# 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 sensory outcome. Though widely used as an implicit measure for the sense of agency, recent studies challenged the link between temporal compression and intention. The debate remains unsettled though, as intention has not been tested against all potential alternatives. Here, we fill this gap by jointly comparing participants' estimates of the interval between three types of triggering events with comparable predictability -voluntary movement, passive movement, external sensory event- and an external sensory outcome (auditory or visual across experiments). Results failed to show intentional binding, i.e., no shorter interval estimation for the voluntary than the passive movement conditions. Instead, we observed substantial temporal (but not intentional) binding when comparing both movement conditions to the external sensory condition. Thus, temporal binding seems to originate from sensory integration and temporal prediction, not from action intention.

**Statement of significance**

Intentional binding refers to the subjective temporal compression between a voluntary action and its sensory outcome. It is nowadays widely used as an implicit measure for the sense of agency, which is the subjective feeling that we are at the origin of our own voluntary actions and of their consequences. In the present study, we demonstrate that the so-called "intentional binding" is actually not related to intention. Participants estimated the time between two causally-related events as being shorter when the first event was their movement than when it was an external sensory event. However, whether the movement was voluntary or participants' finger was moved by an experimenter did not matter, as long as we controlled for the predictability of the movement. Thus, temporal binding seems to originate from sensory integration and temporal prediction, not from action intention, and its use as proxy for the sense of agency should be reconsidered.

## Introduction

The intentional binding effect (also called temporal binding) refers to the subjective compression of the perceived temporal interval between a voluntary action and its sensory consequence (Haggard, Clark, & Kalogeras, 2002; J. W. 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 to measure intentional binding: the single event time estimation procedure, with a variant of the Libet clock paradigm (Desantis, Hughes, & Waszak, 2012; Engbert & Wohlschläger, 2007; Haggard et al., 2002; Kirsch, Kunde, & Herbort, 2019; Kong, He, & Wei, 2017; Ruess, Thomaschke, Haering, Wenke, & Kiesel, 2018; Tsakiris & Haggard, 2003), and the interval estimation procedure (Buehner & Humphreys, 2009; Caspar, Beyer, Cleeremans, & Haggard, 2021; Caspar, Bue, Haggard, & Cleeremans, 2020; Engbert, Wohlschläger, & Haggard, 2008; Engbert, Wohlschläger, Thomas, & Haggard, 2007; Ohata, Asai, Imaizumi, & Imamizu, 2022; Poonian & Cunnington, 2013; Suzuki, Lush, Seth, & Roseboom, 2019; Zapparoli et al., 2020). In the Libet clock variant, participants make 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 and colleagues (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 are separated by a short but variable delay. Similarly 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, Cleeremans, & Haggard, 2015; Engbert et al., 2008; Zapparoli et al., 2020).

Recently, intentional binding studies have been gathering contradictory evidence, as temporal compression similar to the intentional binding was also observed when action intention was absent (Buehner, 2012; 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), suggesting that one's own intention is not necessary for eliciting temporal binding. A recent study found no difference in temporal estimation between voluntary and involuntary actions (Kirsch et al., 2019), further suggesting that intention is not sufficient either for eliciting temporal binding effects. A systematic review revealed that the effect size of temporal binding depends heavily on the condition used as baseline (Tanaka, Matsumoto, Hayashi, Takagi, & Kawabata, 2019). This could be ascribed to some confounding variables, as action intentionality was not always the only feature varying between the operant condition (involving a voluntary movement) and the baseline. For example, when an external sensory event was used at baseline as the outcome triggering cause, participants merely observed (or listened to) two external events. In such cases, actions was not involved in the baseline and participants had

no access to movement-related information, including voluntary motor command and somatosensory feedback that is known to influence time perception (Hagura, Kanai, Orgs, & Haggard, 2012; Tomassini, Gori, Baud-Bovy, Sandini, & Morrone, 2014; Wiener, Zhou, Bader, & Joiner, 2019). Thus, to isolate the "intentional" character of intentional binding, the passive movement condition, whereby an involuntary movement is induced either mechanically or by the experimenter, can serve as a better baseline. To the best of our knowledge, no study has compared the effect of these two baselines (external sensory event and passive movement). Yet, such a comparison is critical to disentangle the role of somatosensory information during action execution from that of intention in temporal binding. Thus, here we addressed this aim by comparing the effects of an active movement condition, a passive movement condition and an externally triggered sensory event condition on an interval estimation task. Intentional binding should be demonstrated by shorter interval estimation for the active than the passive movement condition. Critically, other types of temporal binding (i.e., not intentional) could be shown by different interval estimations between the active and/or passive movement condition and the external event condition.

