Review

What Makes Action and Outcome Temporally Close to Each Other: A Systematic Review and Meta-Analysis of Temporal Binding

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Abstract

Temporal binding refers to the subjective compression of the temporal interval between a voluntary action and its external sensory consequences. While empirical evidence and theoretical accounts have indicated the potential linkage between temporal binding and action outcome prediction mechanisms, several questions regarding the underlying processes and the fundamental nature of temporal binding remain unanswered. Based on the sophisticated classification of predictive processes proposed by Hughes et al. (2013), we conducted a systematic, quantitative review of the binding effect as measured with two representative procedures, i.e., Libet clock procedure and interval estimation procedure. Although both procedures were designed to measure the same phenomenon, we revealed a larger effect size and higher sensitivity to perceptual moderators in binding observed with the clock procedure than with the interval estimation. Moreover, in the former, we observed different characteristics for the two perceptual shifts that comprise temporal binding. Action shifts depended more on whether one can control outcome onsets with voluntary actions. In contrast, outcome shifts depended more on the degree to which participants could predict, rather than control, the action outcome onset. These results indicate that action shift occurs based on the activation of learned action–outcome associations by planning and executing actions, while outcome shift occurs based on comparing predicted and observed outcomes. By understanding the nature of each experimental procedure and each shift, future research can use optimal methods depending on the goal. We discuss, as an example, the implications for the underlying disorders of agency in schizophrenia.

Keywords

Temporal binding, intentional binding, Libet clock procedure, interval estimation procedure, action outcome prediction, comparator model, sense of agency, meta-analysis

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1. Introduction

Temporal binding refers to the subjective compression of the temporal interval between a voluntary action and its external sensory consequence (also called *intentional binding*; Haggard et al., 2002). This illusion in time perception has been thought to depend on a forward action model that predicts the outcome of the action (see Moore & Obhi, 2012), but this idea has been questioned in recent years. Hughes et al. (2013) classified the predictive mechanisms into four different processes (namely temporal, identical, motor, and non-motor prediction), and reviewed previous studies examining the relationship between each prediction and temporal binding, failing to find clear evidence that temporal binding is caused by motor predictive processing. While pointing out the lack of critical comparisons in the available empirical research, they concluded that temporal binding might rather be driven by the ability to control when outcomes would occur.

In the current paper, we begin by reviewing previous works investigating the relationship between temporal binding and prediction, based on the work of Hughes et al. (2013), with the aim of identifying the questions remaining to be answered. To derive a comprehensive conclusion from a large set of observations from different studies, we next consider which shared experimental parameters reflect each prediction process, as classified by Hughes et al. (2013). Based on this, we conduct a meta-analysis to investigate how prediction can modulate the effect size of temporal binding. This allows us to specify the independent effects of different prediction processes that have not been separated in individual studies, considering the differences in experimental procedures. We discuss the potential predictive processes underlying the two perceptual shifts (i.e., action shift and outcome shift) that constitute temporal binding, and the differences in temporal binding obtained by two representative measurement procedures. In addition, we consider the potential usefulness of our results for understanding disorders of agency in schizophrenia.

1.1. Current Theory of Prediction in Temporal Binding

The relationship between temporal binding and the prediction of action outcome has already been proposed since Haggard et al. (2002) first reported this phenomenon. They used the Libet clock procedure (Libet et al., 1983), where participants were required to report the onset time of actions or the presentation of their sensory outcomes with the position of a clock hand rotating at one revolution per 2,560 ms. This procedure measures temporal binding through the time estimation of actions and outcomes in the operant and baseline conditions. In the operant condition, participants perform voluntary actions (i.e., press a key) while watching the clock rotating speedily on the screen. These actions cause specific effects such as the presentation of an auditory tone after a short interval (e.g., 250 ms). In the baseline condition, participants either perform an action that does not cause any outcome or listen to the tone presented at random times without any action. In separate experimental sessions, in the operant and baseline conditions, participants report where the clock hand had been pointing when the action was executed and when the tone was presented, respectively. These judgments of perceived times of actions and tones in the operant condition are then compared with those in the baseline conditions. Haggard et al. (2002) observed two perceptual shifts in time estimation for actions and their outcomes between the operant and baseline conditions.

Specifically, in the operant condition, actions that caused an event were experienced later, and action outcomes triggered by a voluntary action were experienced earlier, as compared to those in the baseline condition, where actions or outcomes occurred in isolation. In this study, we refer to these perceptual shifts in time as action shift and outcome shift, respectively.

At the same time, Haggard et al. (2002) found that this binding was reversed by involuntary movement. When the action was induced via transcranial magnetic stimulation (TMS) over the primary motor cortex, participants experienced perceptual shifts in the opposite direction: The perceived time of their actions was earlier and the perceived time of the tone was later than in the baseline condition. Moreover, their second experiment indicated that the binding effect largely depended on the temporal prediction of the onset of the action outcome. Temporal binding for fixed intervals between actions and outcomes was stronger than that for intervals that varied randomly within a block of trials. They highlighted the correspondence between these characteristics of temporal binding and the nature of action–outcome matching processes for motor control, suggesting that prediction of action outcomes plays a critical role. In the widely accepted forward model theory of motor control, one is assumed to anticipate action outcomes based on the efferent copy of the motor signal. The subject then compares the anticipated outcome with the one actually observed, and uses the mismatch between them to modify ongoing or future movements (comparator model; e.g., Wolpert et al., 1995). Haggard et al. (2002) suggested that temporal binding would occur when the predicted and perceived outcomes were matched. Such linkage of temporal binding and action outcome prediction has been repeatedly claimed based on similarly designed experiments (for the review, see Waszak et al., 2012).

Nevertheless, Hughes et al. (2013) argued that such comparisons between voluntary and involuntary actions, or between fixed and random action–outcome intervals, could not specify the predictive mechanism underlying temporal binding. The current explanation of how action outcome prediction causes temporal binding is that prediction pre-activates a representation of the sensory consequences, thus allowing congruent stimuli to reach the perceptive threshold more easily due to an increased baseline when the anticipated outcomes are observed (Waszak et al., 2012). If temporal binding is linked to such action outcome predictive mechanisms, it should be affected by whether the agent can predict what will occur as a result of one's action as well as when it will occur (Desantis et al., 2012). To investigate what previous studies revealed about the relationship between prediction processes and temporal binding, Hughes et al. (2013) classified the predictive mechanism into four different processes as follows (p. 135):

- Temporal prediction is defined as the ability to predict the point in time at which a sensory event will occur.
- Temporal control refers to using one’s action to control the point in time at which a stimulus will occur. As stimulation here is controlled by the action, temporal control will in most cases include precise temporal prediction.
- Non-motor identity prediction refers to being able to predict the precise stimulus that will appear. In this instance the prediction of the identity of the stimulus is not dependent on any action performed by the participant.
- Motor identity prediction refers to prediction of the identity of a sensory event based on an action performed by the participant.

According to Hughes and colleagues, some studies might unintentionally manipulate different predictions simultaneously. For example, the voluntary and involuntary action conditions in Haggard et al. (2002) were different not only in outcome identity prediction based on action planning (motor identity prediction), but also in the degree to which participants could control the onset of outcomes (temporal control). Thus, they remarked the need for studies in which temporal binding was assessed while manipulating a specific predictive process and keeping the other factors constant. In the experiment by

Desantis et al. (2012), participants performed two alternative actions (i.e., left or right key press) causing one of two action effects, either corresponding to their choice or decided randomly. The predictability of outcome identity and the congruency between the outcome identity associated with the chosen action and the actual outcome identity did not influence outcome shifts. Such evidence led Hughes et al. (2013) to the conclusion that binding is based not on identity prediction but on temporal control. However, they also pointed out that no study investigated temporal prediction and temporal control in a completely independent way. Therefore, it is still unclear whether temporal binding results from a general temporal prediction mechanism or from temporal control based on the motor processes.

Moreover, the discussions on the role of prediction in temporal binding, including the one by Hughes et al. (2013), had some significant limitations. Almost all of them focused on the outcome shift, which is only one side of temporal binding, because of the assumption that outcome shift is caused by predictive processes whereas action shift is caused by postdictive processes. As noted above, the idea that temporal binding results from the action outcome prediction is derived from the action–outcome matching process in the motor forward model. Thus, the pre-activation account can explain only why the outcomes are experienced earlier, but not why actions are experienced later (Waszak et al., 2012).

