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The effects of action choice on temporal binding, agency ratings, and their correlation

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A B S T R A C T

The sense of agency, i.e., the feeling of control over one's own actions and their consequences in the environment, is a crucial part of action taking. In experimental studies, agency is most commonly measured either directly via explicit agency ratings or indirectly via implicit measures, e.g., temporal binding. In order to aid our interpretation of previous and future results, several studies have focused on relating implicit and explicit measures of agency to one another. However, possibly due to different methodological issues, results have been far from conclusive. In the present study, we therefore contribute to this discussion by further characterizing temporal binding and explicit agency ratings in their response to action choice as an experimental manipulation in a high-powered design, and by studying how temporal binding and agency ratings are related in different experimental conditions. Furthermore, we discuss the possible influence of the specific agency question regarding the participants' ratings.

1. Introduction

Healthy human beings feel in control of their own actions and believe themselves to be capable of affecting their environment by acting. This notion of control and causation is often summarized as the sense of agency, and it has wide-reaching consequences in our society. The sense of agency allows the correct identification of actions as "own" or "other" (Haggard & Tsakiris, 2009; Moore, 2016), it has been linked to feelings of responsibility and regret for actions and their effects (Frith, 2014; Moore, 2016), it informs our justice and law systems (Haggard, 2017), and faulty expressions of the sense of agency have been associated with severe mental diseases, such as schizophrenia (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Franck et al., 2017; Haggard, 2017; Oestreich et al., 2016).

The sense of agency has gained considerable attention in empirical research over the recent years, with studies focusing mostly on specific measures to quantify the sense of agency in the laboratory: either explicit ratings asking participants to directly judge their own notion of control, causation or responsibility in a given task or implicit measures using indirect indications of sense of agency such as temporal binding (intentional binding) in behavioral tasks (Chambon, Sidarus, & Haggard, 2014; Haggard & Tsakiris, 2009; Haggard, 2017; Hughes, Desantis, & Waszak, 2013; Moore, 2016; Schwarz, Burger, Dignath, Kunde, & Pfister, 2018; Synofzik, Vosgerau, & Newen, 2008; Tsakiris & Haggard, 2003). Temporal binding refers to the perceived attraction of an action and its subsequent effect on a temporal scale. That is, operant actions are perceived slightly later in time, while the effects of these actions are perceived earlier in time as compared to their physical appearance, so that the interval in between action and effect is subjectively compressed (Beck, Di Costa, & Haggard, 2017; Haggard & Tsakiris, 2009; Pfister, Obhi, Rieger, & Wenke, 2014; Ruess, Thomaschke, & Kiesel, 2017; Tsakiris & Haggard, 2003). Although both types of measures, explicit and implicit, are generally used to study sense of agency, it has been argued that different factors and mechanisms contribute to these measures rendering them not interchangeable, but instead showcasing different aspects of sense of agency (Synofzik et al., 2008; Synofzik, Vosgerau, & Voss, 2013).

Because of the surge of studies using temporal binding as an implicit measure for sense of agency in recent years, the scientific field has begun not only to study the influence of novel experimental manipulations on temporal binding, but also to consolidate past

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findings to estimate their reliability, and to further study the mechanisms underlying temporal binding. For example, there is now convincing evidence that action intentions are not pivotal for temporal binding as was previously thought. Rather, it seems to be based on causal inference and possibly multisensory integration processes (Kirsch, Kunde, & Herbort, 2019). We therefore refer to the phenomenon as "temporal binding" instead of the previous label of "intentional binding". Controversial findings also emerge in the study of outcome valence on agency: some studies have found evidence for the effects of outcome valence, i.e., positive or negative outcomes, on temporal binding with some studies finding stronger temporal binding for positive, others for negative outcomes dependent on the experimental task (Christensen, Yoshie, Di Costa, & Haggard, 2016; Tanaka & Kawabata, 2019; Yoshie & Haggard, 2013). However, other studies including high-powered replication attempts with multiple experiments have failed to show any influence of outcome valence on temporal binding altogether (Barlas, Hockley, & Obhi, 2018; Moreton, Callan, & Hughes, 2017).

These examples indicate that many debates surrounding agency and its measurement call for a larger database to distill consistent findings. In this context, we want to highlight two more aspects relating to temporal binding that we believe to be, as-of-yet, far from clear-cut and therefore wish to address in the present study: The influence of free and forced choice on temporal binding and on the explicit sense of agency, as well as the relation of temporal binding as an implicit measure of agency with explicit agency ratings.