Besides the specific baseline applied, another possible confounding component is the predictability of the first event (Buehner, 2012; Hughes, Desantis, & Waszak, 2013). Indeed, when previous studies used involuntary/passive movements as baseline, their onset was unpredictable for participants (Caspar et al., 2015; Engbert et al., 2008; Zapparoli et al., 2020). To our knowledge, only two studies controlled for the predictability of the movement while comparing active and passive movement conditions. One controlled for the temporal predictability of passive key presses with the method of constant stimuli, and reported that intentional binding was observed for 600-ms intervals, but not for 250-ms intervals (Nolden, Haering, & Kiesel, 2012). However, passive movements came from the key-board popping the participants' fingers upward, thus involving different somatosensory feedback compared to active movements. The other study that controlled for the temporal predictability of the passive movements, actually 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 as measured with the interval estimation task. Indeed, previous studies found that the binding effect increases with increasing intervals when the interval estimation method is applied, but that it decreases when the Libet clock method is used (Buehner & Humphreys, 2009; Haggard et al., 2002). Thus, the second aim of the present study is to test whether binding effects emerge when the temporal predictability of the first event is controlled for, 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 is to compare binding effects between visual and auditory outcomes.

To summarize, 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 with the interval estimation procedure by comparing an active movement condition to two different baselines, namely, the passive movement and the external sensory event conditions. In addition, we controlled for the temporal predictability of the first event. Finally, in order to assess the generality of the action effect across sensory modalities, the outcome was either auditory (Experiment 1) or visual (Experiment 2).

## Method

### 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). However, with this sample size, we did not find any difference between active movement and passive movement conditions. To rule out the lack of binding effect was due to lack of power, we increased the sample size to a total of 44 participants. One participant was excluded due to failure to produce temporal intervals varying monotonically with actual intervals. The remaining 43 participants (28 females, age = 25.2 ± 4.6 years old) participated in all three conditions.

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 varying 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.

In both experiments, 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 a 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.

### Apparatus and setup

In Experiment 1, the action consisted of a key press performed on a keypad, which was placed at 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 (44.1K Hz, 30 ms duration) played over a loudspeaker. Participants' estimates were collected via another external keypad operated by their right hand.

In Experiment 2, the action consisted of a similar keypress on a gamepad and the visual scene including the fixation cross was presented in virtual reality (VR), with participants wearing a head-mounted display (HMD, Oculus rift CV1, resolution 2160 × 1200). The action outcome was a visual effect (the lightening of a light bulb, Figure 2A). The light bulb was presented at either of two task-irrelevant distances from participants (45 cm or 4.5 m). As this manipulation, which was outside the scope of the present study, did not bring any difference in temporal binding, data were pooled together for analysis. Both Experiment 1 and Experiment 2 were programmed using the unity platform (Unity 2018.4.22f1 Personal) and Microsoft Visual Studio 2019.

### Task and procedure

In Experiment 1, participants sat on a chair and viewed the monitor at approximately 60 cm (Figure 1A). Prior to 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 s and 2.5 s (Figure 1A). The fixation cross offset was used as a temporal cue to prompt the first event: informing that key press was allowed at one's own willing time in the active movement condition, informing of the forthcoming passive key press in the passive movement condition, or informing of the forthcoming first tone in the external sensory event condition. Thus, the disappearance of the fixation cross provided participants similar levels of predictability for the first event in all conditions. Therefore, the three conditions differed mainly regarding the information available about the action. In the active movement condition, participants had predictability, intentional efferent and proprioceptive information about their own action. In the passive movement condition, they had predictability and proprioceptive, but lacked intentional efferent information about the action. In the external sensory event condition, no action related information was available to participants, but they had a similar level of predictability of the first event (Table 1).

