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Connecting action control and agency: Does action-effect binding affect temporal binding?

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ABSTRACT

The sense of agency, i.e., the notion that we, as agents, are in control of our own actions and can affect our environment by acting, is an integral part of human volition. Recent work has attempted to ground agency in basic mechanisms of human action control. Along these lines, action-effect binding has been shown to affect explicit judgments of agency. Here, we investigate if such action-effect bindings are also related to temporal binding which is often used as an implicit measure of agency. In two experiments, we found evidence for the establishment of short-term action-effect bindings as well as temporal binding effects. However, the two phenomena were not associated with each other. This finding suggests that the relation of action control and agency is not a simple one, and it adds to the evidence in favor of a dissociation between subjective agency and perceptual biases such as temporal binding.

1. Introduction

An integral part of our (voluntary) actions is the underlying notion that we, as agents, are in control over these actions and that we can affect the world around us through these actions. The corresponding mental state, the sense of agency, is a crucial component of acting and abnormal expressions of agency have been associated with severe mental illnesses, such as delusions of control in schizophrenic patients (Blakemore, Smith, Steele, Johnstone, & Frith, 2000; Franck et al., 2001; Haggard, 2017; Hauser et al., 2011; Voss et al., 2010). Moreover, the sense of agency seems also a fundamental prerequisite for a sense of responsibility for one's own actions, which in turn serves important societal functions (Frith, 2014; Moore, 2016).

Research on the sense of agency has long aimed to establish a distinction between predictive processes that are based on internal models within the agent's sensorimotor circuitry (Blakemore, Wolpert, & Frith, 2002; Synofzik, Vosgerau, & Newen, 2008; Wolpert, Ghahramani, & Jordan, 1995) and postdictive processes that employ explicit inferences by the agent regarding his or her authorship for an action (Synofzik et al., 2008; Wegner, 2003; Wegner & Wheatley, 1999). Whereas such explicit inferences can be assessed directly via rating scales asking about the agents' sense of agency, predictive processes have to be measured indirectly by studying phenomena that are thought to be linked to agency, such as sensory attenuation and temporal or spatial binding[1] (Beck, Di Costa, & Haggard, 2017; Hughes, Desantis, & Waszak, 2012; Imaizumi & Tanno, 2019; Kirsch, Pfister, & Kunde, 2016; Schwarz, Pfister, Kluge, Weller, & Kunde, 2018; Weiss, Herwig, & Schütz-Bosbach, 2011; Weller, Schwarz, Kunde, & Pfister, 2017).

Recent research has shifted away from this distinction – acknowledging that predictive and postdictive processes jointly contribute to

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[1] Please note that we use the term temporal binding instead of intentional binding because recent evidence suggests that action intentions are not pivotal for temporal binding to occur, but it is rather based on causal inference and possibly multisensory integration (Kirsch et al., 2019). Moreover, the term temporal binding allows us to distinguish the phenomenon from spatial binding (Kirsch et al., 2016).

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the sense of agency (Moore, Wegner, & Haggard, 2009) – and has turned towards grounding the subjective experience of agency in basic mechanisms of human action control, i.e., processes of action selection, initiation, and/or evaluation. For example, several studies have reported that dysfluent action selection leads to reduced feelings of agency (Chambon, Sidarus, & Haggard, 2014; Damen, van Baaren, & Dijksterhuis, 2014; Sidarus, Chambon, & Haggard, 2013; Sidarus & Haggard, 2016; Wenke, Fleming, & Haggard, 2010; see also Sidarus, Vuorre, & Haggard, 2017) and we have recently found evidence that basic action control processes such as short-term bindings of actions and effects were associated with explicit judgments of agency (Schwarz, Burger, Dignath, Kunde, & Pfister, 2018).

This latter approach is based on the premise of effect-based, ideomotor accounts of human action control, i.e., the idea of a bidirectional relation between action and effect (Hommel, 2009; Pfister, 2019; Shin, Proctor, & Capaldi, 2010). In other words, ideomotor accounts postulate that actions are represented in terms of their sensory consequences and that the anticipation of these sensory consequences mediates the selection and initiation of the respective action (see e.g., Elsner & Hommel, 2001; Kunde, 2001; Pfister, Kiesel, & Hoffmann, 2011). This presumes the formation of short-term as well as long-term bindings of stimulus, response and effect features (Dutzi & Hommel, 2009; Eder & Dignath, 2017; Elsner & Hommel, 2001; Hoffmann, Lenhard, Sebald, & Pfister, 2009; Janczyk, Heinemann, & Pfister, 2012; Moeller, Pfister, Kunde, & Frings, 2016; Wolfensteller & Ruge, 2011). Such established bindings might in turn affect the sense of agency that accompanies the respective action and the production of corresponding effects.