Previous studies have investigated the influence of action choice on explicit and implicit agency measures. This line of research mainly relates to the question, whether or not the freedom to autonomously choose an action and thereby determine an effect is a crucial component of agency. That is, instructed actions might lead to reduced agency for both, the action as well as potential outcomes. While it may be reasonable to assume that such an effect only presents itself through conscious deliberation and can therefore only be found in explicit measures, thus far results are somewhat mixed. Whereas several studies have found that free choice conditions lead to higher explicit agency ratings than forced choice conditions (Barlas et al., 2018; Sebanz & Lackner, 2007; Sidarus, Vuorre, & Haggard, 2017a; Wenke, Fleming, & Haggard, 2010), others have not observed such differences (Sidarus & Haggard, 2016). Similarly, whereas temporal binding seems to be stronger when participants freely choose their actions compared to no choice conditions in some studies (Barlas & Obhi, 2013; Barlas et al., 2018), results are much more ambiguous in others (Wenke, Waszak, & Haggard, 2009). Related studies on the integration of upcoming action effects in the agent's environment into action representations have also painted a rather mixed picture. While there is evidence that action planning in both free and force choice conditions can draw on such effect anticipations (e.g., Gaschler & Nattkemper, 2012; Hommel, Lippelt, Gurbuz, & Pfister, 2017; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014) other studies have suggested a considerable reduction of these anticipations in forced-choice settings (Herwig & Horstmann, 2011; Pfister, Kiesel, & Melcher, 2010), so that additional data is required to arrive at an accurate characterization of action control in both settings.

The question on whether or not explicit and implicit measures of agency are related has become more and more prominent, especially in recent years, as previous articles have at times discussed both types of measures almost synonymously, and inferences about the participants' explicit sense of agency have been regularly made on the basis of implicit measures alone. However, for a long time, little empirical evidence underlay this assumption. Moreover, several theoretical models argue that explicit and implicit measures of agency might map explicit and implicit components of agency that, in turn, are characterized by different aspects of the task, the situation, and the general context. Whereas explicit measures are likely to be affected by reflection and general knowledge of task and situation, implicit measures are thought to tap into non-conceptual and pre-reflective processes (Synofzik et al., 2008; Wegner & Wheatley, 1999). In short, whether explicit and implicit measures of agency are related is not as definite as one might think. Several previous studies have thus asked precisely this question by correlating temporal binding effects with the participants' agency ratings with ambiguous results: some studies have not found a correlation between explicit and implicit measures of agency (Dewey & Knoblich, 2014; Saito, Takahata, Murai, & Takahashi, 2015), while others have shown such a connection (Imaizumi & Tanno, 2019; Pyasik, Burin, & Pia, 2018). Imaizumi and Tanno (2019), for example, found that temporal binding effects and agency ratings are associated on an inter-individual as well as intra-individual level. However, some of the previous studies have demonstrated a couple of methodological issues that might have decreased their informative value. Such issues include, for example, different tasks for implicit and explicit measures (Saito et al., 2015), measuring explicit agency at the end of a binding block rather than specifically for a given trial (Dewey & Knoblich, 2014), as well as a low sample size for a correlation study possibly decreasing the reliability of the data (Imaizumi & Tanno, 2019).

In the present study, we therefore chose to further pursue the relation between explicit and implicit measures of agency, i.e., agency ratings and temporal binding, as well as the influence of action choice on both types of measures in a high-powered setting. To this end, we employed a classical temporal binding task with free and forced choice conditions and asked the participants to rate their sense of agency on a visual analog scale within the same trials. This allowed us to compute not only inter-individual correlations, but also intra-individual correlations to assess the relation of explicit ratings and temporal binding effects within individuals. The current state of the literature would suggest either a consistent correlation on the inter-individual and the intra-individual level (with stronger temporal binding going along with higher subjective ratings) or, alternatively, a lack thereof at both levels. We further expected higher agency ratings and stronger temporal binding effects for free choice than for forced choice and a similar pattern of correlations for both choice conditions.

2. Methods

2.1. Participants

We recruited 92 participants (mean age = 22.8 years, range 18–61; 77 females, 82 right-handed). This sample size was based on a power calculation assuming a medium effect size of $r = 0.3$ to ensure a power of $1\text{-}\beta = 0.80$ for all correlations across participants ($\alpha = 0.05$; $n = 85$; with an addition of 7 participants to replace possible drop-outs). At the same time, this sample size also ensured a power of 1-β = 0.81 even for small effect sizes of $d_z = 0.30$ for within-subjects correlations (assuming a one-sample *t*-test of Fisher-Z-transformed correlations against 0) and paired *t*-tests, as well as a power of 1-β = 0.98 for the factor action choice (free vs. forced choice), given the effect size of $d_z = 0.42$ reported by Barlas & Obhi, 2013 (overall binding, high choice vs. no choice condition).

Participants gave informed consent prior to the experiment and received course credit or monetary compensation for participation. Two participants had to be excluded because they failed to perform the experimental task.

