarily because the experimental conditions used in previous studies were confounded with various alternative causes for temporal compression, and action intention has not yet been tested comprehensively against all potential alternative causes in a single study. Here, we solve this puzzle by jointly comparing participants' estimates of the interval between three types of triggering events with comparable predictability - voluntary movement, passive movement, and external sensory event - and an external sensory outcome (auditory or visual across experiments). The results failed to show intentional binding, i.e., no shorter interval estimation for the voluntary than the passive movement conditions. Instead, we observed temporal (but not intentional) binding when comparing both movement conditions with the external sensory condition. Thus, temporal binding appears to originate from sensory integration and temporal prediction, not from action intention. As such, these findings underscore the need to reconsider the use of "intentional binding" as a reliable proxy of the sense of agency.

Public Significance Statement

When we press a light switch and observe a bulb lightening, we experience a sense of agency, a feeling of control over these events. We often perceive the temporal interval between our voluntary action and its consequence as shorter compared to the same interval between two events we are not involved. Such temporal binding has commonly been taken as a measure of the sense of agency. However, our study reveals that voluntary actions are neither necessary nor sufficient for temporal binding. Instead, temporal binding relies on predicting and integrating information. The sense of agency can be disturbed in various psychiatric disorders, and its brain mechanisms are currently being actively explored. Our study urges amending how it is measured.

Introduction

The intentional binding effect (also sometimes called temporal binding) refers to the subjective compression of the perceived temporal interval between a voluntary action and its sensory consequence (Haggard et al., 2002; Moore & Obhi, 2012). It has been widely used as an implicit measure for the Sense of Agency (SoA), the human feeling of controlling one's own actions and, through them, their consequences in the external world (Haggard & Chambon, 2012).

There are two well-established paradigms for measuring intentional binding: the single event time estimation procedure, with a variant of the Libet clock paradigm (Borhani et al., 2017; Desantis et al., 2012; Engbert & Wohlschläger, 2007; Haggard et al., 2002; Kirsch et al., 2019; Kong et al., 2017; Ruess, Thomaschke, Haering, et al., 2018; Tsakiris & Haggard, 2003), and the interval estimation procedure (Buehner & Humphreys, 2009; Caspar et al., 2021; Caspar et al., 2020; Engbert et al., 2008; Engbert et al., 2007; Ohata et al., 2022; Poonian & Cunnington, 2013; Suzuki et al., 2019; Zapparoli et al., 2020). In the Libet clock variant, participants perform a self-paced button-press action that triggers a tone (usually 250 ms later) while viewing a small rotating clock hand. It is commonly reported that participants experience a sense of agency over the tone. Haggard et al. (2002) showed that voluntary actions, in contrast to involuntary ones, elicit a binding effect such that the perceived time of the action is delayed (biased towards the outcome) while the perceived time of the outcome is advanced (biased towards the action). In the interval estimation task, participants are typically required to give an explicit numerical estimate of the interval between an action and its outcome (commonly a tone), which is separated by a short but variable delay. Similar to the former paradigm, participants judge the interval as being shorter in the voluntary condition relative to a baseline, which can be the interval between two successive external events (Buehner & Humphreys, 2009; Dewey & Knoblich, 2014; Imaizumi & Tanno, 2019), or the interval between an involuntary action and its outcome (Caspar et al., 2015; Engbert et al., 2008; Zapparoli et al., 2020).

Over the years, studies on intentional binding have yielded conflicting evidence. On one hand, temporal compression similar to intentional binding was also observed when action intention was absent (Buehner, 2012; Gutzeit et al., 2023; Kong et al., 2017; Suzuki et al., 2019), or when participants did not move, but simply observed a movement on a video (Poonian & Cunnington, 2013). Additionally, Buehner (2015) replicated the original Haggard et al. (2002) study with the Libet clock paradigm, but replaced the TMS-induced involuntary muscle twitch with a machine-induced involuntary key press. The results showed a reduced, but still significant binding effect for an involuntary causal movement condition. Thus, these studies suggest that one's own intention is not necessary for eliciting temporal binding. On the other hand, Buehner & Humphreys (2009) showed that intentional action that is not causal is not sufficient for temporal binding to occur, and a recent study found no difference in temporal estimation between voluntary and involuntary actions when the temporal predictability of events was equalized between conditions (Kirsch et al., 2019), further suggesting that action intention alone is not sufficient either to elicit temporal binding effects.

A systematic review revealed that the effect size of temporal binding depends heavily on the condition used as baseline (Tanaka et al., 2019). This could be ascribed to some confounding variables, as action intentionality was not always the only feature that varied between the operant condition (involving a voluntary movement) and the baseline. For example, in cases where an external sensory event was used as the first event at baseline, participants merely observed (or listened to) two external events. In such cases, action was not involved in the baseline and participants had no access to movement-related information, including voluntary motor command and somatosensory feedback, which is known to influence time perception (Cao et al., 2020; Hagura et al., 2012; Tomassini et al., 2014; Wiener et al., 2019). Thus, to isolate the "intentional" character of intentional binding, a passive movement condition can serve as a better baseline. This baseline, whereby an involuntary movement is induced either