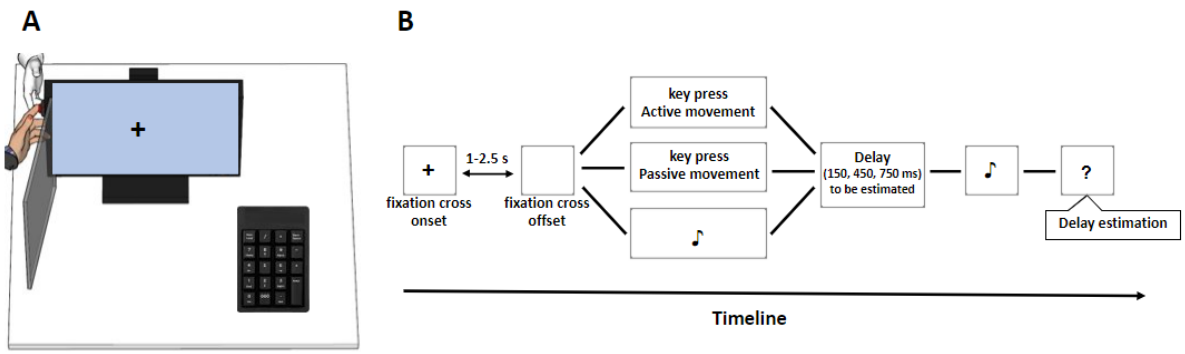


**Figure 1.** Set-up (A) and three experimental conditions (B) of Experiment 1. The set-up (A) is shown here for the passive movement condition. Panel B is a schematic illustration of a trial in the three conditions: active movement, passive movement and external sensory event conditions, which also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

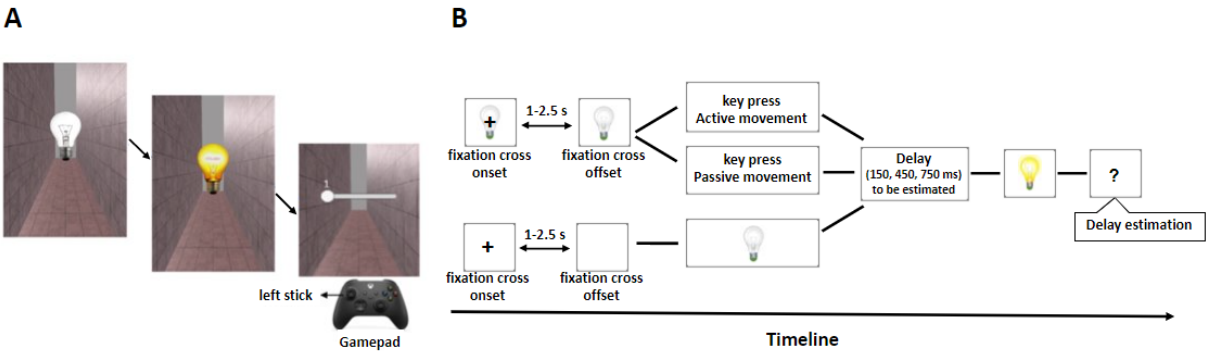


**Figure 2.** The experimental scene of a single trial (A) and experimental conditions (B) of Experiment 2. Panel A shows that, during each trial, an off-bulb was turned on by different causes depending on the condition. The key-press and interval estimates were performed through a gamepad. Participants indicated their estimates by moving a visually depicted slider with the left stick of the gamepad. Panel B is a schematic illustration of a trial in the three conditions: active movement, passive movement and external sensory event conditions. In active and passive movement conditions, the off bulb appeared at the beginning of each trial together with the fixation

cross, while it appeared after the fixation cross in the external event condition. Panel B also shows that there was same number of events occurring during a trial for all the conditions.

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

| *Information* / Cause | *Action intention* | *Somatosensory information* | *Predictability* |
|---|---|---|---|
| Active movement | ✓ | ✓ | ✓ |
| Passive movement | ✗ | ✓ | ✓ |
| External sensory 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: at 150, 450 or 750 ms, to make sure 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 the index finger action and the onset of the tone emission. For the external sensory event condition, they were asked to estimate the interval between the first and 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 ms 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 21 times randomly, resulting in 66 trials per condition. The first three trials were discarded from analysis.