2.2. Stimuli and apparatus

The experiment was presented on a 24″ monitor. All stimuli appeared centrally in white on a black background. 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, double-sided arrows (≪≫) indicated that participants could freely choose between a left and a right keypress. The use of mixed target stimuli (letter for forced choice, arrows for free choice) was motivated by two considerations. First, we aimed to use free choice stimuli that would automatically activate both potential options (as is the case with arrow stimuli) to support spontaneous decisions as compared to pre-selecting a particular response. Second, recent findings suggest that upcoming action effects are less strongly represented in forced settings when response selection is too efficient (Gozli, Huffman, & Pratt, 2016; Huffman, Gozli, Hommel, & Pratt, 2019; Wolfensteller & Ruge, 2014). The clock used for time estimation had a diameter of about 6 cm. Every five "minutes" (5, 10, 15…) were tick-marked on the clock face, and each quarter was labeled ("15", "30", "45", "60"). A full rotation of the clock hand took 2500 ms. A high (600 Hz) and a low (300 Hz) sinusoidal tone of 100 ms duration served as sound effects and were presented via headphones. Participants responded on a standard German QWERTZ keyboard with the keys *C* and *V* and they entered their estimated time of tone presentation using the number keys of the keyboard.

Agency ratings were entered on a visual analog scale ranging from 0 ("a little") to 100 ("a lot"). When the scale appeared on the screen, the cursor line participants were asked to move with the mouse to indicate their sense of agency was always presented at the center of the scale.

The agency question for tones read: "*How strongly did you feel as causal agent for the tone in the current trial?*" (German original: "*Wie sehr hast du dich gerade als Verursacher des Tones gefühlt?*"), and the agency question for keypresses read "*How strongly did you feel responsible for your action in the current trial?*" (German original: "*Wie sehr hast du dich gerade eben für deine Handlung verantwortlich gefühlt?*") We chose the latter question because, in our experience, a question regarding the immediate causation of an own action (i.e., how strongly did you feel as the causal agent for the keypress?) seems odd to most healthy participants ("of course, I am the causal agent, I am pressing the key"), while a question regarding responsibility would elicit more varied answers.

2.3. Procedure

The experiment consisted of four different block types, two operant blocks and two baseline blocks (Fig. 1). The participants' task was to indicate the time of a certain event (either a keypress or a sound) using the presented clock.

The operant blocks started with the presentation of a target stimulus, requiring participants to press the left or right key (forced choice) or indicating that participants could freely choose between a left and right keypress (free choice). The stimulus was presented for 500 ms. Then, the clock face was presented. The clock hand appeared at a random position in each trial and immediately started rotating. Participants were instructed to wait at least half a rotation of the clock hand before pressing the respective key. Errors in forced choice trials (i.e., when participants pressed the wrong response key) were immediately followed by an error message presented for 1000 ms and the trial was terminated afterwards. In correct trials, a sound effect was presented 300 ms after the participant's keypress. The identity of the sound effect (high or low) depended on the identity of the keypress (left or right). For each participant, the mapping of keypress and sound effect was constant, but it was counterbalanced across participants. The clock hand kept rotating for 2000–3000 ms after the sound effect and then 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 action baseline blocks and one type of the operant blocks, participants were asked to estimate the position of the clock hand at the moment when they pressed the key. In the effect baseline blocks and in the other type of operant blocks, 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 ample time to enter their estimation.

In half of the trials in the operant blocks, an agency question was presented after this time estimation had been completed. The presentation of agency questions was random and therefore unpredictable for the participant. Only the agency question for actions was presented in blocks where participants had to report the time of their keypress and only the agency question for tones was presented when participants had to report the time of tone presentation.

Each baseline and operant block was presented twice, so that participants completed eight blocks in total and each of these blocks comprised 40 trials. The experiment always started with two baseline blocks, one in which participants judged the action (baseline action; A_{BL}) and one in which they judged the effect [1](baseline effect; E_{BL}). Then, four operant blocks followed, two where

[1] Please note that the tone only served as an action effect in operant blocks whereas it was not triggered by an action of the participants in baseline blocks. We still label these baseline blocks as effect blocks to stress that they employed the same stimuli as the operant blocks.