mechanically or by the experimenter, was absent in many previous intentional binding studies (Suzuki et al., 2019). Furthermore, the comparison of these two baselines (external sensory event and passive movement as the first event), which is crucial to disentangle the role of somatosensory information during action execution from that of intention in temporal binding, has only been explored by Buehner (2015) and Kirsch et al. (2019). Kirsch et al. (2019) compared, with the Libet paradigm, voluntary and involuntary movements to an external event as a baseline; however, in this study, the baseline was a single event (a tone). Thus, there were different numbers of events in the operant condition (two events: voluntary movement and a tone) and the baseline (one event only: a tone). As interval segmentation by events is known to influence time perception (Bangert et al., 2020; Faber & Gennari, 2017), a different number of events could introduce an additional confounding variable. Buehner (2015) aimed to test the role of perceived causality between the first and second events and equalized it in both the active and passive movement conditions. However, the predictability of the first event was not controlled for across conditions, another potential contributor to binding. Indeed, in addition to the type of baseline, another possible confounding component is the predictability of the first event (Buehner, 2012; Gentsch et al., 2012; Hughes et al., 2013; Suzuki et al., 2019). When previous studies used involuntary/passive movements as baselines, their onset remained unpredictable for participants (Caspar et al., 2015; Engbert et al., 2008; Zapparoli et al., 2020). To the best of our knowledge, only two studies controlled for the predictability of the movement while comparing active and passive movement conditions. One study controlled for the temporal predictability of passive keypresses with the method of constant stimuli (i.e., comparing the duration of an interval to the duration of a tone) and reported that intentional binding was observed for 600-ms intervals, but not for 250-ms intervals (Nolden et al., 2012). However, passive movements came from the keyboard popping the participants' fingers upward, thus involving different somatosensory feedback compared with active movements.

The second study that controlled for the temporal predictability of passive movements reported no difference in temporal estimation between voluntary and involuntary movements (Kirsch et al., 2019). However, this study applied single event time estimation with the Libet clock paradigm, which could differ from the binding effect measured using the interval estimation task. Indeed, previous studies found that the binding effect increases with increasing intervals when the interval estimation method is applied, but decreases when the Libet clock method is used (Buehner & Humphreys, 2009; Haggard et al., 2002). Thus, the second aim of the present study was to test whether binding effects emerge when the temporal predictability of the first event is controlled, using the interval estimation paradigm.

Finally, the sensory modality of the action's consequence (outcome) could also influence the binding effect. While Engbert and colleagues (2008) found comparable amounts of the binding effect across auditory, somatic, and visual modalities, another study reported that the overall intentional binding effect is weaker with visual than with auditory outcomes (Ruess, Thomaschke, & Kiesel, 2018). Thus, the third aim of the present study was to compare the binding effects between visual and auditory outcomes.

In summary, we aimed to tease apart the roles played by action intention, temporal predictability, and somatosensory information in temporal binding. To this aim, we measured the magnitude of temporal binding using the interval estimation procedure by comparing an active movement condition to two different baselines, namely, passive movement and external sensory event conditions. In addition, we controlled for the temporal predictability of the first event. Finally, to assess the generality of the action effect across sensory modalities, the outcome was either auditory (Experiment 1) or visual (Experiment 2). Intentional binding should be demonstrated by shorter interval estimation for the active movement condition than for the passive movement condition. Crucially, other types (i.e., not intentional) of temporal binding or dilation could be demonstrated by comparing different interval estimations, namely

the passive movement condition and the external event condition. Indeed, in this comparison, intention is entirely absent.

Experiment 1

Method

Transparency and Openness

We report how we determined our sample size, data exclusions, manipulations, and experimental measures, and follow the Journal Article Reporting Standards (JARS) (Kazak, 2018). Data, tasks, and materials for all experiments are available on the Open Science Framework page of the project (https://osf.io/n7y8a/). Data were analyzed using Python, version 3.0. The study design and analysis were not preregistered.

Participants

For Experiment 1 (auditory action outcome), we initially recruited 24 participants to match the sample size of a previous study using a similar interval estimation procedure (Caspar et al., 2015) and ensure sufficient power according to this same study (effect size=0.938, desired power=0.95, required sample size=17). However, with this sample size, we did not find any difference between the active movement and passive movement conditions. To definitively rule out a lack of binding effect due to a lack of power, we conducted another power analysis based on a former study with an estimated effect size of 0.593 (Engbert et al., 2008). This analysis suggested a required sample size of 39 participants; therefore, we increased our sample size to 44 participants. This sequential design prevents us from interpreting any significant effect using standard statistical analyses. To assess the existence of binding, we instead relied on Bayesian analyses in the rest of this study. One participant was excluded because of failure to produce temporal intervals that varied monotonically with actual intervals. The remaining 43 participants (28 females, age = 25.2 ± 4.6 years old) participated in all three conditions.

Participants were naive as to the purpose of the study and reported normal or corrected-to-normal vision, normal audition, and no neurological history. All participants provided informed consent before participation and received payment for their participation. Procedures

were approved by the ethics committee (CEEI/IRB Comité d'Evaluation Ethique de l'Inserm, n°21-772, IRB00003888, IORG0003254, FWA00005831) and adhered to the ethical standards of the Declaration of Helsinki, except for registration in a database. Data was collected in 2021.