In Experiment 2, the procedure was similar to that of Experiment 1 except for two things: 1) the external sensory events were visual instead of auditory; 2) the key-press and interval estimates were performed through a gamepad. In the active and passive movement conditions, an off-bulb was turned on after an active or a passive key-press (button "X" on the gamepad, Figure 2A). Participants were 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. For all conditions, participants indicated their estimates by moving a visually depicted slider with the left stick of a gamepad (Figure 2A). The interval between the two

events were the same as in Experiment 1 (Figure 2B) and the same number of repeated trials for each condition and for each interval were performed in Experiment 1 and 2.

**Data Analysis**

We conducted for each experiment a 3 × 3 repeated-measures ANOVA on participants' mean interval estimations with Cause (active movement, passive movement, external sensory event) and Delay (150, 450, 750 ms intervals) as within-subject variables. An intentional binding should be demonstrated by the presence of significantly shorter interval estimates for the active than the passive movement condition. Other types of temporal binding (i.e., not intentional) could be shown by the presence of significantly different interval estimates between the active and/or passive movement condition and the external event condition. Data analysis was conducted by customized Matlab programs (2019b, Mathworks, Natica, MA) and statistical analyses were conducted using the SPSS statistical package (IBM, SPSS 28.0). The significance level was set at $\alpha = 0.05$. Post-hoc one-tailed tests were used to compare the active movement to the passive movement conditions and two-tailed tests were used to compare the two baselines, i.e., the passive movement and the external sensory event conditions.

In addition, to fully explore the existence or the 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 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 (Wagenmakers et al., 2017) (Dienes, 2014; Jeffreys, 1939) (Dienes & Mclatchie, 2018). We also reported the robustness region (RR), giving 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 would lead to the same conclusion (Dienes, 2019).

## Results

### *Experiment 1*

The cause (active movement, passive movement, external sensory event) × the delay (150, 450, 750 ms) repeated-measures ANOVA revealed a main effect of Cause ($F(1.48,62.21) = 6.85$, $p = .005$, partial η2= .14, Greenhouse-Geisser corrected, Figure 3A). Pairwise comparisons showed that the mean interval estimation for the active movement condition (Mean ± SE = 286.93 ± 19.11) was not significantly different from the passive movement condition (Mean ± SE = 303.46 ± 19.72, $t(42) = 1.9$, $p_{one\text{-}tailed,\ corrected} = 0.10$), the evidence being unconclusive ($BF_{HN(0,122.5)} = 0.82$, $RR_{1/3<B<3} = [0, 309]$). On the contrary, the interval estimation for the active movement condition was significantly shorter than that observed in the external sensory event condition (Mean ± SE = 335.74 ± 22.32, $t(42) = 3.36$, $p_{one\text{-}tailed,\ corrected} < 0.01$), with substantial evidence in favor of the existence of such a temporal binding ($BF_{HN(0,122.5)} = 60.6$, $RR_{B>3} = [5, 2694]$). Finally, the interval estimation for the passive movement condition was numerically shorter than the external sensory event condition, the evidence being inconclusive ($t(42) = 2.03$, $p_{two\text{-}tailed,\ corrected} = 0.15$, $BF_{U(13.5,122.5)} = 2.5$, $RR_{1/3<B<3} = [92, 829]$).