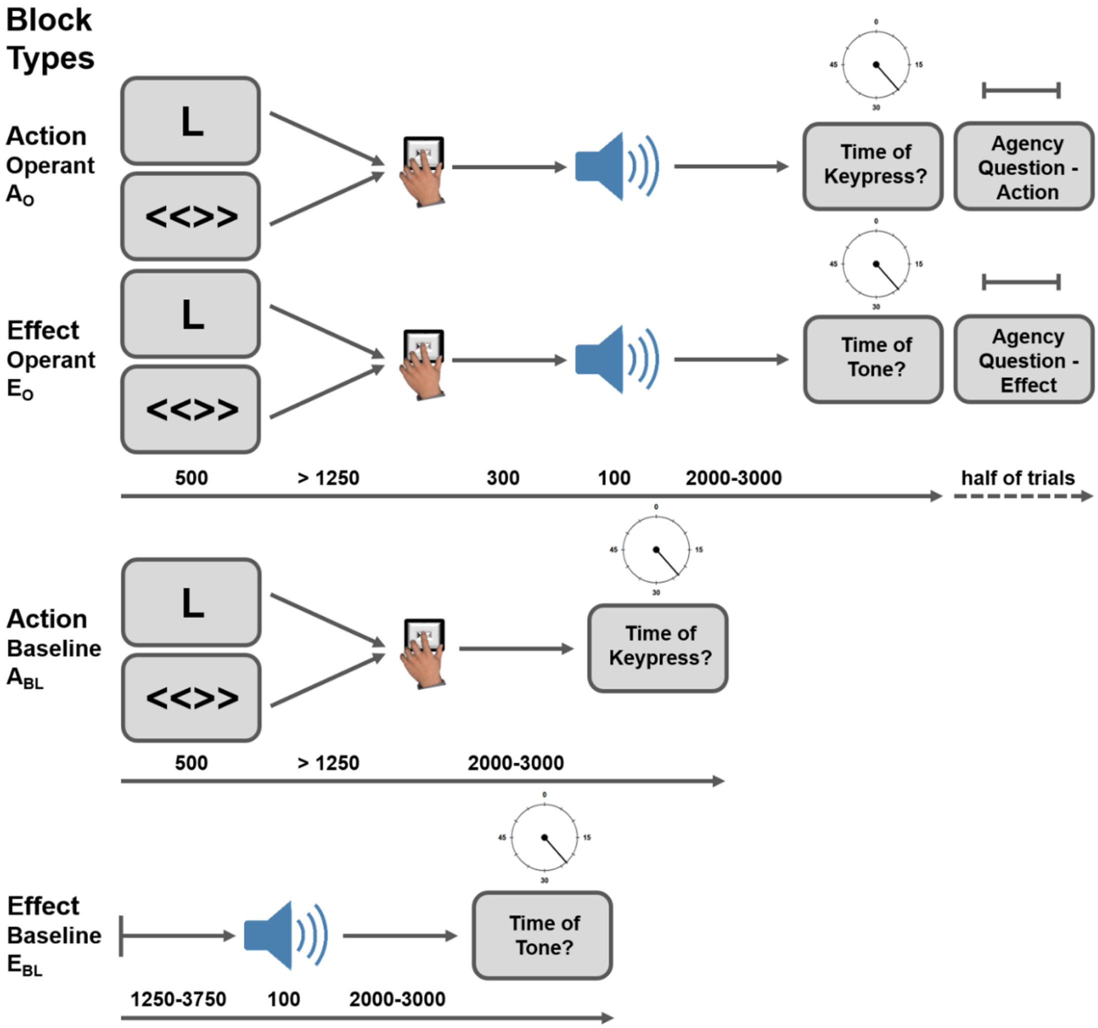

Fig. 1. Trial procedure for each block type. Each trial (except in the effect baseline block) started with a target either asking the participants to press the left ("L") or right ("R") key (forced choice) or to freely choose between those two keys ("≪≫"; free choice). A clock face appeared as soon as the target left the screen and the participants were asked to wait at least half a clock hand rotation before pressing any key (i.e., at least 1250 ms). Their subsequent keypress was then followed by an either high or low tone dependent on the participants' keypress. The clock hand kept rotating until 2000–3000 ms after the tone. After the clock disappeared from the screen, the participants were asked to indicate at which point in time they either perceived their keypress (action blocks) or the tone (effect blocks). In half of the trials in the operant blocks, participants were then asked to indicate their sense of agency on a rating scale, either relating to their keypress (action blocks) or to the tone (effect blocks). In the baseline blocks, either no tone was presented and the timing evaluation of the keypress occurred directly after the keypress (action baseline block) or the participants were not asked to press any key and the tone was presented 1250–3750 ms after trial start (effect baseline block). In this latter case, the trial started directly with the presentation of the clock on the screen. The numbers on the arrows beneath the trial depictions correspond to the timing of the stimuli in ms.

participants had to judge the onset of their action (operant action; A_O) and two where they had to judge the onset of the tone (operant effect; E_O) and then another baseline action (A_{BL}) and a baseline effect (E_{BL}) block were presented. Half of the participants started with the baseline action block and the block order was: A_{BL}, E_{BL}, A_O, E_O, A_O, E_O, A_{BL}, E_{BL}; the other half started with the baseline effect block and the block order was reversed: E_{BL}, A_{BL}, E_O, A_O, E_O, A_O, E_{BL}, A_{BL}.

2.4. Data analysis

Estimation errors were calculated separately for each participant and trial, by subtracting the actual time at the moment of the event in question (keypress or tone) from the estimated time of this event. A negative estimation error therefore indicated that tone or keypress were perceived earlier than they actually appeared, whereas a positive estimation error indicated that tone or keypress were perceived later than they actually appeared. Trials with time estimates exceeding 60 were discarded (0.2%) and so were forced choice trials in which participants performed an incorrect response (1.9% of forced choice trials). Trials with time estimates that deviated more than 2.5 standard deviations from the cell mean, calculated separately for each participant and condition (i.e., Baseline/Operant, Action/Effect, Free/Forced), were excluded as outliers (3.1%). Temporal binding was then computed as the participant's mean estimation in operant blocks minus his or her mean estimation error in the respective baseline blocks (i.e., estimation error ($A_{O,Free}$) – estimation error ($A_{BL,Free}$)). To probe for differences between our experimental conditions, we computed analyses of variances (ANOVAs) with the factors action choice (free vs. forced) and block type (action vs. effect). For follow-up analyses or tests against baseline, pairwise comparisons were analyzed via two-tailed, paired *t*-tests with corresponding effect sizes being calculated as $d_z = t/\text{sqrt}(n)$.

