Consciousness and Cognition 96 (2021) 103219

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Two faces of temporal binding: Action- and effect-binding are not correlated

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ARTICLE INFO

Keywords:
Temporal binding
Inter-individual differences
Multisensory integration
Sense of agency

ABSTRACT

Research on the sense of agency has proliferated a range of explicit and implicit measures. However, the relation of different measures is poorly understood with especially mixed findings on the correlation between explicit judgments of agency and the implicit perceptual bias of temporal binding. Here, we add to the conundrum by showing that the two sub-components of temporal binding - action-binding and effect-binding, respectively - are not correlated across participants either, suggesting independent processes for both components. Research on inter-individual differences regarding the sense of agency is thus well-advised to rely on other implicit measures until the phenomenon of temporal binding is better understood.

1. Introduction

Humans usually attribute their actions and resulting effects to themselves, on a pre-reflective implicit level as well as on a conscious explicit level (Haggard & Tsakiris, 2009; Haggard, 2017; Synofzik et al., 2008). This sense of agency has attracted considerable attention in empirical research and previous work has established various measures for quantifying the sense of agency. However, although frequently used, it is still not clear what exactly these measures do quantify and to which underlying processes they refer (David et al., 2008; Synofzik et al., 2013; Wolpe et al., 2013). Here, we address one of the most widely used methods by investigating the relationship of action binding and effect binding. These two measures constitute temporal binding, which is often regarded as an implicit marker of the sense of agency (Haggard et al., 2002; Moore & Obhi, 2012).

Temporal binding describes the subjective compression of the time interval between an action and its resulting effect. The action is perceived a little later than it actually occurred, i.e., it is shifted towards its effect (action binding), and the effect is perceived a little earlier, i.e., it is shifted towards the action (effect binding; Ruess et al., 2017; Borhani et al., 2017; Schwarz et al., 2019). Both parts of the binding effect can be assessed in variants of the Libet clock setup by comparing time estimates for actions and effects between operant and baseline conditions (Haggard et al., 2002; see also Cornelio Martinez et al., 2018; Muth et al., 2021). With the Libet clock method, action binding and effect binding have been used separately (Moore & Haggard, 2008; Pfister et al., 2021; Weller et al., 2020) as well as summed to an overall binding score (Wolpe et al., 2013; Antusch et al., 2019). This measure had originally been dubbed "intentional binding" (Haggard et al., 2002), stressing the assumption that the binding effect provides a pre-reflective, implicit measure of the sense of agency. Having such an implicit measure at hand would prove useful because it could circumvent limitations of explicit assessments of agency. For instance, explicit measures such as ratings on a visual analogue scale are prone to demand effects, and they are also confined to conscious parts of the sense of agency, whereas unconscious precursors of agency go unnoticed (Haggard

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https://doi.org/10.1016/j.concog.2021.103219
Received 9 March 2021; Received in revised form 2 October 2021; Accepted 3 October 2021

& Tsakiris, 2009).

However, whether temporal binding is an appropriate proxy for the sense of agency is still under debate (e.g., Ruess et al., 2020; Antusch et al., 2019). Findings in favor of this conjecture were reported in the seminal study on the binding phenomenon (Haggard et al., 2002), in which voluntary movements and their resulting effects were attracted to each other, as opposed to involuntary movements which led to temporal repulsion. Action binding has also been reported in the absence of perceivable effects as long as participants intended or expected to produce an effect (Moore & Haggard, 2008) and effect binding has been observed even for nonactions, i.e., deliberate omissions of an action (Weller et al., 2020). Because intentionality is considered one of the basic requisites of the sense of agency, these findings seem to support a reading of temporal binding (as well as action binding and effect binding separately) as an implicit correlate of the sense of agency.