Nevertheless, some studies demonstrated that action shifts are linked to predictive processes, and not only to postdictive processes.

Moore and Haggard (2008) introduced an effective method to separate the influence of predictive and postdictive cues on temporal binding. They manipulated the probability with which the participants' key presses produced a tone. Actions that produced a tone with high probability (75%) were perceived earlier than those with lower probability (50%), even in trials where the tone did not occur. This difference in action shifts related to the occurrence probability of outcomes must result from action outcome prediction. Wolpe et al. (2013) proposed that the action shift, but not the outcome shift, involves the integration of predictive and postdictive cues depending on their relative reliability. As temporal binding has been generally discussed as a single phenomenon, the nature of action and outcome shifts has rarely been compared directly, despite their potentially independent mechanisms (e.g., Moore & Haggard, 2008; Moore et al., 2010a). In the present analysis, we investigate how different prediction processes are related to each perceptual shift.

The elimination of action shift from the analysis has hindered the investigation of another significant problem, namely whether temporal binding as measured by different experimental procedures has consistent features. The clock procedure has been criticized as subject to several problems, such as cognitive demand for monitoring the clock (Engbert et al., 2007), possibility of other spatiotemporal illusions (Baldo & Klein, 1995; Cravo & Baldo, 2008; Nijhawan, 1994), and the high variability in temporal estimates. Therefore, temporal binding has also been assessed with a more direct procedure to obtain numerical estimates of the action–outcome interval, without using the visual clock (Engbert et al., 2007). We refer to this procedure as interval estimation. Within such methods, participants exhibit binding as the underestimation of the interval between an action and its consequence compared to baseline, for example the interval between two successive externally generated events.

Binding observed with this method seems to have different temporal characteristics compared with that observed with the clock method. With the clock method, binding decreased at sub-second intervals such as 450 and 650 ms (Haggard et al., 2002). Meanwhile, binding was observed for far longer intervals of up to 4 s with the interval estimation procedure (Humphreys & Buehner, 2009). Such difference may result from the independent cognitive processes, involved in the perception of time points of events and in their duration, respectively required by the clock and the interval estimation procedures. In fact, Rohde et al. (2014) found that actions influenced interval estimation on one hand, and simultaneity and temporal order judgement on the other, in different ways. Despite the possibility that the effect of moderators might depend on the procedure used to observe binding, most studies used only one procedure, and few compared them directly. This problem may explain the confusing results about the role of prediction in binding.

Regarding experimental procedures, the effect of the sensory modalities of the stimuli presented as action outcome cannot be ignored either. Most studies used auditory stimuli, while others used visual (e.g., Cravo et al., 2013; Engbert et al., 2007; Moretto et al., 2011; Ruess et al., 2018a; Wen et al., 2015) or somatic cues (e.g., Beck et al., 2017; Borhani et al., 2017; Buehner, 2015; Engbert et al., 2007, 2008; Kong et al., 2017, Tsakiris & Haggard, 2003). The visual and somatic outcomes also cause temporal binding, and outcome shift for visual stimuli shows some features in common with auditory stimuli (Ruess et al., 2018a). However, much remains unclear about the differences in the nature of temporal binding among different modalities (Hughes et al., 2013).

In conclusion, as Hughes et al. (2013) pointed out, previous studies failed to specify the underlying mechanism of temporal binding due to the conjunction of several different prediction processes in their experimental design. Based on the studies suitably designed to investigate identity prediction, Hughes et al. (2013) concluded that temporal binding might depend on temporal control, but not on identity prediction in motor control. However, empirical evidence at the time of their research was insufficient, and their discussion was limited to one of the two parts of temporal binding (outcome shifts) observed in a specific experimental procedure. Therefore, in this study, we comprehensively investigated the predictive nature of temporal binding through quantitative meta-analysis, considering the differences between action shifts and outcome shifts, and between experimental procedures.

1.2. Potential Predictive Factors of Temporal Binding

The classification of prediction by Hughes et al. (2013) is sophisticated but involves qualitative and conceptual aspects. In order to directly compare the results between different studies and to integrate them in a conclusive way, it is necessary to quantitatively express each type of prediction involved in experiments by common parameters. Below, we will consider the influence of each prediction as experimental factors in the assessment of temporal binding, referring to the findings of Hughes et al. (2013) and subsequent studies.

1.2.1. Temporal Prediction and Temporal Contiguity

While previous studies compared action outcomes with fixed intervals, and random intervals in one case, to investigate temporal prediction (e.g., Ruess et al., 2017a), they reflected two aspects of temporal prediction. At the level of experimental manipulation, the degree of temporal predictability could be quantified by the range between the minimum and maximum potential delay within an experimental block, as well as by the probability of outcomes occurring at a specific time.

For example, in the unpredictable condition of the first experiment by Ruess et al. (2017a), the action outcomes were presented after one of three possible delays that occurred randomly (200 ms, 250 ms, or 300 ms). Here, the probability that the outcome would be presented at a certain onset was approximately 33% (odds of two to one) and the range was 100 ms (the gap between 200 ms and 300 ms). Meanwhile, in the second experiment in the same study, there were three possible delay conditions (100 ms, 250 ms, or 400 ms) with the same 33% probability for each onset but a different range (300 ms). While the authors did not investigate the effect of the temporal range by comparing experiment 1 and 2 directly, both action and outcome shifts were larger in experiment 1 than in experiment 2 for the same 250 ms action outcome interval, regardless of the temporal probability prediction (predictive condition: action shift: 28.13 ms vs. 21.34, outcome shift: 107.36 vs. 74.37 ms; unpredictable condition: action shift: 28.99 ms vs. 21.87, outcome shift: 98.24 ms vs. 65.30). This indicated that the small range could contribute to temporal prediction and enhance the binding effect.

Temporal contiguity, i.e., the proximity of actions to outcomes in time, also contributes to temporal prediction (Aliu et al., 2009; Niemi & Näätänen, 1981; Schafer & Marcus, 1973). It has been repeatedly reported that temporal binding was stronger when action outcomes were presented after a shorter interval than after a longer interval (e.g., Haggard et al., 2002; Ruess et al., 2017a, 2018b). The forward motor model is assumed to have higher temporal sensitivity at the sub-second level, and the effect of temporal contiguity is consistent with the contribution of prediction to binding. Nevertheless, as noted above, temporal binding was observed with interval estimation even for super-second action outcome intervals (Buehner & Humphreys, 2009; Humphreys & Buehner, 2009).

Although contiguity, coded by the size of the action outcome interval, and more direct cues, coded by the probability and range of the potential outcome onset, may contribute to temporal prediction in an integrated way, their potential conjunction could hinder the investigation of the separate influence of each factor. When an experimenter manipulates temporal contiguity as a within-block factor, participants experience action–outcome sequences with various intervals. Since this procedure prevents participants from predicting when the outcomes are presented, the observed binding should reflect both the contiguity and the degree to which one predicts the time of outcome presentation. This problem is more crucial in the interval estimation procedure. In principle, the action outcome contiguity cannot be fixed within a certain experimental session of this task. This unpredictability may systematically influence the effect of contiguity on the observed temporal binding.

1.2.2. Temporal Control

Temporal control is the most dominant factor of temporal binding according to Hughes et al. (2013). However, their definition of temporal control basically includes temporal prediction. To control the onset of outcomes with an action, participants need to precisely represent the temporal relation between actions and outcomes. Previous studies tried to separate their roles with specific procedures enabling participants to predict but not control outcome onsets. For example, when participants passively observed a cue and a subsequent stimulus, or another's action and its effect with a consistent interval, they could predict the onset of secondary events to some extent, without having temporal control. Desantis et al. (2012) reported much larger outcome shifts in the interval between actions and their outcomes than in those between the two tones, claiming that temporal prediction is not sufficient for temporal binding. Nevertheless, it is still difficult to manipulate temporal control only, while completely controlling temporal prediction, because intentional action planning is a robust cue of temporal prediction, while external cues such as involuntary action or preceding stimulus are unexpected themselves. To control for this confounding factor in the meta-analysis, in the current study we separated temporal control from temporal prediction, coding the former essentially as “whether one can use action to *influence* the point in time at which a stimulus will occur or not”. We can suggest two hypotheses: First, voluntary action only contributes to temporal binding through relatively precise prediction; and second, temporal control with voluntary action is necessary for binding, as well as prediction.