The main effect of Delay was unsurprisingly significant ($F(1.14,47.78) = 203.37$, $p < .001$, partial η2= .83, Greenhouse-Geisser corrected). The estimation for the 150 ms delay was significantly shorter than for the 450 ms and the 750 ms delays, and 450 ms delay was estimated significantly shorter than the 750 ms delay. The interaction between Cause and Delay was also significant ($F(1.94,81.32) = 11.41$, $p < .001$, partial η2= .21, Greenhouse-Geisser corrected, Figure 3B). When estimating the longest delay, the reported intervals were significantly shorter for both active and passive movement conditions compared to the external sensory condition ($t(42) = 3.9$ and $t(42) = 3.2$ respectively, both $p_{corrected} < .01$) and the evidence in favor of the existence of these bindings was substantial for active vs. external sensory conditions ($BF_{HN(0,122.5)} = 591$, $RR_{B>3} = [8, >3000]$) and unconclusive for the passive vs. external sensory condition: $BF_{U(13.5,122.5)} = 0.86$, $RR_{1/3<B<3} = [0, 350]$) . When estimating the middle delay, the reported intervals were significantly shorter only for the active movement condition compared to the external sensory condition ($t(42) = 3.1$, $p_{one\text{-}tailed,\ corrected} < .01$) with substantial evidence in favor of the existence of this binding ($BF_{HN(0,122.5)} = 30$, $RR_{B>3} = [7, 1346]$). There was no other significant difference, in particular, the reported intervals were not significantly different across conditions when estimating the shorter interval. Importantly, the active and passive movement conditions did not significantly differ for any interval, with unconclusive evidence across all intervals (long: $BF_{HN(0,122.5)} = 0.85$, $RR_{1/3<B<3} = [0, 319]$; middle: $BF_{HN(0,122.5)} = 0.38$, $RR_{1/3<B<3} = [0, 141]$; short: $BF_{HN(0,122.5)} = 0.48$, $RR_{1/3<B<3} = [0, 175]$).