Yet, there is growing evidence challenging the role of intentionality in temporal binding. This evidence comprises binding effects for causal event chains that do not involve an action of the observing agent (e.g., Ruess et al., 2020; Buehner, 2012; Suzuki et al., 2019; Antusch et al., 2020) and similar binding effects for involuntary as well as voluntary movements when controlling for temporal predictability (Kirsch et al., 2019). Such findings demonstrate that intentionality is not a necessary precondition for temporal binding, thereby rendering it a somewhat controversial marker of the sense of agency. In other words: Even though intentionality might be sufficient to instill temporal binding (Moore & Haggard, 2008; Weller et al., 2020), the measure seems to tap into additional processes as well (Ruess et al., 2020). One candidate process that has emerged from a range of experimental investigations is multisensory integration (Wolpe et al., 2013; Klaffehn et al., 2021; Cao et al., 2020; Kirsch et al., 2019). The multisensory integration account of temporal binding holds that individual sensory signals that belong to a multimodal event affect the (temporal) perception of that multimodal event. The magnitude of this impact is weighted relative to the certainty of the corresponding sensory signals. I.e., a high perceptual certainty of any individual sensory signal increases the perceptive weight of that individual sensory signal within the perception of the multimodal event, irrespective of whether the signal is caused by the observer. Therefore, from a multisensory integration perspective, temporal binding occurs when an action and its effect are represented as a single (meta-)event.

If action and subsequent effect differ in perceptual certainty across individuals (see Fig. 1), i.e., some agents can effectively pinpoint the action onset but not the effect onset (or vice versa), this would predict a negative correlation between the two components of temporal binding (see Fig. 2A). Specifically, a perceptually uncertain action and a certain effect result in a stronger attraction of the action to the effect and thus larger action binding than effect binding. Vice versa, a perceptually certain action and an uncertain effect result in a stronger attraction of the effect to the action and thus larger effect binding than action binding.

If, however, agents vary greatly in their general effectiveness to judge the timing of any kind of event, this would lead to either low binding scores for both action binding and effect binding (high general perceptual certainty) or high binding scores (low general perceptual certainty) thus predicting a positive correlation of action binding and effect binding (see Fig. 2B). Such a positive correlation of action binding and effect binding would be in line with the mere binding capacity account, another potential explanation for temporal binding. In this view, the size of the binding effect is linked to an individual's proneness to associate action and effect (Hascalovitz & Obhi, 2015; but see Schwarz et al., 2018) independent of the perceptual certainty of any event. Such a trait-like characteristic of action binding and effect binding would provide justification for the usage of action binding and effect binding as interchangeable and freely combinable components of the same measure. It would mirror research on other multisensory illusions, e.g., the McGurk effect in showing substantial but consistent inter-individual variation (Getz & Toscano, 2021; Brown et al., 2018). The mere capacity account in terms of binding is supported by clinical studies that showed certain patient populations – specifically: schizophrenic individuals – to exhibit "hyper-binding" as compared to healthy controls (Haggard et al., 2003; Voss et al., 2010). Furthermore, dopaminergic medication was shown to boost action binding and effect binding alike in patients with Parkinson's disease (Moore et al., 2010). Such findings suggest a positive correlation of action binding and effect binding, which would render temporal binding a promising marker to assess interpersonal differences between "low binders" with low values in both action binding and effect binding and "high binders" with higher values on both components respectively. This is also consistent with a recent meta-analysis that reported a small but positive correlation of action binding and effect binding across different studies (Tanaka et al., 2019). Note, however, that correlations across studies do not necessarily inform about inter-individual correlations but rather about systematic variations across study setups (e.g., relating to different action-effect intervals).[1]

Hence, one can predict both a negative and a positive correlation between action binding and effect binding from literature. In a given sample, the direction of the correlation should depend on which variance is more profound, i.e., the difference in perceptual certainty between action and effect or the difference in overall temporal judgment between participants.

Lastly, action binding and effect binding could also be unrelated. Indeed, some evidence suggests action binding and effect binding to stem (at least partly) from different processes (Wolpe et al., 2013) with action binding and effect binding being affected differently by transcranial magnetic stimulation or induced causal beliefs (Moore et al., 2010; Desantis et al., 2011). It seems as if for action binding a specific action-effect association is required, whereas for effect binding a more general association is sufficient and no specific action-effect mapping is needed (see also Weller et al., 2020). However, there is also evidence suggesting a shared underlying mechanism, e.g., a predictive process (Wolpe et al., 2013). A true absence of a correlation (i.e., not a product of counteracting positive

[1] It might also be possible to accommodate a positive correlation in a multisensory integration framework when drawing upon theories regarding partial multisensory integration/ sensory coupling (Ernst, 2006, see also Roach, Heron, & McGraw, 2006). These theories hold that it is beneficial to retain individual sensory properties more strongly in case of uncertainty whether two separable events belong to the same multisensory event or not. A high variability across participants with some construing keypress and tone as a conjoint event and others construing two single events could also explain the finding of a positive correlation.

