Rethinking Intentional Binding

By

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The sense of agency (SoA), defined as the feeling of control over our actions and their outcomes, is a fundamental aspect of human experience (Haggard, 2017). Intentional Binding (IB), the subjective compression of the perceived time interval between an action and its outcome, is widely regarded as an implicit measure of SoA (Haggard, 2017; Moore & Fletcher, 2012; Moore & Haggard, 2010).

Notwithstanding the fact that SoA is a property of individuals, the IB effect is only documented at the aggregate level in the literature. Here, we present the first systematic study of IB at the individual level of analysis and document a pattern of anomalies in the directionality of the effect. In an experimental study in which we replicate IB at the aggregate level, we show that when the data are de-aggregated, 43% of the participants in our voluntary conditions behave in the opposite direction of what is theoretically predicted. That is, instead of showing subjective compression of the time interval between actions and outcomes, participants show time repulsion between these two classes of events, what one would expect if the actions were involuntary. Based on a reanalysis of nine datasets, we show that the anomaly we report is not an idiosyncratic feature of our study, but rather, that it is an invariant property of the IB effect, detectable across action types, laboratories, and experimental methodologies. These findings call into question the interpretation of IB as a measure of agentic processes and have important theoretical and practical implications.
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<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>v</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Intentional binding and the sense of agency</td>
<td>2</td>
</tr>
<tr>
<td>An anomaly</td>
<td>4</td>
</tr>
<tr>
<td>The anomaly is a norm</td>
<td>6</td>
</tr>
<tr>
<td>Discussions and implications</td>
<td>9</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>13</td>
</tr>
<tr>
<td>Our Study</td>
<td>13</td>
</tr>
<tr>
<td>Participants</td>
<td>13</td>
</tr>
<tr>
<td>Apparatus</td>
<td>13</td>
</tr>
<tr>
<td>Procedure and Design</td>
<td>14</td>
</tr>
<tr>
<td>Other dataset collection</td>
<td>15</td>
</tr>
<tr>
<td>References</td>
<td>17</td>
</tr>
<tr>
<td>Figures and Tables</td>
<td>21</td>
</tr>
</tbody>
</table>
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>Details about study methodologies</td>
<td>41</td>
</tr>
</tbody>
</table>
**Introduction**

Understanding the nature of willed actions has been a longstanding challenge in intellectual history. To be sure, the difference between voluntary and involuntary actions is fundamental and has critical implications for human endeavors as diverse as science, philosophy, the law, politics, and religion. Within the sciences of mind, voluntary actions are understood as giving rise to a Sense of Agency (SoA), broadly defined as the feeling of control over our actions and their outcomes (Haggard, 2017; Moore, 2016; Moore & Fletcher, 2012). SoA has often been measured by relying on explicit reports on the part of participants who are asked to indicate the level of control they experienced over their own actions (Daprati et al., 1997; Metcalfe et al., 2013; Metcalfe & Greene, 2007; Spengler et al., 2009). Such explicit reports, however, are prone to bias and manipulation (Moore & Haggard, 2008). About twenty years ago, work in cognitive neuroscience led to the discovery of a new phenomenon which is widely regarded as an implicit measure of SoA (Moore & Obhi, 2012). This phenomenon, known as intentional binding (IB), is characterized by the subjective compression of the perceived time interval between a voluntary action and its outcome (Haggard et al., 2002).

Here, we report an anomaly in the directionality of the IB effect that has hitherto remained undetected. In an experimental study of IB in which we replicate the effect at the aggregate level – the common practice in the literature - we document, for the first time to the best of our knowledge, that when the data are de-aggregated and analyzed at the individual level, up to 43% of the participants in the voluntary conditions of our study behave in the opposite direction of what is theoretically predicted. That is, instead of showing subjective *compression* of the time interval between actions and outcomes, participants showed time *repulsion* between these two classes of events, what one would expect if the actions were *involuntary*. Based on a reanalysis of nine experiments, including some of the most cited studies in the literature, we show that the anomaly we report is not an idiosyncratic feature of our own study, but rather, that it is an invariant property of the IB effect, detectable across action types, laboratories, and experimental methodologies.
These findings cast doubts on the interpretation of the IB effect as being a reliable marker of the sense of agency. Specifically, our findings demonstrate that the distinction between voluntary and involuntary conditions lacks explanatory force since a similar pattern of results obtains regardless of the nature of the actions involved. The same conclusion holds if we reconceptualize IB as tracking perceived causal links between actions and outcomes on the part of participants; what has been called temporal binding (Cravo et al., 2009; Dogge et al., 2012). Because IB tasks also by necessity engage other cognitive processes such as time perception and memory, the IB effect may turn out to be an epiphenomenon that has little to do with agency. (See Discussion and Implications.) Moreover, the theoretical caution that we advocate here has important implications for endeavors in applied domains such as clinical psychology, robotics, and human machine interactions, all of which have begun to rely on IB as an implicit measure of agency.