Apparatus and setup

The action consisted of a key-press performed on a keypad, which was placed on the left side of the monitor (resolution of 1280 × 1024) used to display a fixation cross (Figure 1A). The view of the keypad was prevented by an opaque board. The action outcome for the interval estimation task was an auditory tone (sampling rate: 44.1 KHz, 30 ms duration) played over a loudspeaker. Participants' estimates were collected via another external keypad operated by their right hand. The experiment was programmed using the Unity platform (Unity 2018.4.22f1 Personal) and Microsoft Visual Studio 2019.

Task and procedure

Participants sat on a chair and viewed the monitor at approximately 60 cm (Figure 1A). Before the experiment, participants were first invited to read the instructions, and the experimenter also provided verbal instructions during the practice phase. Three blocked conditions (active movement, passive moment, external sensory event) were then administered in counterbalanced order (Figure 1B). For all conditions, each trial started with a fixation cross, which was presented with a random duration between 1 and 2.5 s. The offset of this fixation cross served as a key temporal indicator for the occurrence of the first event in each condition. Specifically, in the active movement condition, the offset signalled that participants could initiate a key-press at their own willing time. In the passive movement condition, the experimenter, upon the offset of the fixation cross, pressed the participants' finger, attempting to match the offset typically produced by the participants in a pilot experiment. For the external sensory event condition, a tone was emitted 500 ms after the offset.

Due to a recording error, the duration between the offset of the fixation cross and the first event ("Fix-off/First-event") was not directly recorded. Instead, the duration between the trial onset and the first event ("Trial-on/First-event") was recorded. Given that the duration between the trial onset and the fixation cross offset ("Trial-on/Fix-off") was uniformly randomized between 1 and 2.5 s across all conditions, a similar "Fix-off/First-event" duration across conditions could be inferred from a similar "Trial-on/First-event" duration across conditions. This was indeed the case for the active and passive movement conditions (on average 2.55 s for the active and 2.72 s for the passive movement conditions, Mann-Whitney U test, $p = 0.07$). Concerning the external event condition, the distribution of the "Trial-on/First-event" duration did not mirror the trial-to-trial variability observed with the active and passive movement conditions (on average 2.30 s), but allowed the predictability of the first event to be maintained. A technical error in a subgroup of 12 participants led to altered timings for the external event condition only: the "Trial-on/Fix-off" duration was uniformly randomized between 1 and 1.5 s (instead of 1 and 2.5 s) and the "Fix-off/First-event" was uniformly randomized between 0.5 and 1.5 s (instead of a fixed 0.5 s interval). In this subgroup, the predictability of the first event within the external event condition was compromised because of this issue. Therefore, this manuscript reports the results of the analyses excluding this subgroup (N=31 remaining participants). In addition, to maintain transparency, we also ran the same analysis with the entire group of participants. Any differences between X and Y leading to different conclusions are reported in footnotes within the manuscript.

Ultimately, the disappearance of the fixation cross provided participants with a similar level of predictability for the first event across all conditions, ensuring that the primary distinction between them was the type of action-related information available to participants. In the active movement condition, participants had predictability and both intentional efferent and proprioceptive information about their own action. In the passive movement condition, they

had predictability and proprioceptive information, but lacked intentional efferent information about the action. In the external sensory event condition, no action-related information was available to the participants, but they had a similar level of predictability of the first event (Table 1).

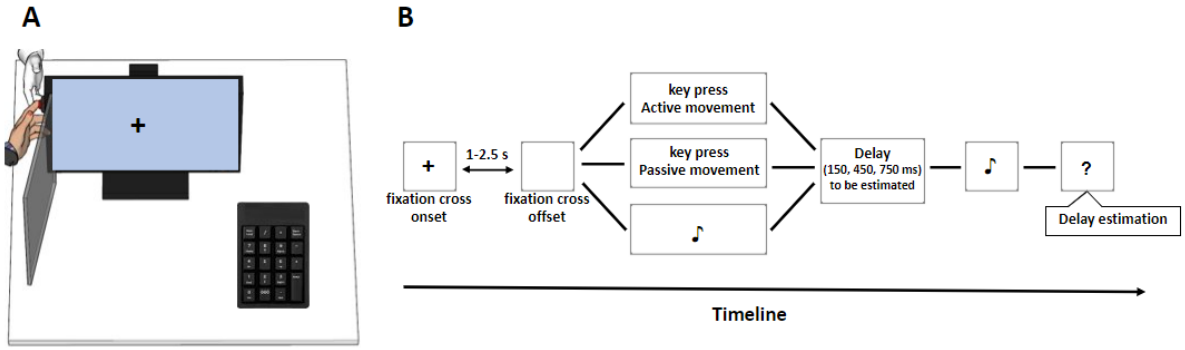

***Figure 1. Set-up (A) and the three experimental conditions (B) of Experiment 1**. **(A)** The set-up is shown here for the passive movement condition. **(B)** Schematic illustration of a trial in the three conditions: active movement, passive movement and external sensory event conditions. Note that the same number of events occurred during a trial for all the conditions.*

Information / First event	*Action intention*	*Somatosensory information*	*Predictability*
Active movement	✓	✓	✓
Passive movement	✗	✓	✓
External sensory event	✗	✗	✓

Table 1. The three conditions and the available information about the first event.