Recently, negative findings were also reported regarding the need for temporal control. Some studies have observed temporal binding in the interval between two tones, as well as between others’ actions and their effects, where participants did not execute any movement (e.g., Braun et al., 2014; Khalighinejad et al., 2016; Poonian et al., 2015; Suzuki, et al., 2019). Considering all the potential differences in the mechanisms discussed above, the roles of temporal prediction and temporal control might not be the same between action shifts and outcome shifts. That is, active temporal control (or intentional action planning) may be more important for action shifts, while general temporal prediction underlying temporal control may be a significant factor for outcome shifts.

1.2.3. Identity Prediction

Hughes et al. (2013) doubted the involvement of identity prediction in temporal binding. This claim was followed by Haering & Kiesel (2014) and Bednark et al. (2015) with their replication of Desantis et al.'s (2012) result through interval estimation. Nevertheless, there are some indirect implications for its relevance. When priming stimuli presented just before a participant's actions were congruent with the subsequent action effect (i.e., a high or low pitch tone associated with each action), there was stronger binding than in case of incongruent conditions (Moore et al., 2009a). This is consistent with the idea that pre-activation of a specific outcome identity contributes to binding. Meanwhile, Moore et al. (2011a) uniquely predicted, based on an assumption from the prediction error theory of associative learning, that only unexpected action–outcome pairs drive acquisition of a new action–outcome relationship. With the outcome blocking technique, they showed that the action–outcome relationship learned under conditions of unpredictability led to stronger binding. A more recent study by Majchrowicz and Wierzchoń (2018) using the oddball task directly supports the possibility that unexpected action outcomes enhance temporal binding.

Although Hughes et al. (2013) defined different types of identity prediction that can be classified in terms of motor specificity, we did not distinguish between motor and non-motor identity prediction in our coding due to insufficient data for the investigation of the role of motor identity prediction. The purpose of this study was to investigate whether temporal binding is driven by temporal prediction or temporal control rather than identity prediction as they proposed. Besides, since binding tasks generally provide no choice of action, with the exception of a few studies (Wenke et al., 2009), we could not judge whether a certain action outcome was action-specific or not.

1.2.4. Occurrence Prediction

Although it was not included in the classification by Hughes et al. (2013), the prediction of whether or not an action will cause any outcome is also a component of prediction contributing to temporal binding. The probability of co-occurrence between action and outcome is significant in learning an action–outcome relationship. Moore et al. (2009b) manipulated an individual's expectancy of which action will cause an outcome, with participants able to choose whether to execute an action in each trial. They reported that temporal binding was sensitive to the contingency, resulting from the probability with which outcomes were presented associated with trials in which action is present or absent. We also mentioned above that the degree to which participants expected the occurrence of any outcome modulated the action shift, regardless of the actual occurrence of the outcome (Moore & Haggard, 2008). We should consider the possibility of confusing occurrence probability with other types of prediction, such as temporal or identity prediction. Internal prediction might be prevented because the outcome was not presented at the anticipated time, rather than because the expected outcome was not presented.

1.3. Present Study

Binding does not seem to be a simple perceptual phenomenon but rather a more complex process, closely linked to causal cognition (e.g., Desantis et al., 2011; Haering & Kiesel, 2012; Moore et al., 2009a). As the purpose of this paper is to investigate the relationship between predictive processes and temporal binding, we do not focus on higher-order causality. However, it is worth exploring how sensorimotor cues construct the subjective experience of actions and outcomes as a primitive source of such higher-order cognition (Synofzik, 2008). Although most studies did not directly manipulate or record the causal beliefs of participants in their experiments, temporal control, contingency, and contiguity are important cues to infer causality between action and outcome (Hume, 1739/1964). In fact, in most situations where temporal binding was measured, perceptual stimuli immediately following the action should cause one to assume that the action triggered the result (Christensen et al., 2019). Therefore, examining the influence of these factors on temporal binding seems to contribute indirectly to the elucidation of the relationship between temporal binding and causal cognition.

Some common characteristics induce researchers to assume a close relationship between temporal binding and sense of agency, i.e., the feeling that one's intentional actions cause specific events in the outside world (Gallagher, 2000). Beside the dependencies on voluntary actions and causal belief, both binding and self-reported agency for action outcomes decrease with longer intervals (Chambon et al., 2015; Haggard et al., 2002; Imaizumi & Tanno, 2019; Wen et al., 2015), as well as with the perceptual or conceptual incompatibility between one's movements and their effects (Sato, 2009; Vastano et al., 2017). Several studies have used degree of binding as an implicit measure to infer the characteristics of sense of agency, avoiding explicit cognition and response bias. However, the validity of measuring binding as a proxy for agency was questioned by reports of the inconsistency between binding and explicit measures of sense of agency (e.g., self-report on a numerical scale; Dewey & Knoblich, 2014).

To use temporal binding as an implicit indicator of higher-order cognition such as causality and agency, it is necessary to understand what processing is reflected by the action shift, outcome shift, and overall temporal binding observed in certain procedures. Otherwise, one may confuse factors of high-order cognition with mere sensory cues of time perception. Therefore, we investigated the fundamental nature of temporal binding with quantitative multifactorial analysis, considering the lack of specific comparison and interactions. More specifically, our main goals were: (1) to investigate if temporal binding, especially outcome shift, is caused by temporal control or temporal prediction but not by identity prediction; (2) to examine the effects of measurement methods and sensory modalities on temporal binding; and (3) to discuss the processes underlying each perceptual shift and their independence, and their potential as a tool for understanding the disorders of agency in schizophrenia.

2. Material and Methods

2.1. Literature Search

We conducted a computer-assisted literature search in the Pubmed, PsycINFO, and Scopus databases. Keywords used for the search were “temporal binding” and “intentional binding”. The computer search algorithm was set to find only articles published after January 2002, when Haggard et al. (2002) published their study. We conducted this search in April 2019.

2.2. Inclusion and Exclusion Criteria

We eliminated studies that did not measure temporal binding with either the Libet clock procedure or the interval estimation procedure. Strictly speaking, we selected studies in which participants experienced the sequence of an action (e.g., pressing a key) and the corresponding feedback (e.g., the presentation of an auditory stimulus), and reported the time of the action or feedback, or the interval between them in at least one experimental condition. Several studies have assessed temporal binding with other psychophysical methods, such as reproduction of intervals (Dewey & Knoblich, 2014; Humphreys & Buehner, 2010; Poonian & Cunnington, 2013), temporal order judgment (Haering & Kiesel, 2012), or simultaneity-judgement tasks (Cravo et al., 2011; Parsons et al., 2013). Some researchers have claimed that these methods do not always reflect the same processing (Eagleman, 2008; Pariyadath & Eagleman, 2007). Therefore, we did not include these studies in our meta-analyses, also due to the heterogeneity of dependent variables and the insufficient number of studies.

In addition to extracting all reported binding data in these studies, we also used the intervals between the observation of others' actions and outcomes or between two externally caused stimuli to assess the effect of temporal control on binding. Since the interval estimation procedure had no single event condition that could be used as a baseline, we used the estimation of the interval between two external events or between passive or others' actions and outcomes in each study as the baseline to evaluate the size of binding. We excluded studies without any potential baseline condition.

We excluded data from participants with (a) clinical symptoms of any kind or administration of medicine, and (b) average age younger than 18 years or older than 65 years. Finally, we excluded studies that did not provide sufficient information to compute effect sizes.

2.3. Coding

We coded each condition in which temporal binding was measured in terms of descriptive information and experimental parameters. First, we coded information about participants, including (1) sample size, (2) gender distribution, and (3) average age of participants. We also coded factors inherent to the experiments, including (4) procedure used (dummy categorical variable; 0: Libet clock method or 1: interval estimation procedure), (5) the modality of action outcomes (dummy categorical variable; 0: auditory, 1: visual, 2: somatic feedback), and (6) the kind of baseline (dummy categorical variable; 0: single event, 1: passive or involuntary movement, 2:

observation of other's movement and/or external event).