Indeed, our previous study suggests that action-effect bindings and sense of agency are related as we found that the formation of short-term action-effect bindings increased subsequent agency ratings (Schwarz, Burger, et al., 2018). The results were obtained by using a two-step paradigm designed to test for short-term action-effect bindings (Dutzi & Hommel, 2009). In this paradigm, participants perform a prime and a probe response in each trial. In the prime segment of a trial, participants are to choose between one of two keypress actions and each action triggers one of two possible effects (e.g., tones of different frequencies). Even though the action-effect mapping varies randomly and unpredictably on a trial-by-trial basis, the temporal coincidence of action and effect should lead to the formation of short-term associations between features of the action and features of its subsequent effect – i.e., action-effect binding. Crucially, repeating one of the features in such action-effect bindings should retrieve the entire action-effect episode (Hommel, 2004; Frings et al., 2018). Whether such retrieval does indeed take place is then tested in the probe segment of the trial. Here, participants are confronted with a stimulus first, and this stimulus either repeats the previous action effect or it is an alternative stimulus (e.g., a tone of a different frequency). They respond to the probe stimulus by choosing between the same set of alternative actions as in the prime segment. Following the above logic, participants are expected to repeat their responses more often from prime to probe if the probe stimulus repeats the prime effect as compared to effect-stimulus alternations, and this pattern of results has been observed reliably in previous work (Dutzi & Hommel, 2009; Janczyk et al., 2012; Moeller et al., 2016; Schwarz, Burger, et al., 2018). Crucially, our previous study further indicated that this effect was correlated with the participants' judgments of agency for the action-effect episode in the prime segment. That is: If participants responded consistently with the predictions of a retrieval approach in the probe segment, they also reported higher feelings of agency for the tone in the prime segment. A plausible mechanism underlying this effect could be that the binding of action and effect into an event file leads to a temporal attraction of both events (Kirsch, Kunde, & Herbort, 2019; Morein-Zamir, Soto-Faraco, & Kingstone, 2003; Recanzone, 2003; Schwarz, Burger, et al., 2018; Van Beers, Sittig, & Denier van der Gon, 1999). As discussed above, such temporal attraction or temporal binding of action and effect has often been discussed as an implicit process underlying agency (Haggard & Tsakiris, 2009).

The present experiments investigate exactly this relationship between action-effect binding and temporal binding. Thus, we employed the two-step paradigm described above and incorporated a time estimation task relating to the participant's action effect to test for temporal binding and an interaction of both phenomena.

In the prime segment of each trial, participants were asked to press one of two keys which then elicited a low or high pitch tone at random. In the probe segment, a second tone was presented that could be either the previous tone (tone repetition) or the alternative tone (tone switch). Participants responded to the tone by again choosing either a left or right keypress, and their choice to the second tone served as an indicator for action-effect binding. In keeping with previous work, we expected a higher frequency of response repetitions after tone repetitions than after tone switches as tone repetitions should reactivate the previously compiled action-effect binding (Dutzi & Hommel, 2009; Hommel, 2004; Schwarz, Burger, et al., 2018). Throughout this procedure, a clock face was visible with a rotating clock hand, and participants were asked after the probe segment to enter the time of the first tone (i.e., the position of the clock hand at the time of tone presentation) to test for temporal binding (Haggard & Tsakiris, 2009). Following our hypothesis that temporal binding might mediate the observed association of action-effect binding and agency, we expected higher temporal binding effects in trials in which action-effect bindings were established.

2. Experiment 1

The experiment was preregistered on the Open Science Framework (https://osf.io/vyp4e) and all raw data and analyses scripts are available at the corresponding project repository (https://osf.io/dtx6k/).

2.1. Methods

2.1.1. Participants

We recruited 49 participants (mean age = 28.0 years, range 19–62; 35 females, 44 right-handed). Sample size was determined by a power analysis with an assumed medium effect size of $d = 0.50$, a power of 0.80, and an expected drop-out rate of 15% ($N >= 40$). Participants gave informed consent prior to the experiment and received course credit or monetary compensation for participation. Six participants were excluded because of technical issues or because they did not perform the task correctly.