In the active movement condition, participants performed a voluntary key-press with their left index finger whenever they wanted after the fixation cross disappeared, which generated a subsequent tone. In the passive movement condition, the experimenter, sitting behind the monitor and wearing a glove, pressed the participant's passive left index finger down onto the button to generate the same tone (Caspar et al., 2015; Zapparoli et al., 2020). In the external sensory event condition, participants merely listened to one tone followed by a second

occurrence of the same tone. The delay between the first event (active/passive keypress or first tone) and the second event (subsequent tone) was chosen pseudo-randomly among the following intervals: 150, 450 and 750 ms, to ensure that participants complied with the temporal estimation instruction (Figure 1B).

For active and passive movement conditions, participants were asked to estimate the elapsed interval (in ms) between the onset of index finger action and the onset of tone emission. For the external sensory event condition, they were asked to estimate the interval between the onset of the first and of the second tone. Participants were told that the delay varied randomly from trial to trial and never exceeded 1000 ms. They were encouraged to use the full range between 1 and 1000 ms to express even slight variations in their experience of the time elapsed. During the practice phase, participants were reminded that 1 s would correspond to a judgment of 1000, 0.5 s would correspond to 500, and so forth. Participants practiced randomly with 10 different intervals from 100 to 1000 ms to have the impression that the delay varied on a trial-by-trial basis. During the formal testing, each interval (150, 450 and 750 ms) was randomly presented once for the first three trials and then randomly presented 21 times, resulting in 66 trials per condition. The first three trials were discarded from the analysis.

Data Analysis

Intentional binding should be demonstrated by the presence of shorter interval estimates for the active movement condition than for the passive movement condition. Other types of temporal binding (i.e., not intentional) could be shown by the presence of different interval estimates between the active and/or passive movement conditions and the external event condition. To explore the existence or absence of an effect of interest (namely intentional or non-intentional bindings), we calculated Bayes factors (BF) for the relevant paired comparisons. To calculate the BF for directional predictions of differences between the active movement condition and the two other conditions (passive movement and external sensory

event), we used a half-normal distribution with a standard deviation of 122.5 ms, which was the size of the largest binding reported in a previous study (Caspar et al., 2015). For the comparison between the passive movement condition and the external sensory event condition, we made no directional prediction and calculated a BF using a uniform distribution with a minimum of 13.5 ms, which was the smallest binding reported in the same study (Caspar et al., 2015), and a maximum of 122.5 ms (see also Suzuki et al., 2019). A BF of above 3 would indicate substantial evidence for the existence of a binding, a BF below 1/3 would indicates substantial evidence for the inexistence of a binding, and intermediate values would not provide any substantial evidence either way (Dienes, 2014; Dienes & Mclatchie, 2018; Jeffreys, 1939; Wagenmakers et al., 2017). We also reported the robustness region (RR), which gives the range of scales (i.e., the minimum and maximum standard deviation of the half normal distribution, or the minimum and maximum difference between the higher bound and the lower bound of the uniform distribution), which leads to the same conclusion (Dienes, 2019).

Results

There was substantial evidence for the inexistence of intentional binding, i.e., no shorter mean interval estimation for the active movement condition (Mean ± SE = 295.23 ± 23.42) than passive movement condition (Mean ± SE = 305.30 ± 25.18) ($BF_{HN(0,122.5)} = 0.22$, $RR_{B<1/3} = [83, >3000]$)[1]. In contrast, the interval estimation for the active movement condition was shorter than that observed in the external sensory event condition (Mean ± SE = 344.75 ± 26.40), with substantial evidence in favor of the existence of such a temporal binding ($BF_{HN(0,122.5)} = 13.8$, $RR_{B>3} = [8, 614]$). Finally, there was substantial evidence for shorter interval estimation for the

[1] With the group of 43 participants, the evidence for an intentional binding was inconclusive ($BF_{HN(0,122.5)} = 0.82$, $RR_{1/3<B<3} = [0, 307]$). The Robustness Regions indicate that even smaller predictions of the size of the intentional binding would lead to the same conclusion.

passive movement condition than for the external sensory event condition ($BF_{U(13.5,122.5)} = 4.5$, $RR_{B>3} = [0, 163]$)[2].

When considering actual delays separately, there was substantial evidence for the inexistence of intentional binding for the long and short intervals (long: $BF_{HN(0,122.5)} = 0.13$, $RR_{B<1/3} = [48, >3000]$; short: $BF_{HN(0,122.5)} = 0.25$, $RR_{B<1/3} = [93, >3000]$)[3] and inconclusive for the middle interval ($BF_{HN(0,122.5)} = 0.41$, $RR_{1/3<B<3} = [0, 153]$). In contrast, the evidence for a non-intentional binding when comparing active movement vs. external sensory conditions was substantial for both the long and middle intervals (long: $BF_{HN(0,122.5)} = 45$, $RR_{B>3} = [13, 2529]$; middle: $BF_{HN(0,122.5)} = 20$, $RR_{B>3} = [9, 922]$); for the short interval, there was substantial evidence for an absence of binding ($BF_{HN(0,122.5)} = 0.21$, $RR_{B<1/3} = [79, >3000]$). Finally, the evidence for a non-intentional binding when comparing passive movement vs. external sensory conditions was substantial for the long and middle intervals (long: $BF_{U(13.5,122.5)} = 125$, $RR_{B>3} = [0, >3000]$; middle: $BF_{U(13.5,122.5)} = 3.4$, $RR_{B>3} = [3, 124]$)[4], and the evidence was inconclusive for the short interval ($BF_{U(13.5,122.5)} = 0.57$, $RR_{1/3<B<3} = [3, 124]$).