In terms of temporal prediction, we coded both (7) the probability with which an outcome occurred at a certain delay after an action (temporal probability prediction), and (8) the range between the minimum and maximum potential delays within an experimental block (temporal range prediction). To investigate the effects of contiguity, we coded (9) the average interval between action and outcome. In addition, we coded (10) whether participants could influence the onset time of outcomes with voluntary actions or not (i.e., whether participants' voluntary actions caused the outcomes or not; temporal control), (11) the probability with which participants could predict what action outcome would be presented (identity prediction), and (12) the probability with which any action outcome was presented (occurrence probability). As discussed above, we coded controllability as a dummy categorical variable (whether participants could exercise: 0, no temporal control or 1, temporal control) to minimize their definitional overlapping with temporal prediction.

For dependent variables, we coded (13) raw values of action shifts, outcome shifts, and binding. Finally, we coded (14) the standard deviation (SD) of each effect or of onset time for actions or outcomes reported in operant and baseline conditions in the Libet clock task or of the reported interval in the interval estimation procedure. Data shown only in figures were converted into numerals with digitizer software (Rohatgi, 2012). To minimize errors derived from this digitization, we averaged values into which two authors converted the same points in figures. When a study only reported mean standard errors or confidence intervals, we calculated the SD from these values. The description of the coding is shown in Table 1 and codes applied to individual samples can be found in supplementary Table S1.

2.4. Coder Reliability

The first author and one of the other authors coded each article, and the coding reliability was assessed by comparing the codes assigned by the two authors using Krippendorff's alpha (Hayes & Krippendorff, 2007; Krippendorff, 2011). The mean alpha across the various codes was sufficient, 0.933 (SD 0.062, min 0.845). Disagreements were discussed until agreement was reached, and the consensus codes were used in the analyses.

2.5. Meta-Analytic Procedure

First, we investigated the potential for publication bias, with the funnel plot trim-and-fill method (Duval & Tweedie, 2000). This procedure estimates the number of potential missing studies producing asymmetry in the funnel plot, and an effect size and confidence interval that is adjusted to account for the missing studies. As we focused on the effect sizes of action shifts, outcome shifts, and binding, we calculated standardized mean differences (*d*) between the perceived time or interval in the operant and baseline conditions.

Because all bindings included in this study were measured as the difference between operant and baseline conditions as a within-subjects factor, *d* can be calculated from the difference in scores and their variability. However, some studies reported information about the SD of the difference in scores (the degree of perceptual shifts) and others did not. Thus, unless we could use this value, we used the average SD of both conditions in accordance with recommendations from previous studies (Lakens, 2013). The notation of outcome shift was not unified among the previous studies, some studies representing the perceived shift of outcome time towards action by negative values (e.g., Haggard et al., 2002) and others by positive values (e.g., Ruess et al., 2017a, 2018a, 2018b, 2018c; Tanaka & Kawabata, 2019). Thus, we inverted the sign of the outcome shifts when they were represented in the former way so as to represent both larger action and outcome shifts with larger (positive) values. Note that we did not merely uniform the sign itself while ignoring their direction, but only the way outcome shifts are represented.

Based on our coding methods, we selected studies with many situational differences in experimental procedures. Given this variability in experimental characteristics, it is likely to be inappropriate to assume a single true *d* for all studies in the present meta-analysis. In addition, effects derived from the same study may be more similar to each other than effects derived from different studies. Ignoring such dependencies could lead to an underestimation of standard error, impaired statistical inference and too strong weighting of studies that provide more outcomes. Therefore, following recommendations by Borenstein et al. (2009) and Konstantopoulos

(2011), we used a multilevel linear mixed-effects models that incorporated variation among and within studies to synthesize results. We assessed heterogeneity among results with the *Q* statistics. Given that qualitative differences between action and outcome shifts, and between binding measured by the Libet clock and interval estimation procedures, remain unclear, we first analyzed them without discrimination. Where statistically significant heterogeneity was observed, we conducted meta-regressions for the factors related to prediction and sub-group analyses with categorical variables representing the experimental procedure and the outcome modality. To investigate the effects of each prediction independently, we first ran multivariate analyses using only the main effect of each factor. Subsequently, the interaction effects of statistically significant variables were included in the analyses. To ensure that the model is parsimonious, we removed non-significant interaction effects from the multivariate model. Accounting for the non-independence of effects within studies, we used the robust cluster tests that allowed for meta-regression with dependent effect size estimates and the utilization of all study outcomes (Hedges et al. 2010). The statistical thresholds for all analyses were set at $p < 0.05$ (two-tailed). All calculations were conducted with functions in the metafor package (Viechtbauer, 2010) using the R statistical software.

3. Results

Figure 1 presents the process used to select studies for our analyses. We included 78 studies providing 199 action shifts, 212 outcome shifts, 56 overall bindings with the clock procedure, and 160 bindings with the interval estimation procedure.

3.1. Meta-Analysis of Action and Outcome Shifts

3.1.1. Effect Sizes of Action and Outcome Shifts

We first investigated whether there was a systematic difference between action shifts and outcome shifts. As we observed high heterogeneity in the datasets including both action and outcome shifts [$Q(410) = 893.866$, $p < 0.001$], we assessed the difference in d between them. This analysis showed a significantly larger overall d for outcome shifts than for action shifts [$F(1, 54) = 23.921$, $p < 0.001$; Table 2]. We confirmed the robust occurrence of both action shifts {$d = 0.451$, 95% CI = [0.345, 0.557], $t(48) = 8.522$, $p < 0.001$; supplementary Fig. S1} and outcome shifts {$d = 0.726$, 95% CI = [0.617, 0.835], $t(48) = 13.424$, $p < 0.001$; supplementary Fig. S2}.

Although the trim-and-fill procedure identified missing data for 27 action shifts and 27 outcome shifts with d below the mean for each dataset, these effects were still significant {action shifts: $d = 0.370$, 95% CI = [0.309, 0.430], $z(225) = 11.981$, $p < 0.001$; outcome shifts: $d = 0.653$, 95% CI = [0.583, 0.723], $z(238) = 18.278$, $p < 0.001$; Fig. 2}. However, these results should be interpreted with caution, because the assumption of homogeneity in the trim-and-fill procedure was violated here. Because the degree of heterogeneity in each shift was high even after separating them into independent datasets [action shift: $Q(198) = 336.999$, $p < 0.001$; outcome shift: $Q(211) = 458.501$, $p < 0.001$], we conducted further analyses of moderators for each shift.

3.1.2. Moderators of Action Shift

The difference in the type of SD used to calculate *d* did not have systematic influence on the *d* of action shifts [$F(1, 47) = 1.660$, $p = 0.204$]. We investigated the effect of the modality of action outcomes in a sub-group analysis. Although there was a much smaller number of action shifts from modalities other than auditory, we observed that the modality of action outcomes was a significant moderator of action shift [$F(2, 46) = 9.092$, $p < 0.001$; Table 3]. We observed robust action shifts for auditory and somatic outcomes but not for visual outcomes.

Since action shifts for auditory outcomes showed high heterogeneity [$Q(174) = 312.300$, $p < 0.001$], we next conducted a meta-regression analysis with the main effects of the prediction factors (Table 3). This found only the temporal control {$\beta = 0.273$, 95% CI =

[0.096, 0.450], $t(37) = 2.207$, $p = 0.003$} significant and other effects of temporal probability prediction {$\beta = -0.049$, 95% CI = [−0.112, 0.014], $t(37) = 1.577$, $p = 0.123$}, temporal range prediction {$\beta = -0.084$, 95% CI = [−0.180, 0.013], $t(37) = 1.759$, $p = 0.087$}, average interval {$\beta = -0.055$, 95% CI = [−0.171, 0.061], $t(37) = 0.955$, $p = 0.345$}, identity prediction {$\beta = -0.055$, 95% CI = [−0.208, 0.099], $t(37) = 0.722$, $p = 0.726$}, and occurrence probability {$\beta = -0.009$, 95% CI = [−0.109, 0.090], $t(37) = 0.190$, $p = 0.850$} non-significant. Although Hughes et al. (2013) focused on outcome shifts, the presence of temporal control largely enhanced action shifts.

3.1.3. Moderators of Outcome Shift

The difference in the type of SD used to calculate d did not have systematic influence on the d of outcome shifts [$F(1, 47) = 0.201$, $p = 0.656$]. We revealed the differences in d for the outcome modality [$F(1, 47) = 17.412$, $p < 0.001$; Table 4]. Unlike action shifts, visual outcomes robustly elicited outcome shifts as well as auditory outcomes, whereas somatic outcomes did not.