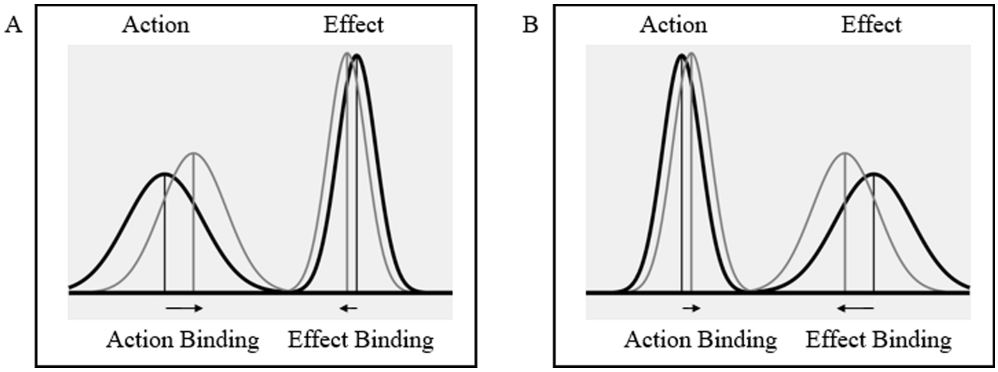

Fig. 1. Multisensory integration approach to temporal binding. Perceptual representations are assumed to come with a given certainty as represented by the spread of the corresponding distribution, e.g., across the temporal dimension. When they are bound into a multisensory event, more certain events should provide a superior temporal anchor, thus being bound less to other components, while exerting stronger pull themselves. A perceptually uncertain action triggering a perceptually certain effect thus results in the action being more strongly attracted to the effect and thus larger action binding than effect binding (A). In case of a perceptually certain action triggering an uncertain effect, the effect is attracted more strongly to the action, thus yielding larger effect binding than action binding (B).

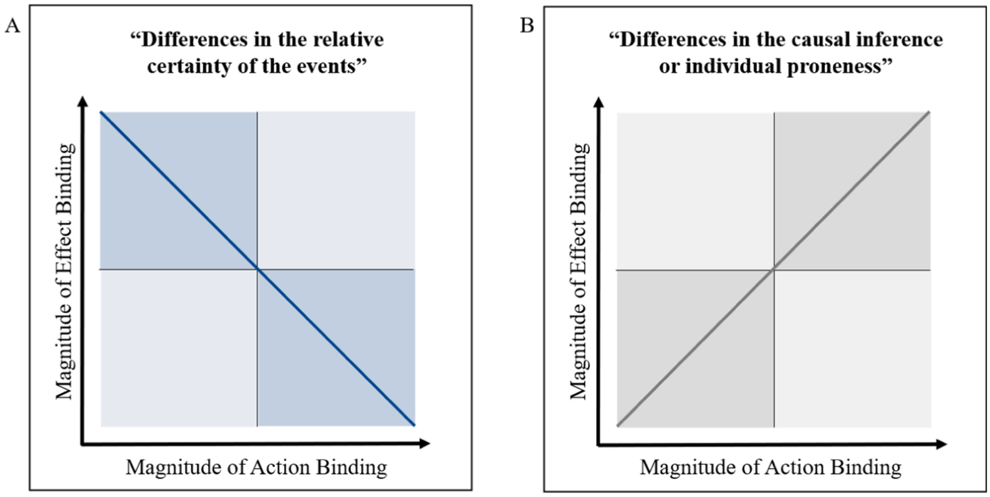

Fig. 2. Predictions of potential correlations between action and effect binding. A. Predictions of a multisensory integration model when the sample shows relatively high variance in their ratio of action certainty to effect certainty. B. Predictions when the sample shows greater variance in causal inference about the action-effect relations or when assuming an individual binding capacity. Please note that both, A and B, might be compatible with the multisensory integration account, whereas only B is in line with a mere binding capacity account. Intensity of the colored fields displays how many values we expect in different quadrants due to the predictions; the darker the color, the more values expected.

and negative correlations) between action binding and effect binding would thus bolster the notion that the underlying processes of action binding and effect binding are indeed independent. Such independence could also partly account for the lack of a correlation between temporal binding and explicit agency ratings (Dewey et al., 2014; Saito et al., 2015; but see Imaizumi & Tanno, 2019 for different results; a discussion of these studies can be found in Schwarz et al., 2019).