**Intentional Binding and the Sense of Agency**

In Haggard, Clark, and Kalogeras’ (Haggard et al., 2002) seminal study, participants were asked to press a button at a time of their choosing. This action was followed several hundred milliseconds later by the occurrence of a tone. Participants were then asked to estimate the timing of their action or the tone. The main finding was that when the action was voluntary – as opposed to an involuntary finger twitch caused by transcranial magnetic stimulation – participants subjectively estimated that their button press occurred later than it objectively did. Moreover, participants also subjectively estimated that the tone occurred earlier than it objectively did. This compression, or binding of these two events in subjective time, is what is known as intentional binding.

Since the initial report, approximately 300 IB experiments have been reported in the literature, and close to 90% replicate the effect. IB has been documented across different populations, including children (Cavazzana et al., 2014) and older adults (Vercillo et al., 2017), as well as patient populations such as individuals with schizophrenia (Graham-Schmidt et al., 2016), autism (Sperduti et al., 2014), and Parkinson’s disease (Moore et al., 2010). As an implicit measure of SoA, IB holds promise not only for the advancement of basic science, but also as a tool ripe with applied potential including already existing
extensions to the law (Pfister et al., 2021; Weller et al., 2020), the study of robotics (Khalighinejad et al., 2016; Roselli et al., 2019), and human computer interactions (Limerick et al., 2014).

When binding occurs in the context of voluntary actions, as in Haggard et al.’s original study (Haggard et al., 2002), the effect is typically regarded as a manifestation of SoA (Barlas et al., 2018; Demanet et al., 2013; Hoerl et al., 2020; Moore et al., 2009). In such contexts, motor-based predictive mechanisms have been hypothesized to give rise to IB. On this view, SoA arises when the predicted sensory consequences of voluntary actions match their motor consequences (Engbert & Wohlschläger, 2007; Synofzik et al., 2008; Tsakiris & Haggard, 2003). Subsequent work, however, revealed that binding can also occur outside the context of voluntary actions. For example, the effect has been documented when participants merely observe somebody else pressing a button to trigger a tone (Moore et al., 2013; Poonian et al., 2015), when the participants’ finger is pressed down by another person to trigger the tone (Caspar et al., 2016; Seghezzi & Zapparoli, 2020), or even when a machine activated the button to trigger the tone (Khalighinejad & Haggard, 2016; Wohlschläger et al., 2003). In some cases, cognitive-level retrospective inferences about causality between the action and the outcome are believed to give rise to what is sometimes referred to in such contexts as temporal – as opposed to intentional – binding (Poonian et al., 2015). Whether two mechanisms or only one are needed to account for the full range of contexts in which IB occurs remains a matter of debate (Hoerl et al., 2020).

Regardless of the precise nature of the mechanisms involved, the signature of the effect, whether temporal or intentional, is what is captured by the idea of binding; that is, the subjective compression of the time interval between the action and the outcome compared to its objective duration. An implicit, but

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1 In the literature, intentional binding is typically defined as the “compression of the perceived interval between action and outcome” (e.g., Haggard, 2017, p. 199). The term “compression”, however, has been interpreted in at least two different ways. The original interpretation is that the perceived time interval is compressed compared to the objective interval between action and outcome (e.g., Haggard et al., 2002; Haggard, 2017). On a different interpretation, the amount of compression has been compared across experimental conditions without any reference to the objective timing of the events. On this interpretation, if the perceived time interval between condition A is shorter than the one between condition B, then the conclusion is that there is more binding in condition A, regardless of the objective timing of the events (e.g., Weller et al., 2020). Our goal is not to adjudicate between these two interpretations but merely to point out that they exist in the literature. Crucially, this difference in interpretation has no bearing on the arguments that we present here. That is, the anomalies that we report are problematic whether or not compression is defined relative to the objective timing of the action and outcome. We briefly return to this issue in the Discussion and Implications section.
nevertheless critical, assumption is that barring exceptional circumstances (e.g., trauma, pathology), SoA is a phenomenon that arises in individual minds. And yet, in the literature, IB is always analyzed at the aggregate level, averaging over participants’ individual behavior. This practice rests on the assumption that the behavior of the group, the average, is representative of the behavior of the individuals within the group. However, this question has never been investigated. In the following section, we report the results of an experiment in which we replicate the standard IB effect at the group level but also analyze the data at the individual level.