[2] With the group of 43 participants, the evidence for shorter interval estimation for the passive movement condition than the external sensory event condition was inconclusive ($BF_{U(13.5,122.5)} = 2.5$, $RR_{1/3<B<3} = [93, 829]$)

[3] With the group of 43 participants, the evidence for an intentional binding was inconclusive for these two intervals (long: $BF_{HN(0,122.5)} = 0.85$, $RR_{1/3<B<3} = [0, 319]$; short: $BF_{HN(0,122.5)} = 0.48$, $RR_{1/3<B<3} = [0, 175]$).

[4] With the group of 43 participants, the evidence was inconclusive for the middle interval ($BF_{U(13.5,122.5)} = 2.86$, $RR_{1/3<B<3} = [104, 932]$).

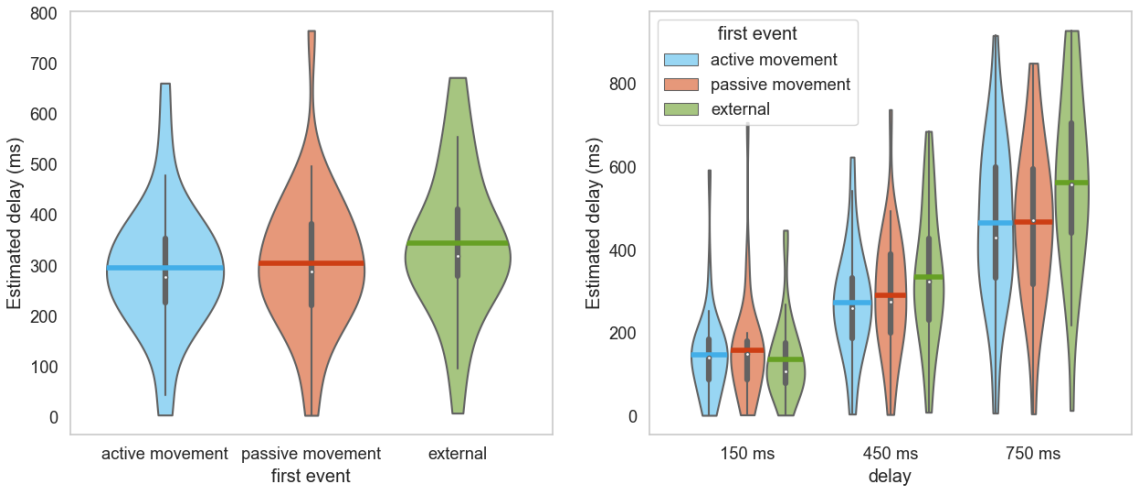

Figure 2. Results from Experiment 1 (auditory action outcome). (A) *Average estimated outcome delay in the three conditions (active movement, passive movement and the external sensory event).* ***(B)*** *Same as a function of the actual interval. Vertical gray lines in each violin refer to the interquartile range and the horizontal lines refer to the means.*

Intermediate discussion

In Experiment 1, we failed to demonstrate the existence of intentional binding. Instead, we found substantial evidence for non-intentional temporal binding. Compared with previous studies, our experiment was not underpowered and appropriately controlled for potential confounding factors. In Experiment 2, we aimed to test whether intentional binding existed (i) with a visual outcome instead of the auditory outcome of Experiment 1 and (ii) when the visual stimulus was presented at different distances from the participants. For this experiment, we used a similarly large sample size and adapted the design of Experiment 1 to the visual modality, using virtual reality (VR) to present the visual stimuli at different distances.

Experiment 2

Method

Participants

For Experiment 2 (visual action outcome), we aimed for a similar sample size as Experiment 1 and recruited 45 participants. Two participants were excluded, one due to failure to produce temporal intervals that varied monotonically with actual intervals and the other due to failure to comply with instructions to control the gamepad to report the interval estimations. The remaining 43 participants (24 females, age = 24.8 ± 4.4 years old) participated in all three conditions. Participants were naive as to the purpose of the study and reported normal or corrected-to-normal vision, normal audition, and no neurological history. All participants provided informed consent before participation and received payment for their participation. Procedures were approved by the ethics committee (CEEI/IRB Comité d'Evaluation Ethique de l'Inserm, n°21-772, IRB00003888, IORG0003254, FWA00005831) and adhered to the ethical standards of the Declaration of Helsinki, except for registration in a database. Data was collected in 2021.