Inter-individual correlations were computed by correlating the mean temporal binding values of a given condition (action/effect, free/forced choice) with the respective mean score of the participants' agency ratings. Intra-individual correlations were computed by first correlating agency ratings with the corresponding estimation errors of any given trial, separately for each operant condition (action/effect, free/forced) and each participant. Please note that because of the trial-wise approach, time estimation errors could not be corrected by baseline conditions for this analysis. The resulting *r* values were then transformed into Fisher-Z values to assure a normal distribution. Mean Fisher-Z values were then tested against 0 via *t*-tests to probe for intra-individual correlations between agency ratings and corresponding estimation errors. This was followed by an ANOVA on the Fisher-Z values to analyze possible differences in correlation values with the factors action choice (free vs. forced) and block type (action vs. effect).

Raw data and analyses scripts are available on the Open Science Framework, https://osf.io/bygf2/.

3. Results

3.1. Temporal binding

We found temporal binding effects for all conditions, that is, keypresses were perceived as occurring later and tones were perceived as occurring earlier in operant conditions compared to the respective baseline conditions; A_{Free}: M = 20.16 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 = −89.55 ms, $t(89) = -9.30$, $p < .001$, $d_z = -0.98$; E_{Forced}: M = −91.03 ms, $t(89) = -9.76$, $p < .001$, $d_z = -1.03$ (Fig. 2A). Moreover, effect binding (i.e., temporal binding for tones) proved to be stronger than action binding (i.e., temporal binding for keypresses), $F(1,89) = 48.62$, $p < .001$, $\eta_p^2 = 0.35$, but free and forced choice conditions did not differ and there was no significant interaction between both factors, *F*s < 1.

3.2. Agency ratings

Agency ratings differed dependent on whether participants were asked to rate their sense of agency related to their actions ("*How strongly did you feel responsible for your action in the current trial?*") or to the effect of their actions ("*How strongly did you feel as causal agent for the tone in the current trial?*"). That is, questions relating to the participants' actions elicited higher agency ratings than questions relating to the effects of those actions, $M_A = 72.53$, $M_E = 59.99$, $F(1,89) = 22.86$, $p < .001$, $\eta_p^2 = 0.20$ (Fig. 2B). Moreover, agency ratings were higher in free choice conditions compared to forced choice conditions, $M_{Free} = 67.34$, $M_{Forced} = 65.18$, $F(1,89) = 8.09$, $p = .006$, $\eta_p^2 = 0.08$, and the interaction between both effects proved also significant, $F(1,89) = 5.89$, $p = .017$, $\eta_p^2 = 0.06$. Subsequent simple effects analyses revealed that the rating difference between free and forced choice conditions mostly relied on ratings relating to the participants' actions whereas agency ratings did not differ between free and forced choice conditions when those ratings related to the effects of the participants' actions, $A_{Free\ vs.\ Forced}$: $t(89) = 3.07$, $p = .003$, $d_z = 0.32$, $E_{Free\ vs.\ Forced}$: $t(89) = 1.25$, $p = .215$, $d_z = 0.13$.

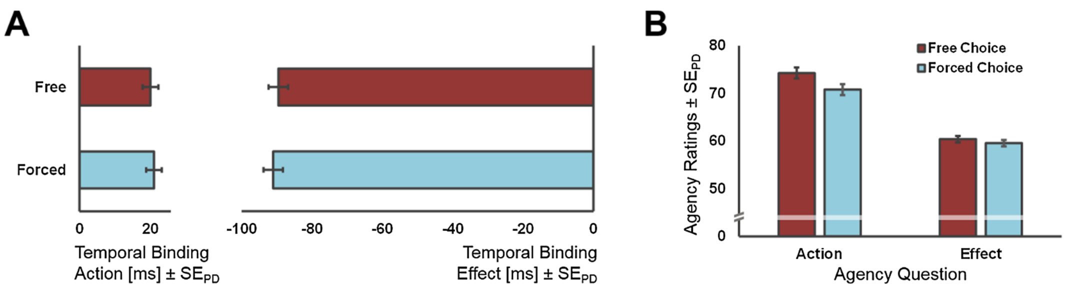

Fig. 2. Temporal binding and agency ratings. A. Action and effect binding in free and forced choice conditions relative to baseline. Temporal binding was present in all conditions, with effect binding being stronger than action binding. Temporal binding did not differ between free and forced choice conditions. B. Agency ratings in free and forced choice conditions, either relating to the participants' keypress or to the tone. Participants rated their sense of agency higher when the question was targeted toward the participants' keypress than to the tone. They also showed a higher explicit sense of agency in the free choice than in the forced choice condition. Simple effects analysis revealed this effect to mostly rely on a rating difference between free and forced choice conditions when the respective question related to the participants' keypress, not to the tone. Error bars depict standard errors of paired differences for the factor action choice (Pfister & Janczyk, 2013).