An anomaly

In a study of IB using the standard Libet clock methodology (Libet, 1985), we manipulated the time interval (250ms vs. 750ms) as well as the congruence (congruent vs. incongruent) between voluntary actions and outcomes. Specific details about study methodology can be found in the “Materials and Method” section below.

Results replicated the IB effect at the aggregate level (Figure 1). A Shapiro-Wilk test on action binding data showed a significant departure from normality at the longer timing interval, $W(35) = 0.85, p < 0.001$, for congruent outcomes, $W(35) = 0.94, p = 0.045$, and for incongruent outcomes, $W(35) = 0.90, p = 0.010$. Separate Shapiro-Wilk tests on outcome binding data also showed a significant departure from normality at the longer timing interval, $W(35) = 0.91, p = 0.006$, for congruent, $W(35) = 0.92, p = 0.012$, and for incongruent outcomes, $W(35) = 0.94, p = 0.039$. As a result, a series of Friedman tests were conducted. Analyses indicated that action binding did not differ by timing interval length, $\chi^2(1) = 1.40, p = 0.237$ nor by congruence of outcome, $\chi^2(1) = 0.57, p = 0.451$. For outcome binding, there was a significant effect of timing interval, $\chi^2(1) = 17.50, p < 0.001$ but no effect of congruence, $\chi^2(1) = 0, p = 0.954$. A post hoc Wilcoxon signed rank test confirmed the presence of more outcome binding in the longer timing interval ($M = -443.25ms, SD = 311.94$) as compared to the shorter one ($M = -188.28ms, SD = 244.43$), $p < 0.001$.

Next, we investigated the behavior of participants at the individual level in action and outcome binding across experimental conditions (Figure 2A-2B). In the 250ms congruent condition, where binding
and feelings of control were predicted to be the strongest (Haggard et al., 2002), we found that 43% of the participants behaved in the opposite direction of what is theoretically predicted. That is, instead of showing compression of the time interval between actions and outcomes, participants displayed temporal repulsion between these two classes of events, what one would expect if the actions were involuntary.

The same unexpected temporal repulsion was found in our other voluntary conditions. In the 750ms congruent condition, 26% of the participants behaved in this anomalous way. In the 250ms incongruent condition, 43% of the participants did so, and in the 750ms incongruent condition the anomalous temporal repulsion pattern was observed in 34% of the participants. This, to the best of our knowledge, is the first reported evidence of temporal repulsion in voluntary action conditions.²

**The anomaly is a norm**

In order to determine whether the anomaly we reported is an idiosyncratic feature of our own study or a more general phenomenon, we reanalyzed nine datasets that were either publicly available or shared with us by the authors. (See “Materials and Method” section for more detail on how the datasets were chosen.) We categorized the experimental conditions based on the type of actions involved (i.e., passive, involuntary, and voluntary). Plots are color coded to simplify comparison across studies. For studies using the Libet clock methodology, action binding is plotted in blue and outcome binding in purple. Studies using interval estimation are plotted in green. We show that the anomaly we reported is not an idiosyncratic feature of our study, but rather, that it is an invariant property of the IB effect, detectable across action types, laboratories, and experimental methodologies.

First, we summarize results from two experiments from one paper representing the passive case (Weller et al., 2020, EXPs 2 and 3A nonaction trials). Passive is defined here as a purely observational condition where no motor action, and therefore no motor feedback, was present. We focus on the nonaction trials in these experiments as they represent an example of a passive experimental condition. In

² To the best of our knowledge, we are the first to highlight and explicitly report repulsion in this case. Repulsion can be gleaned from results of previously published studies. For example, Weller et al. (Weller et al., 2020) do in fact report that participants overestimate the shortest timing interval (i.e., temporal repulsion between action and effect) but do not explicitly mention this or provide an explanation for why this might be the case. In fact, the data are plotted in a way that obscures this overestimation and requires additional calculations on the part of the reader to detect the anomaly. (See Discussion and Implications for more detail.)
these trials, participants chose not to perform an action, and that decision, in turn, elicited either an auditory (EXP 2) or a combination of auditory and visual (EXP 3A) outcomes that were different from trials in which participants performed a motor action. The authors do not provide a specific prediction about directionality for binding on nonaction trials and instead reported that binding should be weaker for trials where participants did not perform an action compared to trials where an action was performed. Thus, if binding is present in both action and nonaction trials (albeit weaker for nonaction trials), one should expect underestimation in both cases.