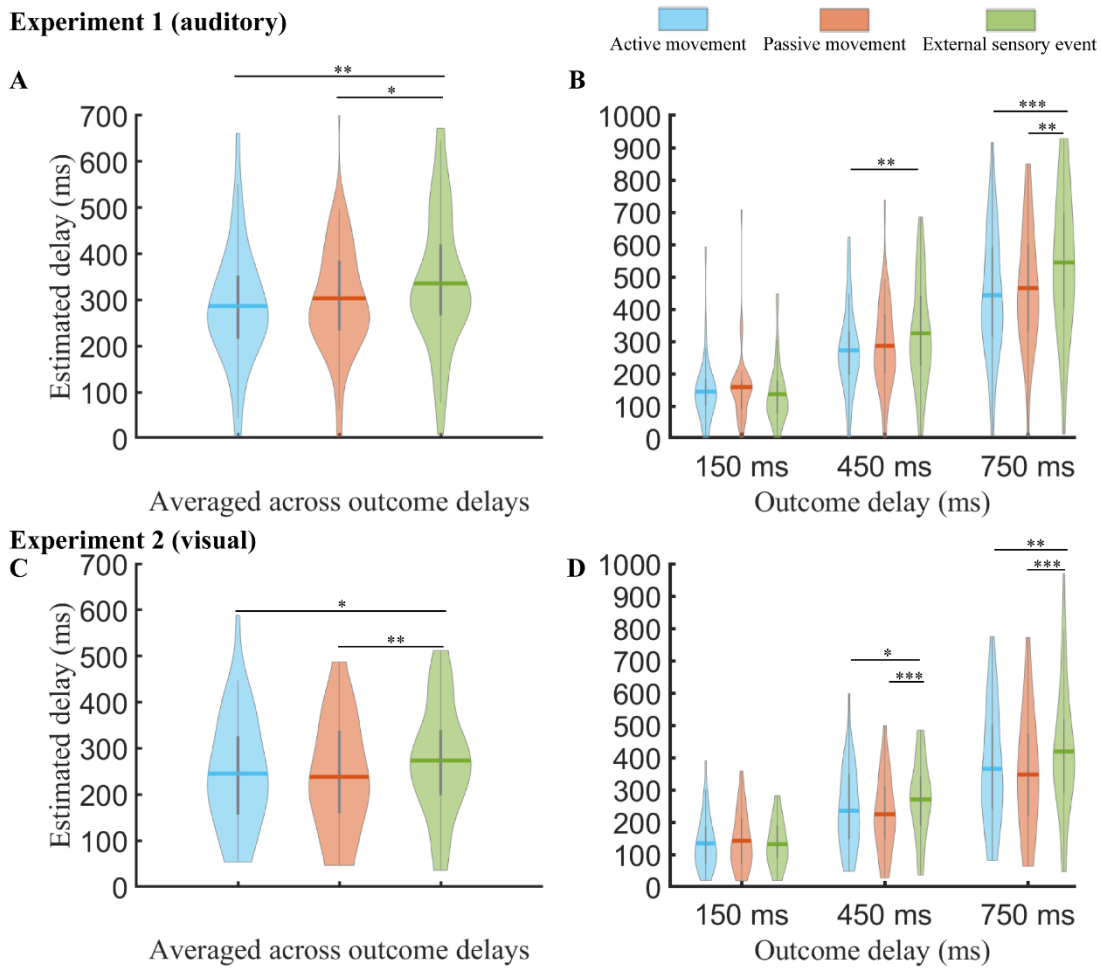


**Figure 3.** Results from Experiment 1 (auditory action outcome, panels A and B) and Experiment 2 (visual action outcome, panels C and D): (B) and (D) Main effect of the "cause" factor after calculating the averaged estimations of the three intervals, respectively. (A) and (C) Mean estimated outcome delay in three conditions (active movement, passive movement and the external sensory event) as a function of their actual interval. The three conditions are indicated by blue, orange and green color, respectively. Vertical grey lines in each panel refers to the interquartile range and the colored horizontal lines refers to the means. * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$.

### *Experiment 2*

The same repeated-measures ANOVA as applied in Experiment 1, again revealed a highly significant main effect of Cause ($F(1.69,71.13) = 6.66$, $p = 0.004$, partial $\eta 2 = 0.14$, Greenhouse-Geisser corrected, Figure 3C). The paired t-tests showed again no significant temporal binding when comparing the active movement condition (Mean ± SE = 245.15 ± 18.61) to the passive movement condition (Mean ± SE = 238.07 ± 18.02, $t(42) = 0.88$, $p_{\text{one-tailed, corrected}} > 1$), with this time substantial evidence in favor of the inexistence of an intentional binding ($BF_{HN(0,122.5)} = 0.15$, $RR_{B<1/3} = [57, >3000]$). As in experiment 1, the active movement condition was on the contrary significantly shorter than that observed in the external sensory event condition (Mean ± SE = 273.62 ± 18.11, $t(42) = 2.39$, $p_{\text{one-tailed, corrected}} < 0.05$), with substantial evidence in favor of the existence of such non-intentional binding

($BF_{HN(0,122.5)}$ = 3.3, $RR_{B>3}$ = [7, 134]). Finally, a significant temporal binding was also shown when comparing the passive movement condition to the external sensory event condition (t (42) = 3.3, $p_{one\text{-}tailed,\ corrected}$ < 0.01), with substantial evidence in favor of the existence of such binding ($BF_{U(13.5,122.5)}$ = 62.7, $RR_{B>3}$ = [0, 2273]).

As expected, the main effect of Delay was again significant (F (1.07,45.05) = 115.69, p < .001, partial η2= .73, Greenhouse-Geisser corrected). Importantly, the interaction between Cause and Delay was also significant (F (2.34,98.29) = 14.25, p < .001, partial η2 = 0.25, Greenhouse-Geisser corrected, Figure 3D). Consistent with Experiment 1, the post-hoc analysis showed that the reported intervals were shorter for both active and passive movement conditions compared to the external sensory condition when estimating the longest interval (t(42) = 2.9 and t(42) = 4.7 respectively, both $p_{corrected}$ < .01), with substantial evidence in favor of the existence of these bindings (active vs. external sensory conditions: $BF_{HN(0,122.5)}$ = 17.9, $RR_{B>3}$ = [8, 810]); passive vs. external sensory condition: $BF_{U(13.5,122.5)}$ = 18364, $RR_{B>3}$ = [0, >3000]) and the middle interval (t(42) = 2.6 and t(42) = 4.0 respectively, both $p_{corrected}$ < .05), with substantial evidence in favor of the existence of these bindings (active vs. external sensory conditions: $BF_{HN(0,122.5)}$ = 5.97, $RR_{B>3}$ = [7, 252]); passive vs. external sensory condition: $BF_{U(13.5,122.5)}$ = 656.7, $RR_{B>3}$ = [0, >3000]). No other significant differences were found, in particular, the reported intervals were not significantly different across conditions when estimating the shorter interval. Importantly, the active and passive movement conditions did not significantly differ for any interval, and the evidence in favor of the inexistence of an intentional binding was unconclusive for the long interval ($BF_{HN(0,122.5)}$ = 0.57, $RR_{1/3<B<3}$ = [0, 214]) and substantial for the two other intervals (middle: $BF_{HN(0,122.5)}$ = 0.25, $RR_{B<1/3}$ = [93, >3000]; short: $BF_{HN(0,122.5)}$ = 0.18, $RR_{B<1/3}$ = [67, 3000]).