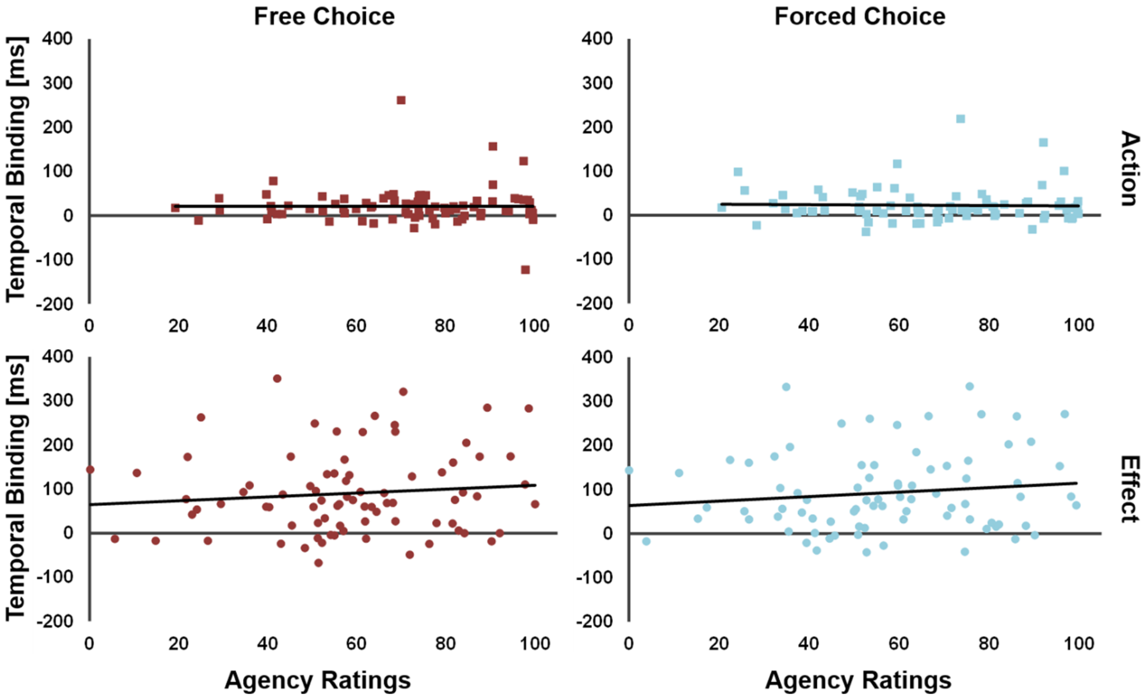

Fig. 3. Inter-individual correlations. Temporal binding and agency ratings did not correlate significantly in any condition ($N = 81$).

3.3. Correlations

For these analyses, we excluded 9 further participants as they showed very little variation in their agency ratings which did not allow for conducting meaningful correlation analyses on an intra-individual level. However, to ensure that this exclusion did not fundamentally change our results of the inter-individual correlations, we repeated the analyses with these participants and report those results in parentheses.

As shown in Fig. 3, the inter-individual correlation between temporal binding effects and agency ratings of any given condition (action/effect, free/forced choice) revealed no significant association between the two, $N = 81$, $|r|$s < 0.13, $ps > .254$ ($N = 90$, $|r|$s < 0.07, $ps > .518$).

Intra-individual correlations for the four operant conditions (action/effect, free/forced choice) revealed significant negative correlations between the participants' time estimation error and their agency ratings in both effect conditions, E_{Free}: $t(80) = -3.78$, $p < .001$, $r = -0.17$, E_{Forced}: $t(80) = -4.83$, $p < .001$, $r = -0.19$, as well as in the free choice condition relating to the keypress, A_{Free}: $t(80) = -2.37$, $p = .020$, $r = -0.08$. However, in all cases, r values were small with an explained variance (R^2) of less than 3.6% in effect blocks and less than 0.6% in action blocks. Time estimation errors and agency ratings were not significantly correlated in the forced choice condition relating to the keypress, A_{Forced}: $t(80) = -0.26$, $p = .798$, $r = -0.01$. These results were confirmed by an ANOVA with the factors action choice (free vs. forced choice) and block type (action vs. effect). For this analysis, we transformed time estimation errors of the effect blocks by a multiplication of -1. This allows a better interpretation of the results as temporal binding is now reflected by positive time estimation errors in both effect and action blocks (in the original coding, temporal binding would have been reflected by positive time estimation errors in the action and negative time estimation errors in the effect blocks due the calculation of the time estimation error [perceived timing – actual timing] so that all analyses of the differences in correlation values between action and effect blocks would be confounded by this effect of the coding scheme). As shown in Fig. 4, correlation values differed between action and effect blocks with higher correlations in the effect than in the action blocks, $F(1,80) = 29.20$, $p < .001$, $\eta_p^2 = 0.27$. Action choice only marginally affected correlation values and the interaction of both factors did not reach significance, Action Choice: $F(1,80) = 2.81$, $p = .097$, $\eta_p^2 = 0.03$, Interaction: $F(1,80) = 0.50$, $p = .480$, $\eta_p^2 = 0.01$.