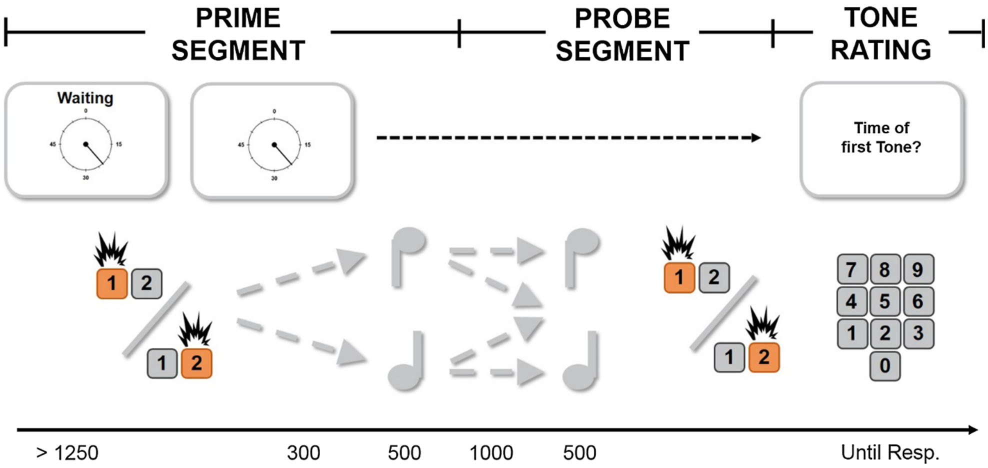

Fig. 1. Procedure. At the beginning of each trial, a clock face with a rotating clock hand appeared. Participants were asked to wait at least half a rotation (> 1250 ms) until pressing either a left or right key which elicited a low or high pitch tone at random. The tone was presented for 500 ms after a short delay of 300 ms. After an interval of 1000 ms, a second tone was presented (low or high pitch) for 500 ms which could be either identical to the previous tone (tone repetition), the alternative tone (tone switch), or no tone occurred (catch trial). Participants responded to the tone by again choosing either a left or right keypress whereas they had to refrain from responding in catch trials. Throughout this procedure, the clock hand kept rotating until another 500–1000 ms after the keypress. Participants were then asked to enter the time (the position of the clock hand) at the time of the first tone. Time estimates were used to assess temporal binding (relative to a baseline condition; see text) whereas response repetitions were analyzed as a function of the tone sequence to probe for action-effect binding.

2.1.2. Stimuli and apparatus

The experiment was presented on a 24″ monitor. All stimuli appeared centrally in white on a black background. 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. The sound effects were an 800 Hz and a 400 Hz marimba MIDI tone of 500 ms duration, delivered binaurally via headphones. Participants responded on a standard German QWERTZ keyboard with the keys F and J, operated with the left and right index finger respectively. They entered their estimated time of tone presentation using the number keys of the keyboard.

2.1.3. Procedure

The trial procedure is depicted in Fig. 1. Each trial consisted of a prime and a probe segment and started with the display of the clock face in the center of the screen (prime segment). The clock hand appeared at a random position in each trial and immediately started rotating. Above the clock, the reminder "Waiting for keypress…" (German original: "Warte auf Tastendruck…") was displayed, prompting participants to randomly select a left or right keypress. However, participants were instructed to wait at least half a rotation of the clock before pressing a key. When participants pressed a key, the reminder disappeared and the program randomly selected one of the two sound effects to be presented 300 ms after the keypress. Participants were instructed to remember the position of the clock hand when they heard the tone. The clock hand continued rotating and 1000 ms after this first sound, a second high or low sound was presented. This second sound marked the beginning of the probe segment, while the clock continued rotating throughout. The second sound could either match the first sound (stimulus repetition) or differ from the sound in the prime segment (stimulus switch; randomly selected) and prompted the participants to choose between a left or right keypress. Participants were instructed to choose the keypress spontaneously and not to use any specific strategies such as always selecting the same key or alternating between keypresses. After the participant's keypress, the clock hand kept rotating for another 500–1000 ms (sampled randomly from a uniform distribution). Then, the clock disappeared and participants were asked to enter the time at which they had heard the first tone. An error message was displayed if participants responded too early in the probe segment (i.e., before the probe tone was presented). In these error trials, participants were not asked for their time estimation and the trial ended directly after the error message.

To prevent participants from pressing a key in the probe segment without paying attention to the probe tone, we implemented catch trials that appeared with a frequency of 11.1% across the experiment. In these catch trials, no sound was presented in the probe segment and participants were not to press a key. These trials ended automatically 500–1000 ms after a tone would have been presented in the normal probe segments. An error message was displayed for 1000 ms if participants pressed the response key a second time in these catch trials (i.e., in the probe segment). Catch trials in which participants committed an error before the probe segment (e.g., if they responded directly after the prime tone), were counted as error trials instead.