The aggregate and individual results are replotted in Figure 3. Though Weller et al. (2020) reported binding as positive values, we replotted their data using the standard calculation taking the objective timing of the events into account. Positive values for actions and negative values for outcomes indicate compression, i.e., the presence of intentional binding. At the aggregate level, there is evidence of time compression in experiment 2 (center line in boxplot top left panel) and repulsion for experiment 3A (center line in boxplot top right panel). At the individual level, however, compression and repulsion can be observed in both experiments. The individual results from the nonaction trials from Weller et al. (2020) show overestimation where underestimation is expected, with 26% in experiment 2 and approximately 67% across all timing intervals in experiment 3A (up to 100% when separated by time interval; see bottom three panels in Figure 3).

Next, we consider examples of involuntary actions. Borhani, Beck, and Haggard’s (2017) passive condition represents such a case. Here, a motor action is present though it is involuntary since it is performed by the experimenter who pushed down the participants’ finger to depress a key. Since the action is involuntary for participants, one would expect repulsion or overestimation of the time interval between the action and outcome. The aggregate and individual results for involuntary action trials are depicted in Figure 4. At the aggregate level, compression is barely detectable for actions (center line in boxplot left panel Figure 4). Compression is stronger (compared to actions) at the aggregate level for outcomes in the involuntary action trials (center line in boxplot right panel Figure 4). At the individual level, up to 95% of participants show compression for outcomes (right panel) and 50% for actions. This
proportion of participants displaying outcome binding for an involuntary outcome is unexpected, especially on the standard assumption that intentional binding is tracking the experience of control.

Finally, and arguably most important, we consider examples of voluntary actions. In these conditions, participants freely perform an action at a time of their choosing which is followed by an outcome (e.g., a tone), typically a few hundred milliseconds later. Voluntary actions represent the most frequently studied cases with >90% of all intentional binding studies in the literature including at least one voluntary action condition. The nine datasets we obtained all included voluntary action trials. Here, we present data from these trials for each study: Buehner and Humphreys EXP 1 (2009); Moore and Haggard (2008); Borhani, Beck, and Haggard (2017) voluntary action trials; Muth et al. (2020) EXP 1; Pansardi et al. (2020); Pfister et al. (2021); Schwarz et al. (2019); and Weller et al. (2020) experiments 2 and 3A, action trials only. The aggregate and individual results from each study are depicted in Figures 5-13.

Aggregate results from Buehner and Humphreys (2009) show slight compression for actions and outcomes at almost every time interval with the strongest binding for events separated by the longest time interval (center line in 1300ms boxplots Figure 5A and 5B). At the individual level, across all three timing intervals, 32-59% of the sample in the baseline condition (Figure 5A) and 27-68% in the causal control condition (Figure 5B) showed the action or the outcome in the opposite of the expected direction (negative or positive, respectively). The aggregate results from Moore and Haggard (2008) show that compression is present for all conditions except for one condition where outcomes, after voluntary actions, were presented 50% of the time (“50% Action Only”) (center line in boxplots Figure 6) but the individual data (raincloud plots and bar plots Figure 6) show that repulsion is present in 39-74% of the sample, depending on the condition.

Aggregate results from Borhani, Beck, and Haggard’s (Borhani et al., 2017) voluntary action condition show both actions and outcomes in the expected direction at the aggregate level (center lines in boxplot Figure 7). At the individual level, only 10% of the sample showed action binding in the opposite of the expected direction (left panel, Figure 7). Aggregate results for Muth et al. (Muth et al., 2020) show both actions and outcomes in the expected direction across the experimental conditions (center line in
boxplots figure 8). At the individual level, across the three interval lengths, 4-19% of the sample have average action or outcome binding in the opposite of the expected direction (raincloud plots figure 8).

Turning to Pansardi et al. (Pansardi et al., 2020), a similar pattern emerges with both action and outcome binding reported in the expected direction at the aggregate level for both a control sample (center line in boxplots figure 9A) and a special population of expert pianists (center line in boxplots figure 9B). However, individual differences reveal that 18-32% of the sample have binding values in the opposite of the expected direction, although this variability is only present for actions (see raincloud plots and bar plots in Figure 9).

Pfister et al. (Pfister et al., 2021) report binding for both operant and prevention trials in the expected direction at the aggregate level (center line in boxplots Figure 10). However, error bars reveal the presence of substantial intra- and inter-individual variability. Between these two conditions, 28-41% of the sample have average binding values in the opposite of the expected direction. Data from Schwarz et al. (2019) follow a similar pattern with aggregate outcome binding in the expected direction (center line in boxplots figure 11) and 5-7% of the sample reporting average outcome binding in the opposite of the expected direction.