We conducted meta-regression analyses with the main effects of the predictors of outcome shifts for auditory outcomes showing high heterogeneity [$Q(177) = 396.448$, $p <$

0.001]. The model suggested significant main effects of the temporal probability prediction {$\beta = -0.068$, 95% CI = [0.009, 0.127], $t(35) = 2.341$, $p = 0.025$; Table 4} and temporal range prediction {$\beta = -0.057$, 95% CI = [−0.180, 0.013], $t(35) = 2.079$, $p = 0.045$}. Average interval {$\beta = -0.080$, 95% CI = [−0.167, 0.006], $t(35) = 1.873$, $p < 0.069$}, identity prediction {$\beta = -0.078$, 95% CI = [−0.187, 0.031], $t(35) = 1.456$, $p = 0.154$} and occurrence probability {$\beta = -0.021$, 95% CI = [−0.046, 0.004], $t(35) = 1.689$, $p = 0.099$} were not significant moderators. Moreover, contrary to action shifts, outcome shifts did not show a tendency to be stronger when participants could exercise temporal control {$\beta = 0.125$, 95% CI = [−0.147, 0.396], $t(35) = 0.932$, $p = 0.357$}. We then added the interaction of two significant factors, temporal probability and range prediction, into the model but finally excluded it because of its non-significant effect {$\beta = -0.018$, 95% CI = [−0.041, 0.005], $t(35) = 1.557$, $p = 0.129$}.

3.2 Effect Size of Overall Temporal Binding

As we observed a significant difference between the binding *d* between the two experimental procedures [$F(1, 32) = 27.688$, $p < 0.001$; Table 5], we separated them into sub-groups. We observed larger overall *d* for experiments with the clock procedure {$d = 0.887$, 95% CI = [0.681, 1.093], $t(55) = 9.130$, $p < 0.001$; supplementary Fig. S3} than for those with interval estimation procedure {$d = 0.300$, 95% CI = [0.192, 0.408], $t(160) = 5.871$, $p < 0.001$; supplementary Fig. S4}. The trim-and-fill procedure indicated that 16 missing studies were needed to make the plot symmetrical for the clock procedure dataset (Fig. 3a), while 48 studies were needed for the interval estimation procedure dataset (Fig. 3b). The adjusted overall d for the two datasets was smaller than the original values but remained significant {clock procedure: $d = 0.735$, 95% CI = [0.597 0.874], $z(71) = 10.409$, $p < 0.001$; interval estimation procedure: $d = 0.159$, 95% CI = [0.104, 0.213], $z(207) = 5.699$, $p < 0.001$}. We investigated whether the type of baseline influenced the temporal binding in interval estimation or not, revealing that the effect size significantly depended on what condition was used as baseline [$F(1, 15) = 5.656$, $p = 0.031$; Table 5].

3.3 Relationship between Action Shift, Outcome Shift, and Temporal Binding

Finally, we investigated the correlation between d for action and outcome shifts (Fig. 4). Our sample included 145 pairs of both shifts observed within the same condition, showing a weak correlation ($r = 0.281$, $p < 0.001$). We also assessed the correlation between either action or outcome shift and overall binding in the clock procedure with 47 samples that measured all parameters. As predicted from the larger d for outcome shift, overall binding was strongly correlated with outcome shift ($r = -0.851$, $p < 0.001$) but not with action shift ($r = 0.082$, $p = 0.584$).

4. Discussion

In this review, we aimed to explore the predictive processes regulating temporal binding and the nature of such effects observed in different ways. Our results confirmed highly robust effects of action and outcome shifts, and overall binding in the clock procedure and binding effects in the interval estimation procedure. Furthermore, we directly compared these effect sizes between action and outcome shifts, and between overall binding from the clock and the interval estimation procedure, revealing significant differences.

4.1. Potential Processes Underlying Action Shift and Outcome Shift

Only the effect size of action shifts was significantly larger for outcomes temporally controlled by voluntary actions. Meanwhile, in terms of the outcome shift, outcome shifts depended on the temporal prediction based on the probability and range of potential action outcome onsets. We should note that the effects of temporal control were investigated in the model considering the temporal prediction separately. While Hughes et al. (2013) proposed that outcome shifts might be driven by temporal control, our analysis showed that the variance in effect size of outcome shifts could be sufficiently explained by temporal prediction, without temporal control. In the predictive account based on the comparison process, whether predicted action outcome *matches* the observed one or not would be the critical issue for the occurrence of temporal binding. If so, outcome shifts must require strictly precise prediction of the specific outcome onset time. This might result in strong dependency on temporal predictive cues, rather than on temporal control.

Given the robust effect of temporal control, in contrast, action shifts might not only depend on general predictive function but also on the processing peculiar to voluntary actions in comparison to outcome shifts. The precise coincidence between expected and actual outcome onsets may thus be less important for the action shift than for the outcome shift. In fact, action shift can occur even without any action outcomes (Moore & Haggard, 2008). Such evidences propose the possibility that the action shift may depend on the execution of actions that have been associated with any outcomes throughout prior learning, whereas the outcome shift may depend on the results of the comparison between predicted and actual outcomes. Assuming the framework of sensorimotor processing for motor control, action shifts may be based on the feed-forward signal comprising the predictive information generated from the efferent copy of a motor signal, whereas outcome shifts may depend on the feedback signal generated from the comparison between predicted and observed action outcomes. In this sense, we could say that action and outcome shifts are respectively driven by predictive and postdictive processes, contrary to the widespread conception (e.g., Moore et al., 2010a).

In brief, showing that temporal binding was increased by temporal prediction and control but not by identity prediction, empirical evidence allows us to agree with the claim by Hughes et al. (2013), at least in part. However, while they concluded that outcome shifts could be driven by temporal control, we indicated that they might depend on general temporal prediction, whereas action shifts are the ones based on temporal control. The two conclusions are not contradictory, as Hughes et al. (2013)'s definition of temporal control basically includes temporal prediction. Nevertheless, it is interesting that their idea of outcome shifts may actually fit action shifts more adequately.

4.2. Measurements of Temporal Binding

We next introduce some new implications of our results for the measurement of temporal binding. The binding effect size was shown to strongly depend on the experimental procedure, with binding observed in the interval estimation procedure much smaller than in the clock procedure. There was no heterogeneity in the dataset in terms of interval estimation procedure, which indicates the little variance derived from potential moderators. Thus, the small effect size seemed not to be due to experiments having interval estimation that included more conditions that could reduce binding, such as longer action–outcome intervals or lower temporal probability prediction. However, the kind of baseline that we used to quantify the binding effect in each experiment significantly influenced the effect sizes. This difference, derived from the coding process, might be an artifact concealing the systematic influence of independent experimental variables. We discuss other potential biases and qualitative differences in comparing data of the two procedures in the Limitation section below.

We cannot conclude from our analysis whether the difference between the two procedures results from the independence of their underlying processes or from mere lower sensibility or reliability of the measurement by interval estimation. As mentioned in the Introduction, the perception of specific time points and intervals between events might be based on different cognitive processes. Thus, potential mechanisms such as internal clock alteration (Fereday & Buehner, 2017), event time recalibration (Rohde et al., 2014), or pre-activation of action outcome representation (Waszak et al., 2012) can result in distorted timing and duration perception in different ways. On the other hand, interval estimation might not be reliably sensitive to potential factors that could influence time perception, or might be subject to other experimental artifacts including moderators that were not considered in our analysis. The lower sensitivity to the temporal delay of binding in interval estimation supports this hypothesis (Humphreys & Buehner, 2009). In either case, we cast doubt on the validity of using interval estimation procedures to detect subtle differences in binding derived from the manipulation of sensorimotor parameters.

Another finding emphasizing the difference between experimental procedures was the dependency on modality. Although there were not sufficient studies using action outcomes other than auditory stimuli, our results implied that temporal binding for visual and somatic stimuli might not be as robust as that for auditory stimuli. Moreover, meta-analysis revealed another potential difference in characteristics between action shifts and outcome shifts. While we confirmed outcome shifts for visual outcomes reported by a few studies such as Ruess et al. (2018a), our results showed the absence of action shifts for visual outcomes. On the other hand, somatic outcomes elicited small but robust action shifts, but not outcome shifts. These tendencies might result from the temporal resolution of each modality (Formby et al., 1992; Shimojo et al., 2001; Welch & Warren, 1980). This evidence supports the hypothesis that binding, at least partly, reflects a sensory perceptual phenomenon, as well as causal inference.