4. Discussion

In the present study, we pursued the relation between explicit and implicit measures of agency, i.e., agency ratings and temporal binding, as well as the influence of action choice on both types of measures in a high-powered design. We found strong temporal binding in all conditions (action/effect blocks, free/forced choice) with especially high temporal binding scores in the effect blocks compared to the action blocks, as could be expected from previous studies (Ruess et al., 2017; Wolpe, Haggard, Siebner, & Rowe, 2013). However, temporal binding did not differ with action choice. In contrast, agency ratings differed between free and forced choice conditions with free choice trials eliciting higher agency ratings than forced choice trials, especially in effect blocks. Against

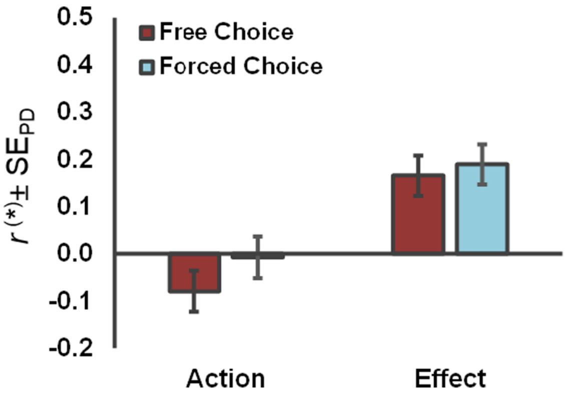

Fig. 4. Average intra-individual correlations. For the effect blocks, the transformed correlation values (r^*) are shown (correlation of agency ratings with time estimation errors multiplied by -1) so that positive correlation values represent a positive correlation of temporal binding (as measured by time estimation errors) and agency ratings in both action and effect blocks. Temporal binding and agency ratings correlated positively in both effect blocks, but correlated negatively in the action block with free action choice. Please note, however, that *r* values are generally small with an explained variance (R^2) of less than 3.6% in effect blocks and less than 0.6% in action blocks. Error bars depict standard errors of paired differences for the factor action choice (Pfister & Janczyk, 2013).

our hypotheses, inter-individual correlations revealed no association between temporal binding scores and agency ratings in any condition. However, intra-individual correlations, i.e., trial-wise correlations of time estimation errors and agency ratings within individuals, revealed positive correlations of temporal binding and subsequent agency ratings in effect blocks, albeit with small *r* values.

4.1. Implicit and explicit agency

The sense of agency has been associated with many crucial functions, ranging from the distinction between one's own actions and those of others to feelings of responsibility and regret. In recent years, many studies have been conducted to characterize agency on an implicit and explicit level, focusing on how the sense of agency is formed and on its sensitivity to various experimental manipulations. These efforts resulted in several theoretical models and ideas regarding mechanisms underlying the different components of agency (Haggard & Tsakiris, 2009; Haggard, 2017; Schwarz, Burger, et al., 2018; Sidarus, Vuorre, & Haggard, 2017b; Synofzik et al., 2008, 2013; Waszak, Cardoso-Leite, & Hughes, 2012). Different measures are used to quantify the sense of agency in the laboratory from different ratings (ratings of control or causation) to behavioral and/or physiological correlates of implicit measures associated with agency such as temporal binding and sensory attenuation (Pfister et al., 2014; Tsakiris & Haggard, 2003; Weiss, Herwig, & Schütz-Bosbach, 2011; Weller, Schwarz, Kunde, & Pfister, 2017). In recent years, more and more studies have employed these measures, testing their reliability, consolidating past findings, and relating them to one another in order to improve our capability to interpret previous and future results (Dewey & Knoblich, 2014; Pyasik et al., 2018; Schwarz, Pfister, Kluge, Weller, & Kunde, 2018). The present study contributes to this discussion by further characterizing temporal binding and agency ratings in their response to action choice as an experimental manipulation, and by studying how temporal binding and agency ratings are related in different experimental conditions.

4.2. Temporal binding and agency ratings

Contrary to some previous studies (Barlas & Obhi, 2013; Barlas et al., 2018), we found no evidence for an influence of action choice on temporal binding, despite a power of 1-β = 0.98, given previously reported effect sizes. This is somewhat in line with more ambiguous reports on this effect (Wenke et al., 2009) insofar as it highlights temporal binding to be sensitive to seemingly minor experimental variations (i.e., action vs. effect blocks), but not necessarily to action choice per se. Should this null-effect be corroborated in the future, it can be considered evidence that certain higher-level deliberations do not affect temporal binding.