Apparatus and setup

The action consisted of a keypress on a gamepad, and participants viewed the visual scene including the fixation cross through a head-mounted display (HMD, Oculus rift CV1, resolution 2160 × 1200) in virtual reality (VR). The action outcome was a visual effect (the lightening of a light bulb, Figure 3A), which was presented at either of two task-irrelevant distances from participants (near: 45 cm, far: 4.5 m). The decision to employ a VR setup in Experiment 2 was primarily driven by an additional goal to simultaneously investigate the impact of the spatial distance dimension on temporal binding. VR technology offered us the advantage of accurately and simultaneously manipulating and measuring the spatial aspects within the experiment. As this manipulation did not yield any difference in temporal binding,

data from both distances were pooled together. The experiment was programmed using the Unity platform (Unity 2018.4.22f1 Personal) and Microsoft Visual Studio 2019.

Task and procedure

The procedure was similar to that of Experiment 1 except for two aspects: 1) the external sensory events were visual instead of auditory; 2) the key-press and interval estimates were performed using a gamepad. In the active and passive movement conditions, a light bulb was turned on once an active or passive key-press (button "A" on the gamepad, Figure 3A) was performed. After the bulb had been lightened for 1 s, the participants were then asked to estimate the interval between the onset of the key-press and the onset of the bulb lighting. In the external sensory event condition, participants merely viewed an off bulb being turned on by the computer. Participants were asked to estimate the interval between the appearance of the off bulb and its lighting onset. As participants were wearing the headset during Experiment 2, they indicated their estimates for all conditions by moving a visually depicted slider with their left thumb operating the stick of the gamepad (Figure 3A). The slider was presented to participants at a distance of 87 cm with a length of 54 cm and a width of 10 cm, and ranged from a minimum value of 1 on the far left to a maximum value of 1000 on the far right. Values appeared in real-time above the slider while participants moved it to the desired value, and they pressed the "LB" button on the gamepad to submit their responses. The intervals between the two events were the same as those in Experiment 1 (Figure 3B), and the same number of repeated trials for each condition and for each interval were performed in Experiments 1 and 2. As in Experiment 1, the "Fix-off/First-event" duration was not directly recorded, but the "Trial-on/First-event" duration was recorded and shown to be similar for both the active and passive movement conditions (on average 2.67 s for the active and 2.77 s for the passive movement conditions, Mann-Whitney U test: $p = 0.19$). The distribution of the "Trial-on/First-event" duration in the external event condition did not mirror the trial-to-trial variability observed with the active and

passive movement conditions (on average 2.23 s), but allowed the predictability of the first event to be maintained. Similar to Experiment 1, the timings for the external event conditions were altered in a subgroup of 10 participants. Therefore, this manuscript reports the results of the analyses excluding this subgroup (N=33 remaining participants). In addition, we also ran the same analysis with the entire participant group of participants. Any differences between X and Y leading to different conclusions are reported in footnotes within the manuscript.

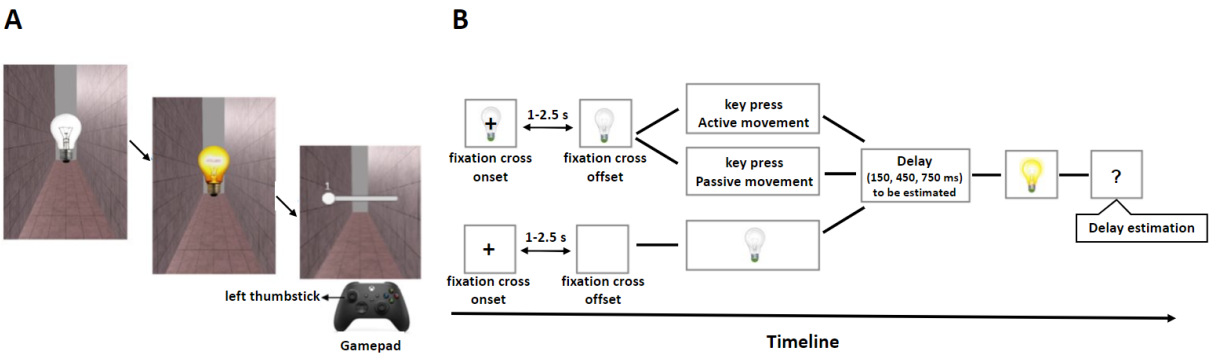

Figure 3. The experimental scene of a single trial (A) and experimental conditions (B) of Experiment 2. (A) *During each trial, an off-bulb was turned on by different first events depending on the condition. The key-press and interval estimates were performed through a gamepad. Participants indicated their estimates by moving a visually depicted slider with the left thumbstick of the gamepad.* ***(B)*** *Schematic illustration of a trial in the three conditions: active movement, passive movement and external sensory event conditions. In the active and passive movement conditions, the light bulb (switched off) appeared at the beginning of each trial together with the fixation cross, while it appeared after the fixation cross in the external event condition. The light bulb remained visible prior to being illuminated. The lightened bulb lasted for 1 s before participants were asked to estimate the intervals. Note that the same number of events occurred during a trial for all the conditions.*

Data Analysis

The same analysis as that for Experiment 1 was conducted.