The comparison of action and outcome shifts revealed larger effect sizes for outcome shifts. In addition to differences in effect size and susceptibility to moderators, the weak correlation between them supports the possibility that different mechanisms underlie each shift (Wolpe et al., 2013). Overall binding largely depended on outcome shifts relative to action shifts. Therefore, some part of the characteristics of binding reported with the clock procedure might actually reflect those of outcome shifts. This could make it difficult to interpret results from studies reporting overall binding as the main dependent variable. When each shift leads to different results for an identical experiment, it is difficult to know how one's subjective agency or causal cognition is altered by them. Therefore, we are required to consider carefully which measure to use depending on the purpose of each study.

4.3. Implication for Understanding Disorder of Agency in Schizophrenia

Based on these considerations about the nature of each shift, their different behaviors could provide insight into the processes regulating them. For example, they may contribute to our understanding of the processes underpinning the abnormal experience of agency in certain psychiatric disorders. By manipulating outcome probability with the procedure used in Moore & Haggard (2008), Voss et al. (2010) revealed a lack of predictive modulation of binding in patients with schizophrenia, which was correlated with the severity of positive symptoms and the accentuation of postdictive modulation action shifts. The authors suggested that disturbances in sense of agency in schizophrenia might result from a deficit in precise sensorimotor prediction and a resulting change in the relative weight of predictive and postdictive cues.

While this tendency in action shifts was thought to result from a less precise prediction system in schizophrenia, our analysis implies less dependency of action shifts on temporal prediction compared with outcome shifts. If *inaccuracy* of prediction is the core cause of symptoms in schizophrenia, a detailed investigation of outcome shifts may provide a feature more characteristic of the patients' specific experience. This provides evidence of a specific impairment in action planning or generating action outcome prediction, rather than in the matching process between predicted and actual outcomes. More practically, the altered action shifts in schizophrenia may reflect the deficits in the dopaminergic system involved in action execution. The close relationship between temporal binding and dopaminergic activities has been supported by many evidences (Moore & Obhi, 2012; Moore et al., 2010b; Moore et al., 2011b). Patients with Parkinson's disease, which is characterized by the degeneration of dopamine-producing neurons and disturbances in willed behavior caused thereby, also showed a specific lack of action shift (Saito et al., 2017).

Moreover, while predictive modulation of action shifts was correlated with positive symptoms in schizophrenia, top-down modulation of binding by causality seemed to be related to passivity symptoms such as a lack of normal sense of ownership for thoughts and actions (Graham-Schmidt et al., 2016). Patients without passivity symptoms showed comparable binding for the outcomes of their own and others' actions, indicating an increase in the postdictive contribution. However, patients with passivity symptoms showed no binding for either type of outcome. This absence of inferential modulation cannot be explained by a lack of contribution from prediction. Given that the participants' causal beliefs modulated outcome shifts but not action shifts (Desantis et al., 2011), outcome shifts may tell us about the basis of another aspect of the schizophrenia experience. Thus, the separate investigation of each shift may provide evidence for the different bases of certain symptoms, and offer a potential tool to measure latent impairments.

5. Limitations

Although our meta-analyses allowed us to observe some moderators of temporal binding, we must consider the presence of various biases in our samples. We failed to observe either robust action shifts for the visual outcome or robust outcome shifts for the somatic outcome. Most experiments in our samples used auditory action outcomes, only a small number of studies using visual or somatic stimuli. Since the procedures to measure binding are well established, many studies use the typical procedures and few use modified methods. While the mixed-effects model is thought to be robust to mere sampling bias (Faraway, 2016; Yang et al., 2018), it is also possible that experiments with derivative manipulations are less likely to be reported, due to their undesirable results, such as the absence of binding. It is difficult to judge whether a bias in the frequency of specific experimental parameters was derived from mere popularity or publication bias. These potential biases might prevent the detailed investigation of binding in atypical procedures.

The present study did not cover some ecological aspects of actions and outcomes.

For instance, identity prediction could modulate temporal binding by interacting with other contextual cues such as number of action alternatives and the emotional valence of the action outcome (e.g., Beck et al., 2017; Di Costa et al., 2018; Moretto et al., 2011; Takahata et al., 2012; Tanaka & Kawabata, 2019; Yoshie & Haggard, 2013). As our goal was to investigate the role of prediction involved in sensorimotor processing, we also did not account for direct factors regarding participants' causal beliefs such as the method of experimental instruction. While the critical role of causal cognition for temporal binding has been repeatedly claimed (e.g., Buehner, 2012, 2015; Buehner & Humphreys, 2009; Cravo et al., 2009, 2011; Desantis et al., 2011), most studies did not manipulate, control, or measure the participants' causal perceptions. This makes it difficult to code contextual information quantitatively. However, although we investigated some indirect cues of causality, it was surprising that we failed to observe any effect of the temporal contiguity, i.e., size of action–outcome interval, and contingency, i.e., probability of occurrence of action outcome, on each shift. The contiguity might indirectly modulate the temporal binding via temporal prediction. Otherwise, our analyses might not appropriately detect its effect because the relationship between binding and contiguity was non-linear as indicated by Ruess et al. (2018a). In terms of the contingency, we should note that the contingency between actions and outcomes is defined not only by the probability with which actions cause specific events, but also by the probability that these events occur without such actions. The relationship between temporal binding and outcome occurrence probability has rarely been discussed, despite its importance in forming the association and causal perception between actions and outcomes. Future research should investigate the nature and role of the prediction of whether action would cause any outcome, as well as when and what outcome would be caused.

It is also possible that the effects of temporal control on action shifts resulted from differences in the attribution of action outcomes, not the temporal sensory processing. Our coding of temporal control could reflect whether participants intentionally perform an action and whether they could attribute sensory events to their own actions, as well as whether they could control temporal onsets. This account is consistent with the idea that action shifts depend on postdictive as well as predictive process, but inconsistent with the report that only outcome shifts were modulated by the direct manipulation of causal beliefs (Desantis et al., 2011). Typical procedures for temporal binding define actions that are executed at a freely chosen time as an *intentional* action, making it difficult to distinguish between intentionality and temporal control. Such definitional difficulties are shared with other factors. As temporal prediction could be defined by both the range of possible onset times and the number of experimental conditions, the notion of prediction in previous studies was highly conceptual and thus not quantitatively determined. Our analyses suggested that such differences could induce different modulations of binding. A stricter definition of these concepts for experimental investigations may help to elucidate the complexities of the binding effect.

Finally, our coding did not allow the investigation of the effect of temporal control on binding measured with the interval estimation procedure, in which we used conditions without temporal control (with voluntary action) as the baseline. Moreover, our results provided the possibility that such qualitative differences in the type of baseline condition contributed to the difference in effect sizes between experimental procedures, as well as their variance within the interval estimation procedure. Although temporal binding has significant potential usefulness, it might bring about erroneous or artifactual results unless the research is conducted with experimental procedures appropriate to their specific purposes. Revealing some fundamental nature of this effect to be considered, our analyses provide methodological and theoretical implications for future studies.