However, action choice did affect agency ratings with higher ratings in free choice conditions than in forced choice conditions supporting several previous studies (Barlas et al., 2018; Sebanz & Lackner, 2007; Sidarus et al., 2017a; Wenke et al., 2010), although simple effects analysis revealed that this effect was only significant in action blocks, i.e., when participants rated their agency regarding the keypress, not the subsequent tone. A possible explanation for this effect could be that participants generally felt less agency for the effects (see next paragraph) because they attributed the appearance of the tone less to themselves and their own actions and more to the computer program playing the tone which would counteract any effect of action choice. An alternative explanation relates to the semantic content of the agency question: whereas the agency question related to the tone asked participants to rate how strongly they felt as the causal agent eliciting the tone, the agency question related to the keypress asked participants how strongly they felt responsible for their action. That is, in effect blocks, participants were asked about immediate causation, whereas in action blocks they were asked about the broader concept of responsibility. We chose these questions because, in our experience, a question regarding the immediate causation of an own action (i.e., how strongly did you feel as the causal agent for the keypress?) seems odd to most healthy participants, while a question regarding responsibility would elicit more varied answers. Nevertheless, it seems eminently plausible that the question of immediate causation would be unaffected by action choice, as the causal agent does not change no matter whether the action was freely chosen or not, while the question of responsibility would be more sensitive to action choice. Further studies are needed to shed light on this intriguing question.

Furthermore, agency ratings differed between blocks with action blocks eliciting higher ratings than effect blocks. This seems counterintuitive at first as one might expect that immediate causation would be more prominently attributed to oneself as the only possible agent, especially as the effects were completely predictable in identity and timing. In contrast, it is more easily fathomable to distribute or redirect responsibility for actions, especially in forced choice conditions, to the experimenter or computer program. There are two possible explanations for this effect: whereas the action is clearly perceived as “own” since sensory feedback coupled with action intention are present, the appearance of the tone could be more ambiguously attributed to the participants themselves as well as the computer program playing the sound. An alternative, and at present very speculative, explanation again relates to the agency questions: one could argue that questions of immediate causation are less frequently verbalized in everyday life than questions of responsibility and therefore participants might be less practiced in explicitly thinking and evaluating simple task sequences in terms of causation. These speculations could be addressed by thorough methodological work on the influence of linguistic (semantic and pragmatic) features which may exert hidden biases on the overall level and variability of these measures.

4.3. Correlations

Several previous studies have pursued the question whether or not explicit and implicit measures of agency are related with varied results (Dewey & Knoblich, 2014; Imaizumi & Tanno, 2019; Pyasik et al., 2018; Saito et al., 2015). In order to contribute to this discussion, we chose a design that measured temporal binding scores and agency ratings within the same trials thereby allowing inter- and intra-individual correlations and we invited enough participants to allow for a minimum power of $1\text{-}\beta = 0.80$ for medium (in case of inter-individual correlations) or even small effect sizes (in case of intra-individual correlations). We believe that these testing parameters allowed us to circumvent some of the previous methodological issues.

We calculated inter-individual correlations separately for all conditions (action/effect blocks, free/forced choice) and found no evidence for any association between temporal binding and agency ratings across participants, despite a considerable variance regarding both temporal binding scores and agency ratings.

Of course, this does not mean that temporal binding and agency ratings could not correlate within single trials and within individuals, and, indeed, our results hinted at small effects in this regard. As expected, we found that higher temporal binding scores (as measured by time estimation errors) correlated with higher agency ratings in the effect blocks. That is, the earlier the participants perceived the tone relative to its actual physical occurrence, the higher the subsequent agency ratings. Please note, however, that even in the effect blocks less than 3.6% of the recorded variance in one agency measure can be explained by the second agency measure and that more than 96.4% of that variance are still left unexplained. Given these numbers, we suggest that, even though the intra-individual correlations are clearly significant, this contribution to the explained variance may not be particularly relevant and rather points to profound differences rather than similarities of both measures.

The correlation values of temporal binding scores and agency ratings were significantly lower in the action than in the effect blocks. In addition to the considerable smaller range of binding scores in effect blocks, a possible explanation could again lie with the agency questions: it has been argued that rather than being based on action intention, temporal binding is more likely to be based on causal inference (e.g., Kirsch et al., 2019). Thus, it seems very plausible that temporal binding could be more associated with questions regarding immediate causation (as in the effect blocks) than with questions regarding responsibility (as in the action blocks). Further studies are needed to pursue this hypothesis.

5. Conclusions

The present study aimed at shedding further light on the relation between temporal binding and agency ratings, i.e., implicit and explicit measures of the sense of agency, and explored how both measures are influenced by action choice. We found action choice to affect agency ratings, but not temporal binding, and that temporal binding and agency ratings were not related on an inter-individual level, whereas significant but notoriously small correlations resulted on an intra-individual level. These findings support claims that both measures tap into different processes rather than being a pre-conscious (temporal binding) and conscious (agency ratings) assessment of a single, unitary phenomenon.

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