Studying the relationship of action binding and effect binding on an inter-individual level has the potential to inform the current theoretical understanding of the binding phenomenon and its relation to other measures of the sense of agency. It can further help to determine whether temporal binding could make for a useful measure in studies on inter-individual differences. To investigate whether and how action binding and effect binding scores are associated, we re-analyzed data of a previous study from our lab that had a sufficient sample size to compute meaningful correlations (Schwarz et al., 2019).

2. Methods

The present analyses build on the data of Schwarz et al. (2019). In the following, we summarize the methodological setup of this study with a special focus on the aspects that are relevant for the follow-up analyses.

2.1. Participants

The data comprised 92 participants (mean age = 22.8 years, range 18–61; 77 females; 82 right-handed) of which two were excluded because they failed to perform the experimental task.

2.2. Apparatus and stimuli

Participants observed a 24″ monitor and operated the keys *C* and *V* on a standard German QWERTZ keyboard. Different target stimuli (arrows or letters) announced the current condition. A double-sided arrow (≪≫) indicated a free-choice condition, whereas the letters "L" (left) and "R" (right) served as target stimuli for the forced-choice conditions and indicated that participants had to respond with a left or right keypress. The monitor showed a clock face (diameter: 6 cm) with a rotating clock hand (frequency: one rotation per 2500 ms) which was used for time estimations. Every five "minutes" (5, 10, 15…) were tick-marked on the clock face, and each quarter was labeled ("15", "30", "45", "60"). Auditory effects were presented via headphones and included a high (600 Hz) and a low (300 Hz) sinusoidal tone of 100 ms duration.

2.3. Procedure

The experiment consisted of four different block types, two operant and two baseline blocks. Participants always had to estimate the time of a certain event (either the keypress or the sound) using the presented clock.

The operant blocks started with the presentation of a target stimulus (duration: 500 ms) announcing either a forced choice ("L" or "R") or a free choice trial (≪≫). Then, the clock face was presented. The clock hand appeared at a random position in each trial and started rotating immediately. Participants were instructed to wait at least half a rotation of the clock hand before pressing the respective key. When participants pressed the key within this requested time interval, a sound effect was presented 300 ms after their keypress; when they pressed the key earlier or when they pressed the wrong key in a forced choice trial, this was counted as an error trial and subsequently excluded from analysis. Whether a high or low tone was played, depended on the identity of the keypress (left or right). The mapping of keypress and sound effect was constant for each participant but counterbalanced across participants. After the sound effect, the clock hand kept rotating for further 2000 to 3000 ms before the clock disappeared.

Baseline blocks were similar to operant blocks, but either no tone followed after action execution (baseline action), or no action was required, and one of the two tones was presented randomly 1270–3750 ms after trial start (baseline effect). In this latter case, no target stimuli were presented and a trial started directly with the display of the clock.

In the baseline action blocks (A_{BL}) and operant action blocks (A_O), participants were asked to estimate the position of the clock hand at the moment when they pressed the key. In the baseline effect blocks (E_{BL}) and in operant effect blocks (E_O), they were asked to estimate the position of the clock hand when the tone was presented. The respective question was displayed immediately after the clock disappeared and participants had unlimited time to enter their estimate via keypress. For baseline action blocks we distinguished between free- and forced-choice. Please note, that this distinction was not possible in a baseline effect condition, where tones were played without a preceding action.

Each baseline and operant block was presented twice, so that participants completed eight blocks in total and each of these blocks comprised 40 trials. For half of the participants, the blocks followed the order A_{BL}, E_{BL}, A_O, E_O, A_O, E_O, A_{BL}, E_{BL}; for the other half, the blocks followed the order E_{BL}, A_{BL}, E_O, A_O, E_O, A_O, E_{BL}, A_{BL}.