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Supplementary Material

Supplementary material is available online at:

https://osf.io/ur5dg/

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Figures

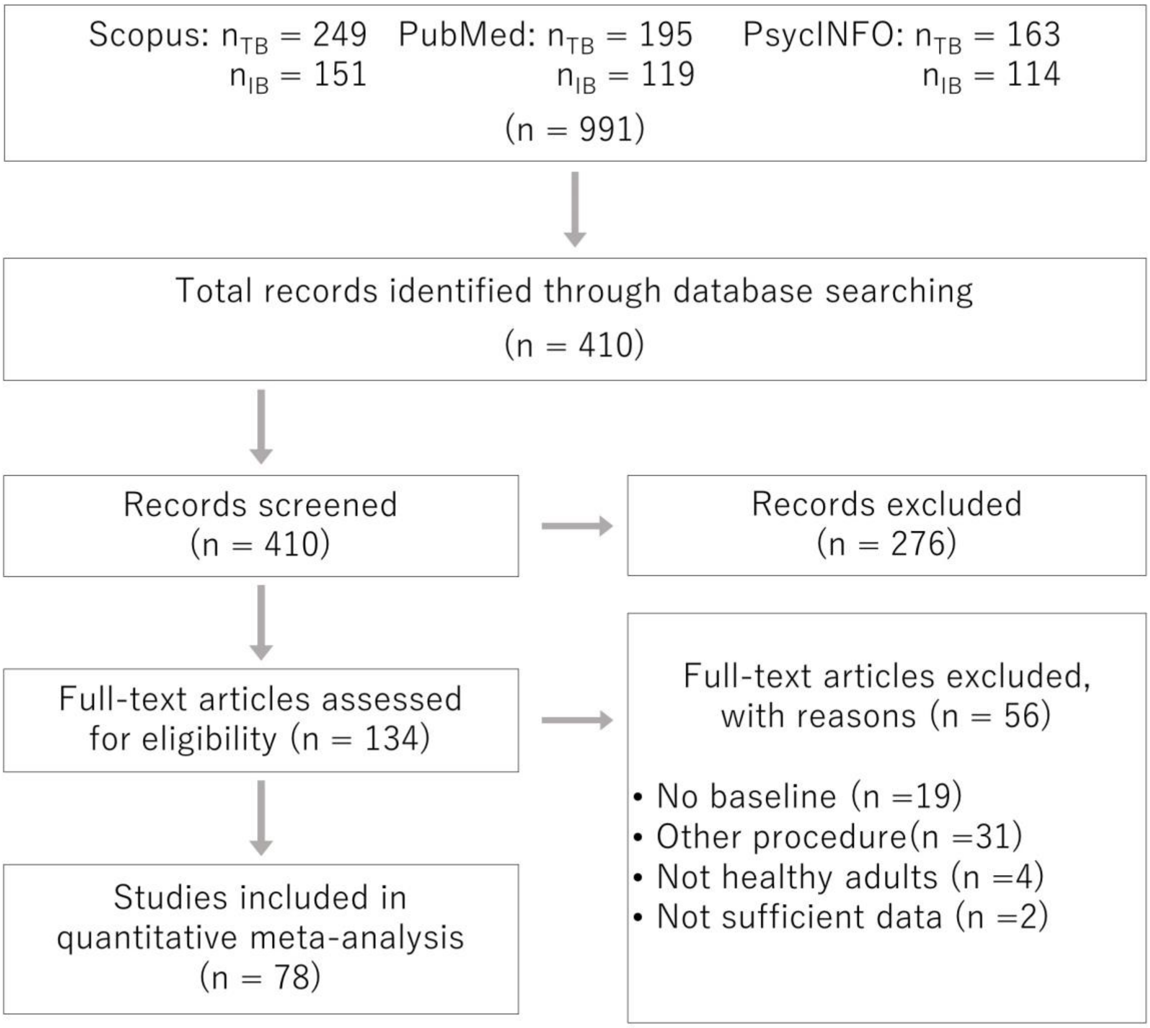

Figure 1. Flowchart of the study selection process.

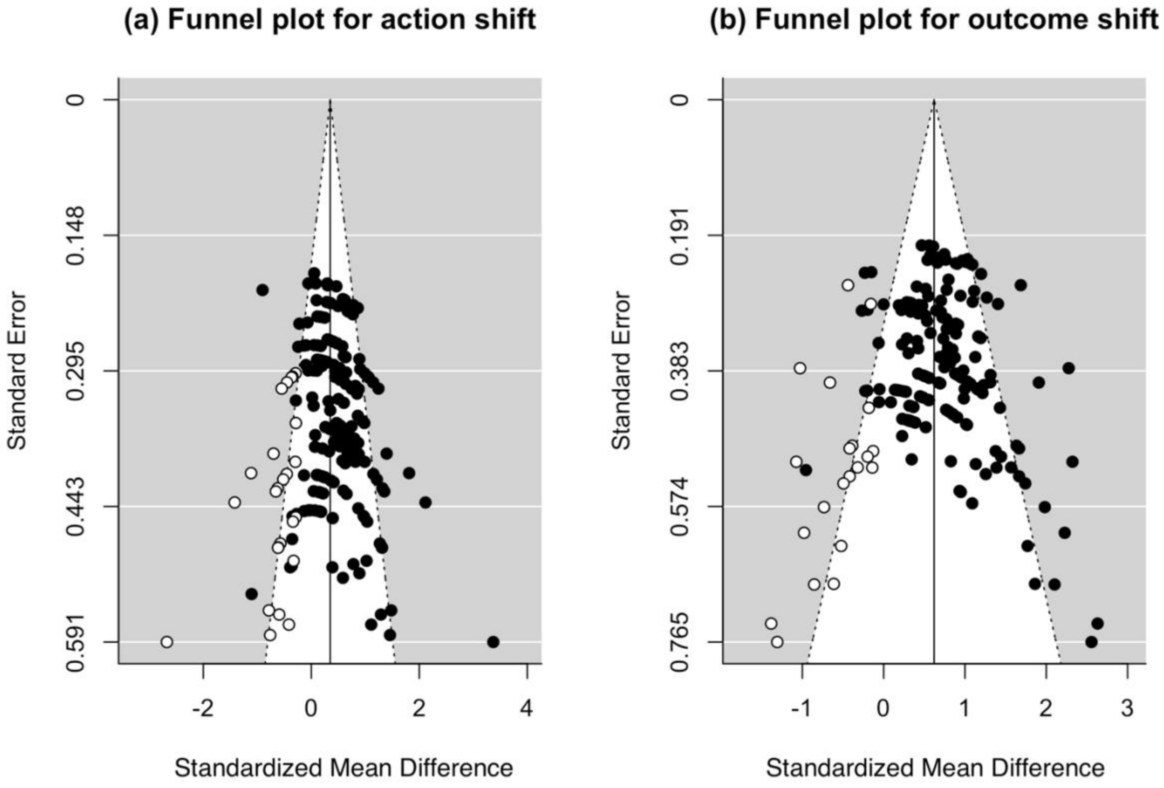

Figure 2. Funnel plots showing (a) action and (b) outcome shifts after the trim-and-fill procedure (*d* as a function of standard error). While black points indicate effect sizes actually observed, white ones indicate data estimated as missing due to potential publication bias.

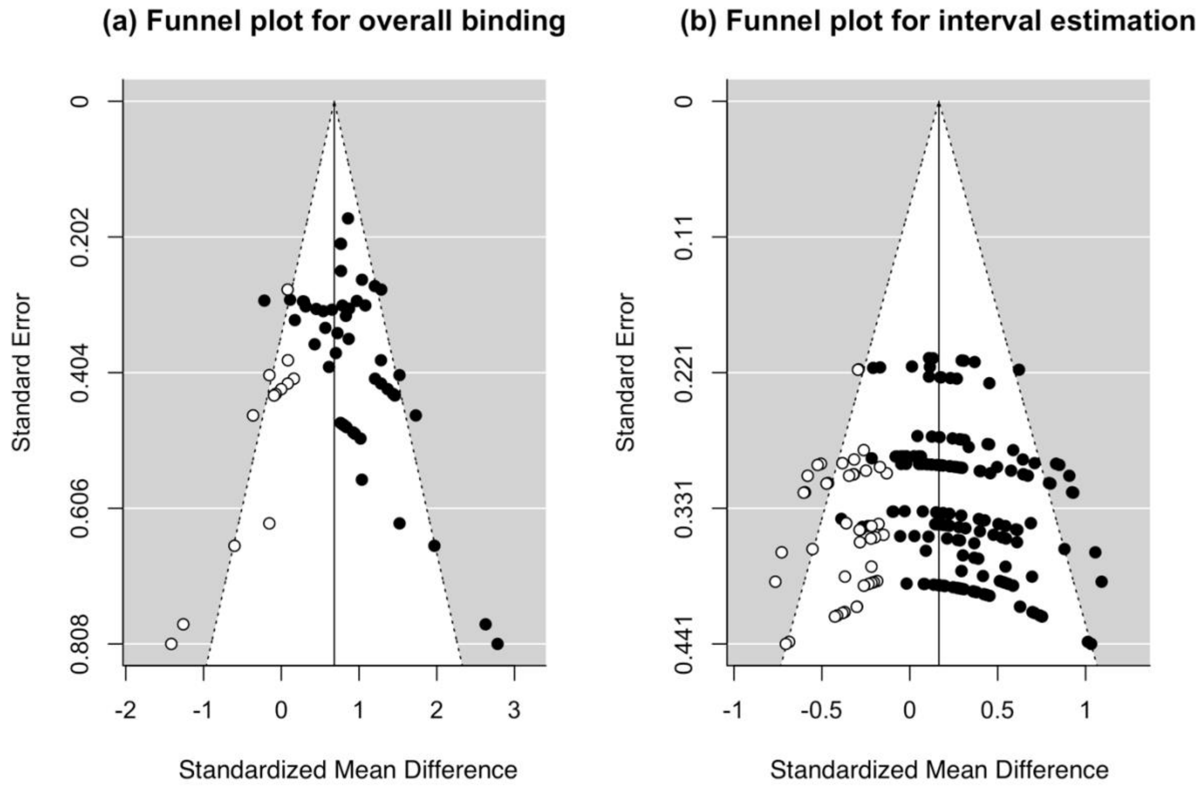

Figure 3. Funnel plot showing the effect sizes of binding measured with (a) the clock procedure and (b) interval estimation procedure after the trim-and-fill procedure (*d* as a function of standard error). While black points indicate effect sizes actually observed, white ones indicate data estimated as missing due to potential publication bias.