Results

There was substantial evidence in favor of the inexistence of temporal binding when comparing the active movement condition (Mean ± SE = 256.40 ± 21.37) with the passive

movement condition (Mean ± SE = 244.72 ± 20.68, $BF_{HN(0,122.5)}$ = 0.28, $RR_{B<1/3}$ = [103, >3000]). As in experiment 1, there was substantial evidence for the existence of non-intentional binding when comparing the active movement condition to the external sensory event condition (Mean ± SE = 291.12 ± 20.33, $BF_{HN(0,122.5)}$ = 3.3, $RR_{B>3}$ = [9, 134]). Finally, there was substantial evidence in favor of temporal binding when comparing the passive movement condition with the external sensory event condition ($BF_{U(13.5,122.5)}$ = 205, $RR_{B>3}$ = [0, >3000]).

When considering the delays separately, the evidence in favor of the inexistence of an intentional binding was inconclusive for the long and middle intervals (long: $BF_{HN(0,122.5)}$ = 0.68, $RR_{1/3<B<3}$ = [0, 259]; middle: $BF_{HN(0,122.5)}$ = 0.54, $RR_{1/3<B<3}$ = [0, 201]) and substantial for the short interval ($BF_{HN(0,122.5)}$ = 0.12, $RR_{B<1/3}$ = [45, >3000])[5]. There was substantial evidence in favor of the existence of non-intentional temporal bindings for the longest interval (active vs. external sensory conditions: $BF_{HN(0,122.5)}$ = 11.1, $RR_{B>3}$ = [12, 521]); passive vs. external sensory condition: $BF_{U(13.5,122.5)}$ = 11214, $RR_{B>3}$ = [0, >3000]) and the middle interval (active vs. external sensory conditions: $BF_{HN(0,122.5)}$ = 6.33, $RR_{B>3}$ = [9, 273]); passive vs. external sensory condition: $BF_{U(13.5,122.5)}$ = 9951, $RR_{B>3}$ = [0, >3000]). There was substantial evidence in favor of the inexistence of such bindings for the short interval (active vs. external sensory conditions: $BF_{HN(0,122.5)}$ = 0.09, $RR_{B<1/3}$ = [32, >3000]); passive vs. external sensory condition: $BF_{U(13.5,122.5)}$ = 0.09, $RR_{B<1/3}$ = [30, >3000]).

[5] With the group of 43 participants, the evidence for the inexistence of the intentional binding was substantial for the middle interval ($BF_{HN(0,122.5)}$ = 0.25, $RR_{B<1/3}$ = [93, >3000]).

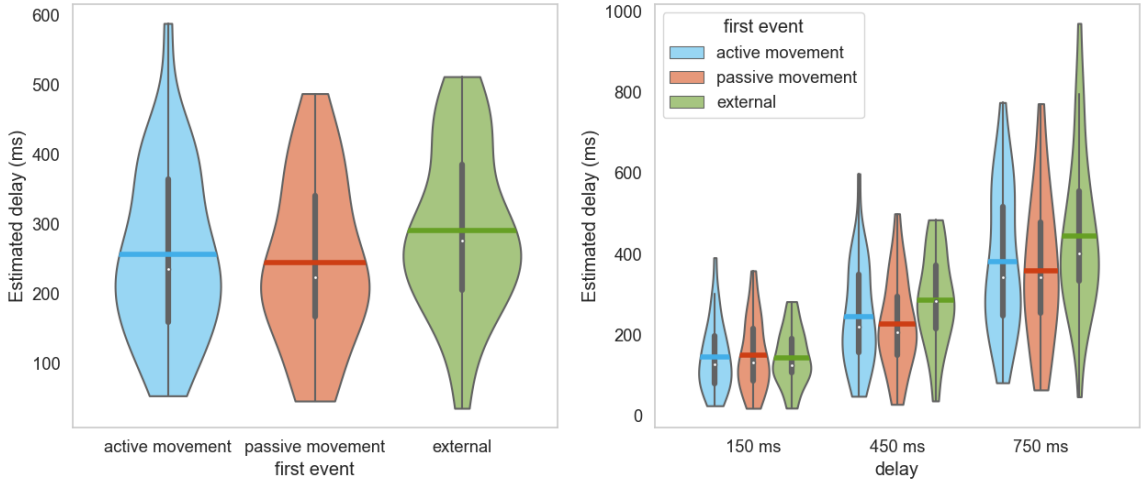

Figure 4. Results from Experiment 2 (visual action outcome). (A) *Average estimated outcome delay in the three conditions (active movement, passive movement and the external sensory event).* ***(B)*** *Same as a function of the actual interval. Vertical gray lines in each violin refer to the interquartile range and the horizontal lines refer to the means.*

Intermediate discussion

Experiment 2 led to results similar to those observed in Experiment 1, with evidence in favor of the inexistence of intentional bindings but supporting the existence of non-intentional bindings. The scope of these results is discussed below.