2.4. Data analysis

Raw data and analysis script are available on the Open Science Framework, https://osf.io/kwjte/. In keeping with the previous publication (Schwarz et al., 2019), we calculated estimation errors for each participant and trial, by subtracting the actual from the estimated time of the keypress or tone (depending on what estimate was requested in the current trial). This resulted in negative estimation errors if participants perceived tone or keypress earlier and in positive estimation errors if they perceived these events later than they actually occurred. We excluded trials in which participants' time estimates exceeded the time range displayed on the Libet Clock (1–60; 0.2%) as well as forced choice trials in which participants performed an incorrect response (1.9% of forced choice trials). Besides, we excluded trials with time estimates that deviated more than 2.5 standard deviations (*SD*s) from the cell mean as outliers, calculated separately for each participant and condition (3.1%).

Temporal binding was computed as the participant's mean estimation error in operant blocks minus his or her mean estimation error in the respective baseline blocks. Because binding scores would be expected to be positive for the action condition, but negative in effect conditions, we inverted effect binding for all following analyses (corrected score = −1 * original score). Thus, larger action binding and effect binding are both represented by increasing positive numbers. Pairwise comparisons were analyzed via two-tailed, paired *t*-tests with corresponding effect sizes being calculated as $d_z = t/\text{sqrt}(n)$. Please note that these calculations were the same as reported in Schwarz et al. (2019).

Inter-individual correlations of action binding and effect binding were computed by correlating the mean action binding value of a given condition (free/forced choice) with the corresponding effect binding value across participants. Furthermore, we calculated inter-individual correlations of binding scores across free- and forced-choice conditions for action binding and effect binding. This was done correlating the individual mean binding scores for one event (action/effect) in the free-choice condition with the corresponding scores in the forced-choice condition.

3. Results

3.1. Temporal binding

Replicating the results reported in Schwarz et al. (2019), temporal binding effects occurred in all conditions. That is, keypresses were perceived later and tones were perceived earlier in operant conditions compared to the respective baseline conditions; A_{Free}: $M = 20.18$ ms, $t(89) = 4.74$, $p < .001$, $d_z = 0.50$; A_{Forced}: $M = 21.15$ ms, $t(89) = 5.37$, $p < .001$, $d_z = 0.57$; E_{Free}: $M = 89.54$ ms, $t(89) = 9.30$, $p < .001$, $d_z = 0.98$; E_{Forced}: $M = 91.02$ ms, $t(89) = 9.76$, $p < .001$, $d_z = 1.03$.

3.2. Correlations of action binding and effect binding

Inter-individual correlation analyses between action binding and effect binding revealed no significant correlation, neither for free-choice trials, $r(88) = 0.06$, $p = .578$, 95% CI [−0.15; 0.27], nor for forced-choice trials, $r(88) = 0.03$, $p = .766$, 95% CI [−0.18; 0.24] (Fig. 3).

A possible but unfavorable explanation for the absence of a correlation could lie in the nature of the collected data. Cognitive-experimental tasks often create a strong effect on the group level by diminishing inter-individual variation, effectively working against meaningful inter-individual differences (Hedge et al., 2018). Conversely, if binding scores were too erratic, potential correlations are likely to be overlooked because of insufficient data quality rather than a true absence of a correlation. This interpretation is not in line with the results of the second sets of correlations, however. Action binding in free and forced choice conditions correlated strongly, $r(88) = 0.86$, $p < .001$, as did effect binding across the two choice conditions, $r(88) = 0.96$, $p < .001$ (Fig. 4), indicating that action binding and effect binding both yield reliable estimation errors across different conditions.

3.3. Assessing the cancellation hypothesis

Yet, the absence of a correlation between action binding and effect binding can be explained two-fold: it can be based on a true absence of any correlation, or it can be the product of a cancellation of counteracting positive and negative correlations.

To test this latter possibility, we first checked whether estimation errors were indeed related to perceptual uncertainty as the multisensory integration approach suggests (Fig. 1). To this end, we tested the relationship of perceptual certainty and estimation errors by calculating correlations of the mean binding score for each condition (action/effect, free/forced) and the *SD* of the estimation errors in the respective baseline condition as a measure of perceptual uncertainty. We chose the baseline conditions because they allow a measure of perceptual (un-)certainty for action and effect conditions, separately, while still remaining unbiased by binding processes.