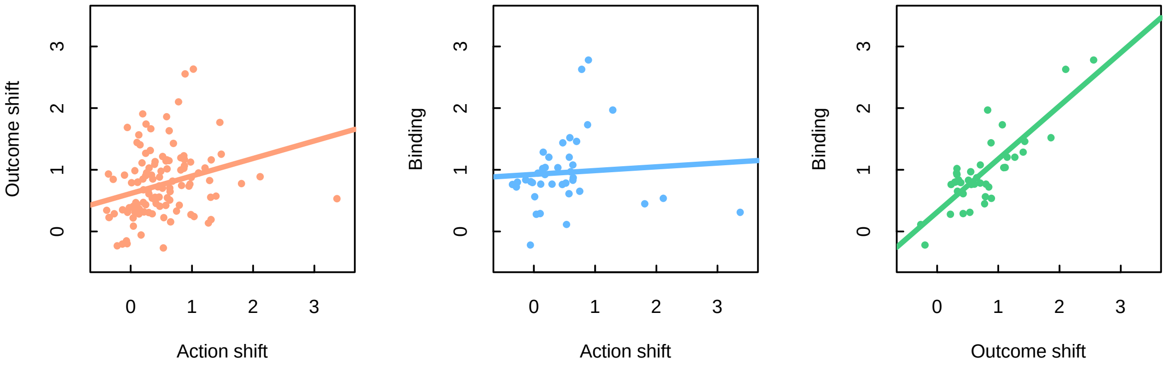

Figure 4. Correlation (a) between action shifts and outcome shifts, (b) between action shifts and binding, and (c) between outcome shifts and binding.

Tables

Table 1. Description of the coding and coder reliability examined with Krippendorff's alpha.

Variable	Description	Values	α
N	Sample size	8–126	0.997
Gender	Number of female participants	0-–87	0.998
Age	Average age of participants	19.29–64.90	0.845
Procedure	Procedure used to measure the temporal binding	0 = Libet clock procedure 1 = Interval estimation procedure	1
Outcome modality	Modality of action-outcome	0 = Auditory 1 = Visual 2 = Somatic	0.847
Baseline	Type of baseline condition used to calculate the degree of perceptual shifts or binding effects	0 = Single event condition 1 = Passive/involuntary movement 2 = observation of other's movement and/or external events	1
Temporal probability prediction	Probability with which an outcome occurred at a certain delay after action	0.00–1.00	0.881
Temporal range prediction	Range between the minimum and maximum potential delay within an experimental block (ms)	0–4000	0.966
Interval	Average interval between action and outcome within an experimental block (ms)	0–4000	0.877
Temporal control	Whether participants could cause outcomes with voluntary actions or only received pre-cues for the observation of others' actions.	0 = No control 1 = Control	0.898
Identity prediction	Probability with which participants could predict what action outcome would be presented	0.00–1.00	0.927
Occurrence probability	Probability with which any action outcome was presented	0.00–1.00	1
Type of SD	Type of standard deviation used to calculate effect sizes of perceptual shifts or binding effects	0 = SD of observed shifts or binding effects 1 = Mean SDs in operant and baseline conditions	0.899

Table 2. Comparison of action and outcome shifts.

Perceptual shift	Sub-group analysis					
	k	Estimated *d*	95% CI	*t*	*p*	*Q*
Action shift	199	0.451	[0.345, 0.557]	8.522	**<0.001**	*Q*(198) = 336.999, *p* < 0.001
Outcome shift	212	0.726	[0.617, 0.835]	13.424	**<0.001**	*Q*(211) = 458.501, *p* < 0.001

Table 3. Moderation analyses for the action shift.

Modality	Sub-group analysis					
	k	Estimated *d*	95% CI	*t*	*p*	*Q*
Auditory	175	0.471	[0.357, 0.585]	8.357	**<0.001**	*Q*(174) = 312.300, *p* < 0.001
Visual	14	0.306	[−0.805, 1.417]	1.185	0.358	*Q*(13) = 13.701, *p* = 0.395
Somatic	10	0.216	[0.014, 0.154]	44.065	**0.014**	*Q*(9) = 2.652, *p* = 0.977

(In the auditory outcome dataset)

	Meta-regression analysis					
Moderator		Estimated β	95% CI	*t*	*p*	*Q*
Intercept		0.246	[0.052, 0.441]	2.565	**0.015**	*Q*(168) = 273.968, *p* < 0.001
Temporal probability prediction		−0.049	[−0.112, 0.014]	1.577	0.123	
Temporal range prediction		−0.084	[−0.180, 0.013]	1.759	0.087	
Interval		−0.055	[−0.171, 0.061]	0.955	0.345	
Temporal control		0.273	[0.096, 0.450]	2.207	**0.003**	
Identity prediction		-−0.055	[−0.208, 0.099]	0.722	0.726	
Occurrence probability		−0.009	[−0.109, 0.090]	0.190	0.850	

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Visual	14	0.306	[−0.805, 1.417]	1.185	0.358	$Q(13) = 13.701$, $p = 0.395$
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Occurrence probability		−0.009	[−0.109, 0.090]	0.190	0.850	

Table 4. Moderation analyses for the outcome shift.

Modality	Sub-group analysis					
	k	Estimated *d*	95% CI	*t*	*p*	*Q*
Auditory	178	0.769	[0.656, 0.882]	13.742	**<0.001**	$Q(177) = 396.448, p < 0.001$
Visual	19	0.440	[0.131, 0.749]	4.536	**0.020**	$Q(18) = 15.381, p = 0.636$
Somatic	15	0.537	[−0.964, 2.039]	1.540	0.264	$Q(14) = 26.910, p = 0.020$

(In the auditory outcome dataset)

Moderator	Meta-regression analysis					
		Estimated *β*	95% CI	*t*	*p*	*Q*
Intercept		0.656	[0.401, 0.910]	5.227	**<0.001**	
Temporal probability prediction		−0.068	[0.009, 0.127]	2.341	**0.025**	
Temporal range prediction		−0.057	[−0.180, 0.013]	2.079	**0.045**	
Interval		−0.080	[−0.167, 0.006]	1.873	0.069	$Q(171) = 313.492, p < 0.001$
Temporal control		0.125	[−0.147, 0.396]	0.932	0.357	
Identity prediction		−0.078	[−0.187, 0.031]	1.456	0.154	
Occurrence probability		−0.021	[−0.046, 0.004]	1.689	0.099	

Table 5. Sub-group analyses of temporal binding in the clock and interval estimation procedures.

Procedure	Sub-group analysis					
	k	Estimated *d*	95% CI	*t*	*p*	*Q*
Libet clock	56	0.887	[0.681, 1.093]	9.130	**<0.001**	$Q(55) = 100.021$, $p < 0.001$
Interval estimation	160	0.300	[0.192, 0.408]	5.871	**<0.001**	$Q(159) = 141.564$, $p = 0.836$

(In the interval estimation dataset)

Baseline	*k*	Estimated *β*	95% CI	*t*	*p*	*Q*
Passive movement	46	0.241	[−0.006, 0.488]	2.250	0.0546	$Q(45) = 40.552$, $p = 0.661$
External event	114	0.354	[0.295, 0.413]	14.228	**<0.001**	$Q(113) = 91.335$, $p = 0.933$