Finally, aggregate results for action trials in experiment 2 of Weller et al. (2020) indicate a replication of the expected effect – the presence of outcome binding during action trials. Individual differences reveal that only 9% in this sample showed repulsion in this case (Figure 12). Aggregate results from experiment 3A indicate that collapsed across timing intervals (Figure 13A), 48% of the sample show repulsion or overestimation in the voluntary action condition – the opposite of what is expected. When broken down by timing interval (Figure 13B), up to 100% of the sample (see 100ms interval) show repulsion in a voluntary action condition.

**Discussion and Implications**

The defining feature of the IB phenomenon is the compression of the subjective time interval perceived to occur between an action and its outcome. Throughout the literature, IB is exclusively measured at the aggregate level, averaging over participants’ behavior. However, the sense of agency is a property of individuals. What we uncovered at the individual level of analysis is surprising in this regard.
In voluntary conditions, where binding should be the strongest, almost half of the participants in our study displayed the effect in the opposite direction of what is theoretically expected. Moreover, this anomaly appears to be an invariant property of the effect, detectable across action types, laboratories, and experimental methodologies. Why should this be?

One possibility is that what we uncovered simply reflects typical individual variation even for robust psychological phenomena. However, two lines of evidence militate against this interpretation. The first is that historically, for robust psychological phenomena, approximately 2-15% of participants do not show the effect (Deese & Kaufman, 1957; Geissler (Geißler) et al., 2020; McGurk & MacDonald, 1976; Stroop, 1935). IB is different. Participants do not fail to show the effect; they show the effect in the opposite direction of what is theoretically predicted. Moreover, the proportion of participants who behave in this anomalous fashion is often much larger than the reported 10-15%. The second line of evidence comes from work in sensory-motor integration also concerned with the nature of voluntary actions. Ryu and Torres (2020), for example, have systematically tracked motor action trajectories within individuals and discovered different kinematic signatures depending on whether the movements were intentional or not. Crucially, unlike IB, these signatures are robust and can be observed at the individual level in every single participant.

Another possibility is to change the metric by which the effect is conceptualized and untether subjective temporal values from their objective counterparts. This has been done, for example, by comparing different subjective values to each other across conditions (Barlas et al., 2018; e.g., Weller et al., 2020). However, on this interpretation of the effect, we should still expect differences between conditions to be consistently present across individuals. If we replot the Weller et al. (2020) EXP 3A data to compare individuals across conditions, we would expect to see the greatest magnitude of binding (indicated by smaller or more negative values) for actions compared to nonactions with both action and nonaction binding magnitudes greater than binding for baseline trials. Moreover, we would also expect this relationship to be consistently detectable at the individual level. As depicted in Figure 14, we see that when we compare across experimental conditions at the individual level, 63% of the sample (depicted in
red) does not show the expected pattern of results. Thus, even if IB is regarded as a relative difference in compression between conditions, the predicted pattern does not obtain at the individual level of analysis.

If we take the anomaly that we uncovered at face value, either of two conclusions follow. The first is that IB does measure the sense of agency albeit quite poorly. If so, efforts should be made to better understand what else IB is tracking, and much more caution should be exercised in interpreting the results of IB studies. This is in line with Synofzik and colleagues’ (2009) observation that “the stronger interpretation that binding indicates just and only agency does not necessarily follow in all contexts.”

The other possible conclusion is that IB is not measuring the sense of agency. To be sure, in addition to potentially tracking agency or causality, IB tasks are also time perception and memory tasks. The relevant time intervals need to be committed to memory and then recalled in order to be subsequently reported. Thus, independently established memory or time perception mechanisms may give rise to binding. For example, regression to the mean is a pervasive memory effect that has obscured the interpretation of psychological results for decades (Nesselroade et al., 1980; Thorndike, 1942), most recently and notably the Dunning-Kruger effect (Gignac & Zajenkowski, 2020). A replotting of the results from Weller et al.’s (2020) experiment 3A reveals a clear regression to the mean effect (Figure 15A) which can also be detected at the individual level (Figure 15B). Using a simple and independently validated Bayesian model of memory (Hemmer et al., 2015; Hemmer & Steyvers, 2009), we have already successfully separated the role of memory, in the form of regression to the mean, in this dataset (Saad et al., 2021, in prep). This model can also account for differences in timing estimations between conditions by reconceptualizing them as errors in encoding, rather than altered experience of agency. Importantly, our analyses show that results from a binding task can be explained without appealing to agency or control.