Binding scores correlated with perceptual certainty for the free-choice, effect condition, $r(88) = 0.29$, $p = .007$, the forced-choice, effect condition, $r(88) = 0.33$, $p = .001$, and the forced-choice, action condition, $r(88) = 0.36$, $p = .001$, but not for the free-choice, action condition, $r(88) = -0.01$, $p = .924$ (Fig. 5). These results indicate that overall perceptual certainty is indeed related to temporal binding, as temporal binding is increased when perceptual certainty is decreased (i.e., variability is higher), which is in line with a multisensory integration approach.

To eliminate the factor perceptual certainty from our correlational analyses, we then calculated linear regression analyses for every condition using binding scores as criterion variable and entering relative perceptual certainty as predictor. Relative perceptual certainty was determined by computing an asymmetry score for every condition; e.g., the asymmetry score for the free-choice, action condition was computed as the *SD* of the estimation errors for the free-choice, action baseline condition divided by the *SD* of the estimation errors for the effect baseline condition; likewise, the asymmetry score for the free-choice, effect condition was computed as the *SD* of the estimation errors for the effect baseline condition divided by the *SD* of the estimation errors for the free-choice, action condition, etc. We chose to calculate a ratio of perceptual certainty measures of action and effect conditions because if we expect differences in the relative certainty of the events to be the decisive element eliciting binding, high perceptual certainty in action conditions should be associated with low perceptual certainty in effect conditions (and vice versa). We then used the residual values of action and effect conditions, separately for free- and forced-choice conditions, to probe for underlying correlation. Additionally, we calculated partial correlations of action binding and effect binding, separately for free- and forced-choice conditions, controlling for perceptual certainty (as measured by the standard deviations of the estimation errors in the respective baseline conditions and by asymmetry scores as described above).

Again, we did not find evidence for correlations between action binding and effect binding, Free Choice: $r(88) = 0.05$, $p = .626$, 95% CI [-0.16; 0.26], Forced Choice: $r(88) = 0.04$, $p = .686$, 95% CI [-0.17; 0.26]. A partial correlation controlling for perceptual certainty also found no association of action binding and effect binding, $|r|s < 0.13$, $ps > 0.256$, suggesting that the absence of a correlational relationship between action binding and effect binding is not based on underlying, counteracting associations, but rather an indication of independent processes.

As outlined in the introduction the multisensory integration approach would have been especially compatible with a negative correlation, under certain circumstances also with a positive correlation or an absent correlation due to counteracting associations. However, it is not compatible with a true absence of a correlation between action binding and effect binding. To complement the

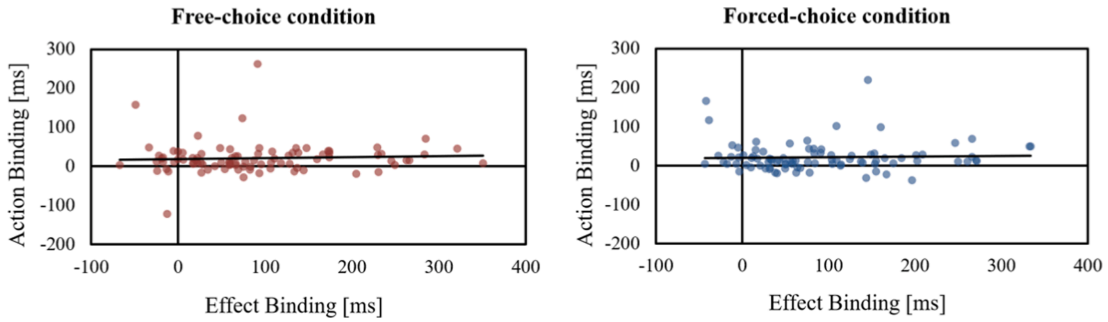

Fig. 3. Inter-individual correlations. Action binding and effect binding did not correlate significantly for free- or forced-choice condition (N = 90).