**Discussion**

The present study examined whether the nature of temporal binding effect is genuinely intentional, while controlling for both the presence of somatosensory information and predictability of the cause event, by comparing interval estimates between the active movement, passive movement and external sensory event conditions across two sensory modalities of the action outcome. Our findings, based on a larger number of participants than in previous studies with significant intentional binding but lacking appropriate controls, did not show intentional binding, i.e., no substantial difference in interval estimation for the voluntary movement condition as compared to the passive movement condition. Furthermore, the Bayes factors indicated either substantial evidence in favor of the inexistence of the intentional binding (Experiment 2), or unconclusive evidence (Experiment 1, with Robustness Regions indicating that even smaller prediction of the size of the intentional binding would lead to the same conclusion). On the contrary, we found a temporal (but not intentional) binding when comparing both the voluntary movement and passive movement conditions to the external sensory event condition. Moreover, the presence of this temporal binding was modulated by the actual delay between the two events (longer delays leading to more consistent bindings than shorter delays), but not by the sensory modality of the effects (auditory or visual).

Here we carefully controlled for the available information between the active movement condition and the baselines. The difference of the available information for active and passive movements was that there was a voluntary motor command induced by the action 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 does not induce intentional binding when the temporal predictability of the action is controlled for. Our results are in keeping 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 for (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 the passive movement conditions, when compared to the external sensory event condition, in both experiments. Compared to active and passive movements, the external sensory event condition lacks intentional efferent and somatosensory information about the action. This result is consistent with a previous study in which the temporal predictability for the first external event was also controlled for in the baseline condition of two external events: the temporal binding effect was still observed when comparing the voluntary action condition to the baseline condition (Cravo, Claessens, & Baldo, 2011). It has been proposed that binding phenomena result from cue integration (J. Moore & Haggard, 2008; J. W. Moore & Fletcher, 2012; J. W. Moore, Wegner, & Haggard, 2009; Wolpe, Haggard, Siebner, & Rowe, 2013), but this framework mainly relied so far on the role of efferent motor signals. The present findings stress the role of somatosensory information, in which efferent motor signals do not necessarily need to be present.

It is worth noting that, when comparing between the external sensory event condition and the active/passive movement condition, the 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 be resulting from the causal relationship between two events, a claim made in previous studies (Buehner, 2012; Buehner & Humphreys, 2009; Desantis & Buehner, 2019; Desantis, Roussel, & Waszak, 2011). Compared to longer delays, the cause and effect are more likely to be perceived as causally linked in the shortest delay, as they follow each other closely in time. A strong enough causality-related binding between the first and the second events (their subsequent outcomes) in all the three conditions would explain the absence of difference between the three conditions.

In sum, we did not observe intentional binding when comparing active vs. passive movements. Instead, temporal binding emerged when comparing both active and passive movements to 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 care should be taken when using this phenomenon as an implicit measure of the sense of agency. The results argue that intentional binding between voluntary and involuntary actions found by 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 on the temporal attraction instead of motor command or action intention.

## Author Contributions

Conception and design of the study: G.K., M.V. and A.F.; Setup preparation and Software: G.K., and C.D.; Data collection: G.K. and C.A.; Data analysis: G.K and M.V.; Data interpretation: G.K., M.V. and A.F.; Original draft: G.K.; Critical revisions: M.V. and A.F.; All the authors approved the final manuscript for submission.

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## Declaration of Interests

The authors declare no competing interests.

## Open practices:

Experiments were not pre-registered. Data and materials have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/n7y8a/

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