Finally, in two of the datasets we analyzed, the proportion of individuals who show anomalies in the directionality of binding was smaller compared to the other datasets; notably, Schwarz et al. (Schwarz, Weller, Pfister, et al., 2019) and Muth et al. (Muth et al., 2020). On the standard interpretation of binding as a measure of SoA, this would mean that participants felt more agency in these studies compared to the others we analyzed. However, this is puzzling. Schwarz et al. (Schwarz, Weller, Pfister, et al., 2019) used
a slight modification on the standard IB paradigm where participants were asked to press a button at a specific location on a Libet clock (which one would assume may reduce agency). Muth et al. (Muth et al., 2020) used a new auditory timer method in which participants had to report the letter of the alphabet they heard at the time of a specific event. Both studies report sample sizes comparable to other studies in the literature, the results are unlikely to be explained by insufficient power. If IB is tracking agency, it is unclear why more consistent agency should be experienced in these studies compared to typical setups where participants can press the button at a timing of their choosing.

We conclude that while IB remains a robust effect at the aggregate level, the systematic anomalies we have uncovered at the individual level call into question the interpretation of the phenomenon. At issue is whether IB measures the sense of agency construed either as involving voluntary actions or a perceived causal link between actions and outcomes. The alternative is that binding is an epiphenomenal artifact that arises from the operation of cognitive mechanisms other than those implicated in the regulation of agency. Until these issues can be fully disentangled, claims about the relationship between IB and agency should be interpreted with caution.

**Materials and Methods**

**OUR STUDY**

All materials for our study including experiment and analysis code can be found here (https://osf.io/4qk7u/). All methods were reviewed and approved by the Institutional Review Board at Rutgers University.

**Participants**

We recruited 47 undergraduate students and volunteers from Rutgers University and the surrounding area. Participants agreed to complete the study either in exchange for course credit or for monetary compensation ($5/30mins). All participants completed the consenting process before beginning the experiment. Participants (N=12) were excluded based on poor performance during single-event (baseline) trials on the assumption that difficulty with the simpler, single-event condition would translate to increased difficulty on the dual-event (operant) trials. Poor performance is defined here by error values greater than 300ms or less than -300ms on more than 4 out of 10 baseline trials. Additionally, due to
experimenter error with randomization, some of the earlier participants did not complete any incongruent action trials. As a result, the reported statistical analysis was completed on a subset of participants, N=28.

Apparatus

Participants completed the task on desktop computers with a standard keyboard and mouse. Computers were organized in a computer lab with separated cubicles for participants. The experiment, including the Libet clock, was programmed in and administered using MATLAB Release 2019a and Psychophysics Toolbox Version 3. GStreamer was used to program the auditory outputs. Auditory stimuli were presented using headphones connected through the audio output of the desktop computers.

Procedure and Design

Participants first completed an intake form and provided information about their gender, handedness, and age. On each trial, participants observed a red dot rotating around a circle at an approximate rate of 2.5 seconds per rotation. Participants were asked to make a voluntary action at a timing of their choosing and were instructed to wait one full rotation before responding. This action was linked to one of two audio clips. The instructions stated, “Press ‘Z’ if you want to hear a new clip” or “Press ‘M’ if you want to hear a music clip”. Each audio clip was three seconds long. Participants were instructed to do their best to press each key an even number of times without switching back and forth between the two. To increase attention and effort, participants were also informed that at the end of each trial they would be asked to make an estimate about the location of the dot on the screen at the time of either their button press or the start of the audio clip. At the end of each trial, participants made estimations of event timings by placing the dot on the location on the circle where they believed it was when the event occurred.

Trials were dividing into two blocks of 60 operant trials and two blocks of 10 baseline trials. Operant trials refer to those trials where a participant presses a button and hears the auditory outcome and were further divided into operant action or operant outcome depending on which event the participant was asked to estimate the timing of. For example, in an operant action trial, the participant pressed a button, heard an auditory clip, and was then later asked to report the location of the dot when they pressed the button. Baseline trials were divided into baseline action, where participants pressed a button and then
reported the timing of that action, or baseline outcome, where participants heard an audio clip and reported the timing of when the audio clip began. Baseline trials were blocked together for 10 baseline action and 10 baseline outcome whereas operant trial type was randomized within two blocks of 60 trials.

Responses to the timing estimation were self-paced and participants could change the location of the dot on the circle as many times as they liked until they were satisfied with their response. Participants proceeded through the task by pressing the space key when they were ready to continue.