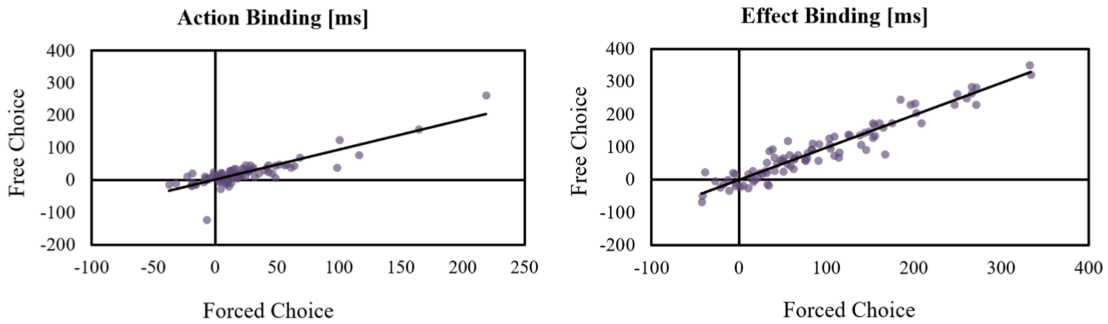

Fig. 4. Inter-individual correlations of free- and forced-choice trials, computed separately for action binding and effect binding. Free- and forced-choice trials correlated significantly for both action binding and effect binding.

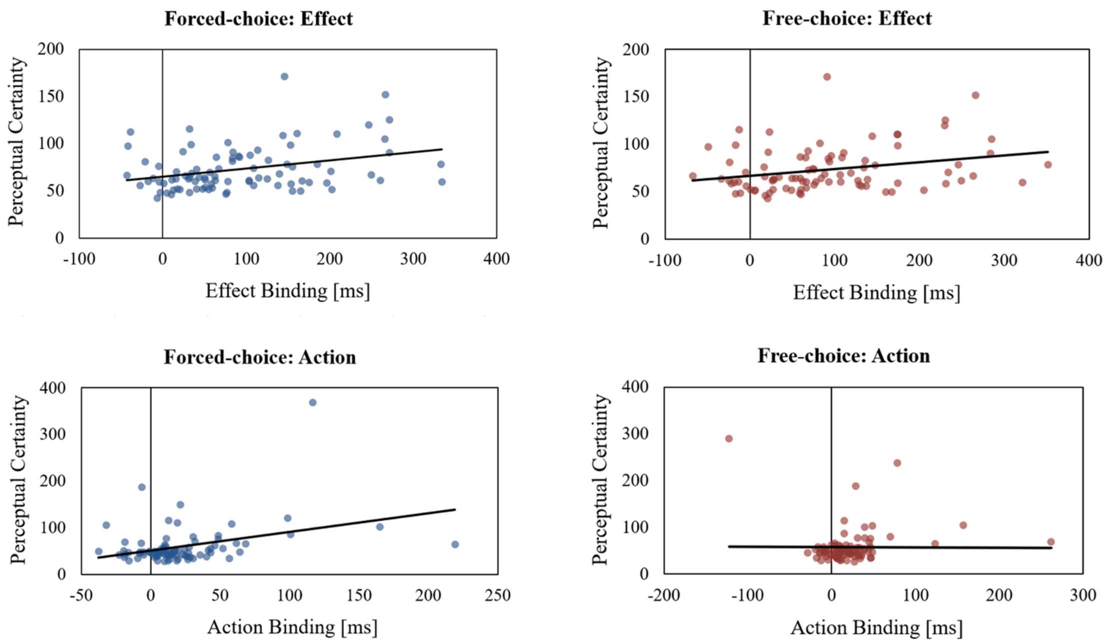

Fig. 5. Correlations of Perceptual Certainty (i.e., SD of estimation errors) and binding scores for action binding and effect binding in the free- and forced-choice condition.

previous analyses, we also tested whether the ratio of action binding and effect binding is correlated with the ratio of action and effect certainty. On the basis of multisensory integration, we would expect a positive relationship between the binding ratio and the ratio of standard deviations, with higher variance going along with stronger relative binding in a component. However, the results did not show such correlations,[2] neither for free-choice, $r(87) = -0.05$, $p = .623$, 95% CI [−0.27; 0.16], nor for forced-choice trials, $r(87) = -0.12$, $p = .280$, 95% CI [−0.33; 0.10].

4. Discussion

Our results do not show any signs of inter-individual correlations between action binding and effect binding – the two components of temporal binding. This observation even withstood thoroughly testing for alternative explanations: Follow-up analyses showed that the absence of a correlation neither depicted an interplay of counteracting negative and positive correlation components, nor was an outcome of insufficient data quality or reliability. This suggests a true absence of a correlation and thus, independent processes underlying action and effect binding.