General Discussion

The present study examined whether the nature of the temporal binding effect is genuinely intentional, while controlling for both the presence of somatosensory information and predictability of the first event, by comparing interval estimates between the active movement, passive movement, and external sensory event conditions across two sensory modalities of the action outcome. In Experiment 1 and 2, we found that regardless of whether the outcome was auditory or visual, action intention was neither necessary for observing binding (conclusive evidence for the existence of a non-intentional binding when comparing passive movement to the external sensory event conditions) nor sufficient (conclusive evidence for the inexistence of the intentional binding when comparing active to passive movement conditions). Thus, even with a larger number of participants than in previous studies with significant intentional binding but lacking appropriate controls, we could not demonstrate the existence of intentional binding. However, we found a temporal (but not intentional) binding when comparing the passive movement condition to the external sensory event condition in both modalities that was modulated by the actual delay between the two events, with conclusive evidence for such binding mostly with the longest delay.

Here, we carefully controlled for the available information between the active movement condition and baselines. The difference in the available information for active and passive movements was that there was a voluntary motor command induced by intention in the active movement condition but not in the passive movement condition. The absence of a substantial difference in temporal estimation between these two conditions suggests that action intention alone is not sufficient to induce intentional binding. This aligns with Buehner and Humphreys (2009) finding that intentional action that is not perceived as causally related to the second event is not sufficient for temporal binding to occur. Instead of the intentionality of an action, the 'intentional' binding observed in previous studies could be due to the uneven level

of temporal predictability and/or causality for active and passive movements. Our results are also consistent with a recent study showing that the binding difference between voluntary and involuntary movements, as measured with the Libet clock procedure, vanishes when the temporal predictability of to-be-judged movements is controlled (Kirsch et al., 2019). Our results go further by showing that intentional binding also vanishes with the interval estimation method in both auditory and visual outcome modalities.

Interestingly, we further observed that the perceived temporal interval was shorter for both the active and passive movement conditions when compared with the external sensory event condition in both experiments. This result indicates that the intentionality of action is also not necessary for temporal binding. This finding aligns with that of Suzuki et al. (2019); however, intention, predictability and proprioception differed between their compared conditions, whereas we varied only one piece of information between two compared conditions. This approach allowed us to disentangle the confounders of action intention, somatosensory information, and predictability. Our results also align with those of Buehner (2015), and here we additionally control for the predictability of the first event. Compared with active and passive movements, the external sensory event condition lacks intentional efferent and somatosensory information about the action. It has been proposed that binding phenomena result from cue integration (Moore & Haggard, 2008; Moore & Fletcher, 2012; Moore et al., 2009; Wolpe et al., 2013), but this framework has mainly relied on the role of efferent motor signals. The present findings stress and support the role of somatosensory information in which efferent motor signals do not necessarily need to be present (Kirsch & Kunde, 2023; Kirsch et al., 2019). Of interest, somatosensory events conceivably have a fuzzier perceived time point than auditory or visual events, and the binding has been shown to be modulated by the reliability of the events to be bonded together (Klaffehn et al., 2021). Thus, the contribution of somatosensory information to binding might be related to the less reliable temporal estimation

of somatosensory information in the active and passive movement conditions than that of the visual or auditory first event in the external sensory event condition. Future studies, where the reliability of the baseline estimation is manipulated, will need to be conducted to explore this possibility.

It is worth noting that when comparing the external sensory event condition and the active/passive movement condition, temporal attraction did not occur for the shortest 150-ms interval in either experiment. This observation is reminiscent of the hypothesis that temporal bindings might result from the causal relationship between two events, rather than from intentionality per se, as suggested by previous studies (Buehner, 2015; Buehner, 2012; Buehner & Humphreys, 2009; Desantis & Buehner, 2019; Desantis et al., 2011). Compared with longer delays in the present study, the first event and the effect are more likely to be perceived as causally linked in the shortest delay, as they follow each other closely in time. This could create a "causal" binding, i.e., a perception of the events closer than they really are, in all three conditions, strong enough to mask any additional binding revealed by comparing the conditions between them.

In our experimental design, we attempted to match the level of predictability for the first event across the active, passive, and external event conditions as closely as possible. However, it is essential to recognize the inherent distinctions between active and passive movements, which introduce an element of limitation to our study. Indeed, in the passive condition, despite our efforts to closely match the timing, the experimenter's control over the action inherently introduced a degree of unpredictability from the participants' perspective. This factor is evidenced by the non-perfectly congruent timing of active and passive keypresses, a phenomenon that was anticipated and documented in our study. The degree of this discrepancy, while expected, introduces a variable that merits further consideration. Future research could explore more sophisticated and even cleverer methods to equalize the predictability of passive

and active body movements. Such advancements may provide deeper insights into the nuances of predictability's role in temporal binding.

In summary, we did not observe intentional binding when comparing active vs. passive movements using the interval estimation procedure. Instead, temporal binding emerged when both active and passive movements were compared with an externally triggered sensory event. Taken together, these findings indicate that the link between the presence of a temporal binding effect and the intentionality of an action is neither necessary nor sufficient. Instead, temporal binding is not "intentional" and caution should be exercised when using this phenomenon as an implicit measure of the sense of agency. Our findings argue that intentional binding between voluntary and involuntary actions found in previous studies could be due to confounding factors and that experimental procedures such as the choice of the baseline are crucial. These findings further stress the role of somatosensory integration and temporal prediction in temporal attraction instead of motor command or action intention.

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