Using a within-subject design, we manipulated both congruence of outcome and timing interval between action and outcome in a 2 (congruence) x 2 (timing interval) design. On 20% of operant trials the outcome was incongruent, i.e., a button press of “z” presented a music clip. To manipulate timing interval, on half of the trials, the audio clip began 250ms after the button press and on the other half of the trials the audio clip began 750ms after the button press. Both congruence and timing intervals were randomized so that presentation of trial type was not blocked. The interval between the end of the auditory clip and the presentation of the timing estimation question was fixed at one second and the inter-trial interval was fixed at two seconds. A blank screen was presented in between trials. Explicit agency was also obtained using a self-report measure, but results will not be discussed here as they are not relevant to the scope of this paper.

OTHER DATASET COLLECTION

All datasets and completed re-analysis can be found online (https://osf.io/4qk7u/). There are nine datasets included in the analysis of this paper. Our selection method for inclusion of those papers is as follows. We first identified papers within the intentional/temporal binding literature that were among the most highly cited and contacted the corresponding authors directly via email. Of the five contacted, three individuals returned either the dataset we requested or another relevant dataset (Borhani et al., 2017; Buehner & Humphreys, 2009; Moore & Haggard, 2008). Additionally, from July 2020-February 2021, the primary author conducted a systematic literature search for open-source datasets in the published intentional/temporal binding literature. This was conducted in PubMed and PsycINFO using the keyword phrases “intentional binding”, “temporal binding”, and “causal binding”. From this search we found 13 additional datasets from six papers (Kirsch et al., 2019; Muth et al., 2020; Pansardi et al., 2020; Pfister et
al., 2021; Schwarz, Weller, Klaffehn, et al., 2019; Weller et al., 2020). One dataset could not be opened via the link provided (Kirsch et al., 2019). After compiling all available datasets, we next removed those using study methodologies that were not directly relevant to the scope of the paper (19, EXP 1; 40) as well as those that were replications with modifications of an experiment within the same paper (19, EXP 3B; 39, EXP 2). The remaining nine datasets are reported here from eight papers (9; 19, EXPs 2 and 3A; 38; 39, EXP 1). See Table 1 for specific details about the methodology and variables of interest in each dataset included. Data were replotted with all available materials. Analyses and data organization/cleaning followed the exclusion criteria reported in the respective publication. Where possible (i.e., where individual trial data was made available) error bars were included in bar plots.
References


Figures and Tables

Saad et al. (2021) Aggregate Results

Figure 1. Aggregate results from the replication study. Error represents the standard IB calculation; a first subtraction of the objective timing from the subjective timing. Averages are computed for all operant and baseline trials separately and the averages of baseline trials are subtracted from their respective operant trials (e.g., congruent actions – baseline action). * indicates significance at the 0.05 level. N=28. Error bars represent standard deviation.
Figure 2A. Individual differences in replication study. Action (left column) and outcome (right column) binding results at the 250ms timing interval for congruent (top row) and incongruent (bottom row) outcomes. N=28. Error bars represent standard deviation.
Figure 2B. Individual differences in replication study. Action (left column) and outcome (right column) binding results at the 750ms timing interval for congruent (top row) and incongruent (bottom row) outcomes. N=28. Error bars represent standard deviation.
Figure 3. Replotting intentional binding results for studies with passive actions. (Top left) Weller et al. (Weller et al., 2020) EXP 2. Individual and aggregate binding values for outcomes after nonactions. Nonactions in this case indicate that the participant made a choice not to act in order to allow the predetermined set of events to continue. Error here represents a standard IB calculation as described in figure 1. N=34. Error bars represent standard deviation. (Top right) Weller et al. (2020) EXP 3A. Individual and aggregate binding values for nonaction trials. Error here is simply the objective or actual timing of the interval subtracted from the participants average estimate for this trial type (e.g., participant reports 127ms for a 100ms interval = 27ms error value). N=27. Error bars represent standard deviation. (Bottom) Weller et al. (19) EXP 3A. Individual and aggregate nonaction binding across 100ms (bottom left), 400ms (bottom center), and 700ms (bottom right) timing intervals. N=27. Error bars represent standard deviation.
Figure 4. Replotting intentional binding results for studies with passive actions. Borhani, Beck, and Haggard (2017) involuntary actions (left) and outcomes (right). N=20.
Figures 5-13. VOLUNTARY ACTIONS