Within the recent discussion on underlying processes of implicit measures, our results bolster the interpretation of distinguishable processes (Wolpe et al., 2013; Tanaka et al., 2019), and add to this discussion by providing evidence that the processes underlying action binding and effect binding are independent.

But what do our results mean for the interpretation of temporal binding results in general and for the use of temporal binding as an implicit marker of agency in empirical studies? An absent correlation between action binding and effect binding indicates that both sub-components of temporal binding cover unique aspects. Prior studies mainly focused on the relationship between implicit and explicit measures of the sense of agency. They showed that both measures do not cover the same aspects, as they displayed no correlation between explicit measures and their corresponding implicit proxies – neither intra-individually across different trials nor inter-individually across different agents (Schwarz et al., 2019; Dewey et al., 2014; Saito et al., 2015). We extend these results by revealing that there is no correlation, not only across measures covering different levels of subjective experience, but also within sub-components of implicit proxies targeting a single level.

The independency of action binding and effect binding and the additional absence of correlations between temporal binding (when used as an overall binding score, and when using separate scores for either action binding or effect binding) and explicit agency ratings indicate that temporal binding cannot be equated with the sense of agency. This calls for maximally cautious interpretations when using temporal binding to investigate the sense of agency. We now add that the sub-components cannot be used interchangeably either, as they appear to tap into different processes. Researchers thus need to consider carefully whether to operationalize temporal binding with an overall score, a separate action binding score, or a separate effect binding score.

As outlined in the introduction, clinical studies support a link between the size of the binding effect and an individual proneness to associate action and effect (Haggard et al., 2003; Voss et al., 2010), predicting a positive correlation. With the absence of a positive correlation, our data imply that temporal binding does not represent a promising marker to assess interpersonal differences between “low binders” and “high binders” in healthy individuals. This conclusion likely generalizes to alternative measures of the binding effect via direct verbal estimates or interval reproduction tasks (e.g., Pfister et al., 2014; Ebert & Wegner, 2010; Humphreys & Buehner, 2010).

Although the present analyses indicate that processes underlying action binding and effect binding are independent, it is still not clear, which processes exactly drive the occurrence of temporal binding. Therefore, at this time we cannot preclude that temporal binding might function as an implicit marker of agency under certain circumstances.

As described above, one account to explain temporal binding which has recently gained traction is multisensory integration (Kirsch et al., 2019; Klaffehn et al., 2021; Suzuki et al., 2019; Wolpe et al., 2013), stating that a smaller binding effect on a more certain event should be associated with a larger binding effect observed on a less certain event (Wolpe et al., 2013; Rohde et al., 2016). Our results reveal mixed findings on the question whether action binding and effect binding are driven by multisensory integration processes. We found no correlation of action binding and effect binding and no correlation between the ratio of action binding and effect binding and the ratio of action and effect certainty, providing evidence against the multisensory integration account. However, we did find correlations of binding scores with the corresponding perceptual certainties which shows that perceptual certainty and temporal binding are related – a critical prerequisite for the multisensory integration approach.

This suggests that multisensory integration can *partly* account for temporal binding. The present results therefore indicate that temporal binding likely originates from multiple, independent mechanisms. While multisensory integration seems to be one part of this puzzle, current theorizing would nonetheless benefit from a search for additional contributions.

5. Conclusion

We provide evidence that action binding and effect binding are independent processes with results indicating that current theories are insufficient to explain the origin of temporal binding. As this is only one in several controversial aspects regarding temporal binding as an implicit measure of the sense of agency, we urge researchers to use and interpret temporal binding values with due caution. This holds true when using a combined score or when dividing the measure into its sub-components. Furthermore, the present results stress

[2] In these analyses one further participant was excluded due to an absent binding value in the free-choice effect condition which would result in a division by zero error when computing the ratio as described.

once more that additional research is needed to arrive at a satisfactory understanding of the processes underlying temporal binding.

Funding

This research was supported by a grant of the German Research Council (Deutsche Forschungsgemeinschaft; DFG) to KS (grant number: SCHW 1955/1-1).

Declaration of Competing Interest

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

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