Figure 5A. Replotted individual and aggregate results from Buehner and Humphreys (2009). Action (left column) and outcome (right column) binding for baseline trials by individual across 500ms (top row), 900ms (center row), and 1300ms (bottom row) intervals between the action and outcome. N=34.
Figure 5B. Replotted individual and aggregate results from Buehner and Humphreys (2009). Action (left column) and outcome (right column) binding for causal control trials by individual across 500ms (top row), 900ms (center row), and 1300ms (bottom row) intervals between the action and outcome. N=34.
Figure 6. Moore and Haggard (2008). Individual and aggregate results for trials where there was only an action 50% of the time (top left), trials where there was an action and tone present 50% of the time (top right), trials where there was only an action 75% of the time (bottom left), and trials where there was an action and tone 75% of the time (bottom right). N=61.
Figure 7. Borhani, Beck, and Haggard (2017). Intentional binding for voluntary actions (left) and outcomes (right). N=20.
Figure 8. Muth et al. (2020) EXP 1. Individual and aggregate results for action (left column) and outcome (right column) binding for the 150ms (top row), 200ms (middle row), and 250ms (bottom row) intervals between actions and outcomes. N=48.
Figure 9A. Pansardi et al. (2020) Intentional binding results for control participants. Panels depict action (left column) and outcome (right column) binding for trials in which the outcome was a tone (top row) and a piano note (bottom row). N=28.
Figure 9B. Pansardi et al. (2020) Intentional binding results for expert pianists. Panels depict action (left column) and outcome (right column) binding for trials in which the outcome was a tone (top row) and a piano note (bottom row). N=28.
Figure 10. Pfister et al. (2021) Individual and aggregate binding for operant (left) and prevention (right) trials. N=99. Error bars represent standard deviation.
**Figure 11.** Schwarz et al. (2019). Individual and aggregate outcome binding results for tone alternating (left) and repeating (right) trial types. N=61.
Figure 12. Weller et al. (2020) EXP 2. Binding results for outcomes after actions. N=34. Error bars represent standard deviation.
Figure 13A. Weller et al. (2020) EXP 3A. Intentional binding results for action trials. N=27. Error bars represent standard deviation.
Figure 13B. Weller et al. (2020) EXP 3A. Action trials by timing interval. Pane depict individual results across 100ms (left), 400ms (center), and 700ms (right) intervals between actions and outcomes. N=27. Error bars represent standard deviation.
Figure 14. Weller et al. (2020) EXP 3A. Comparing individual binding results by condition. Participant averages can be compared moving across plots horizontally. The left plot represents individual averages for action trials, center represents nonaction trials, and the right panel represents baseline trials. The published prediction of the magnitude of binding from the paper was as follows: action ≥ nonaction > baseline. Here participant averages are collapsed across timing intervals. N=27.
Figure 15A. Weller et al. (2020) EXP 3A. Regression lines at aggregate across all trials and separated by experimental condition. See legend for slope and intercept values. N=27.
Figure 15B. Weller et al. (2020) EXP 3A. Regression lines across individuals by experimental condition. The left panel depicts individual results across three timing intervals in the baseline condition. The center panel depicts individual results in the nonaction trials. The right panel depicts individual results in the action trials. N=27.
Table 1: Details about study methodologies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Citations (as of 9/13/21)</th>
<th>N</th>
<th>Variable(s) of interest</th>
<th>Timing estimation method</th>
<th>Action Type</th>
<th>Outcome Modality</th>
<th>Interval Between Action and Outcome</th>
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<tbody>
<tr>
<td>Buehner &amp; Humphreys Exp 1</td>
<td>2009</td>
<td>195</td>
<td>34</td>
<td>Causality</td>
<td>Event anticipation paradigm</td>
<td>Button press</td>
<td>Visual</td>
<td>500, 900, or 1300ms</td>
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<td>Borhani, Beck, &amp; Haggard</td>
<td>2017</td>
<td>46</td>
<td>40</td>
<td>Intentionality, active versus passive movement, and outcome type</td>
<td>Libet clock</td>
<td>Button press (voluntary or machine caused)</td>
<td>Somatic</td>
<td>250ms</td>
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<tr>
<td>Moore &amp; Haggard</td>
<td>2008</td>
<td>398</td>
<td>10</td>
<td>Contingency; Prospective versus retrospective influences</td>
<td>Libet clock</td>
<td>Button press</td>
<td>Auditory</td>
<td>250ms</td>
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<td>Libet clock</td>
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<td>Auditory</td>
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<td>100</td>
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<td>Libet clock</td>
<td>Button Press</td>
<td>Auditory</td>
<td>300ms</td>
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<td>Agency for deliberate nonactions</td>
<td>Libet clock</td>
<td>Button press or nonaction</td>
<td>Auditory</td>
<td>300ms</td>
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<td>5</td>
<td>34</td>
<td>Predictability of outcome</td>
<td>Interval Estimation</td>
<td>Button press or nonaction</td>
<td>Auditory</td>
<td>100, 400, or 700ms</td>
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