To familiarize participants with the trial structure, they completed 10 practice trials at the beginning of the experiment. In the main experiment, trials were presented in blocks of 72 trials each (including 8 catch trials). Apart from these operant blocks (O), participants also completed baseline blocks (B; block order OBOOBO) with 40 trials per block. These blocks provided a baseline for the time estimation. Baseline trials started with the presentation of the clock face and the clock hand at random position. Participants were instructed not to press a key. A tone was presented 1000–1500 ms after trial start and the participants' task was to report the position of the clock hand at which they had heard the tone. The clock hand continued rotating until 1000–2000 ms after tone presentation, then the clock disappeared and participants were asked to enter their estimate.

2.1.4. Data analysis

The percentage of response repetitions was analyzed with a two-tailed, paired *t*-test comparing response repetitions after tone repetitions with response repetitions after tone switches. Corresponding effect sizes were calculated as $d_z = \frac{t}{\sqrt{n}}$.

Estimation errors were calculated separately for each participant and trial, by subtracting the actual onset time of the event in question (keypress or tone) from the participants' estimate. 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 estimation errors deviating > 2.5 standard deviations from the cell mean, calculated separately for each participant and condition (i.e., baseline/operant), were excluded (2.0%). We tested for temporal binding comparing estimation errors in operant blocks with estimation errors in the baseline blocks via a two-tailed, paired *t*-test.

To probe for differences in temporal binding as a function of choice consistency, we computed a two-tailed, paired *t*-test comparing estimation errors in operant blocks between consistent and inconsistent choices. Choices were considered consistent if participants chose to repeat their response in tone repetition trials and when they chose to switch their response in tone switch trials during the probe segment.

We followed-up all non-significant tests by calculating Bayes Factors (BF_{01}) with the BayesFactor package version 0.9.12–2 of the R software environment version 3.3.1 (scale parameter = 0.707, the current default in the BayesFactor package). BF_{01} were computed as $f(data|H_0)/f(data|H_1)$ (with f denoting marginal likelihoods) and we considered $BF_{01} > 3$ as evidence for the null hypothesis over the alternative hypothesis and BF_{01} less than 1/3 as evidence for the alternative hypothesis over the null hypothesis. Our interpretations are based on directional BF_{01} as we have a clear hypothesis as to the direction of the effect (temporal binding for consistent choices > temporal binding for inconsistent choices). However, for a maximum of transparency, we also report the corresponding nondirectional BF_{01} in parentheses.

Catch trials (9.5%), practice trials (2.6%), and trials during which an error occurred (4.8%) were excluded from all data analyses.

2.2. Results

Four participants showed almost no variation in their response patterns, in that they either almost never chose to repeat responses or almost never chose to switch responses, leading to less than five trials in the respective conditions. As these data may be statistically unreliable, we performed all analyses twice: once including the entire sample (except for the six excluded participants, see Methods) and once without these four participants to ensure that they did not fundamentally affect our results. Results without these participants are reported in parentheses (see Fig. A1 in the Appendix A for individual data).

2.2.1. Response repetitions

The percentage of response repetitions for each condition is shown in Fig. 2. Response repetitions were higher after tone repetitions (TR) than after tone switches (TS), $M_{TR} = 31.85\%$, $M_{TS} = 28.58\%$, $t(42) = 2.89$, $p = .006$, $d_z = 0.44$ ($N = 39$, $M_{TR} = 34.94\%$, $M_{TS} = 31.24\%$, $t(38) = 3.01$, $p = .005$, $d_z = 0.48$). This difference in response repetition rates dependent on tone sequence indicates the establishment of short-term action-effect binding during the experiment.

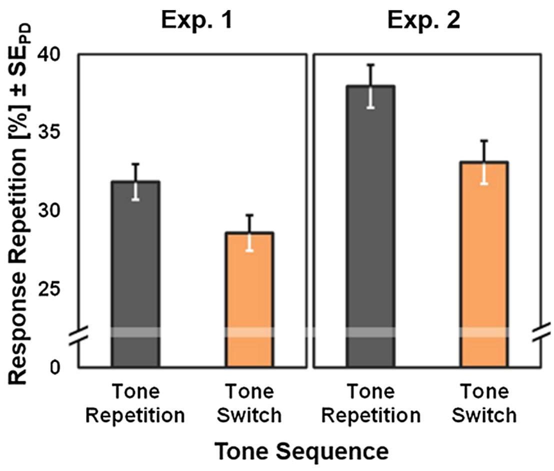

Fig. 2. Percentage of response repetitions in Experiments 1 and 2. Data analysis revealed significant differences in the percentage of response repetitions dependent on tone sequence (tone repetition vs. tone switch) which indicates the establishment of short-term action-effect binding. Error bars depict standard errors of paired differences (SE_{PD}; Pfister & Janczyk, 2013).

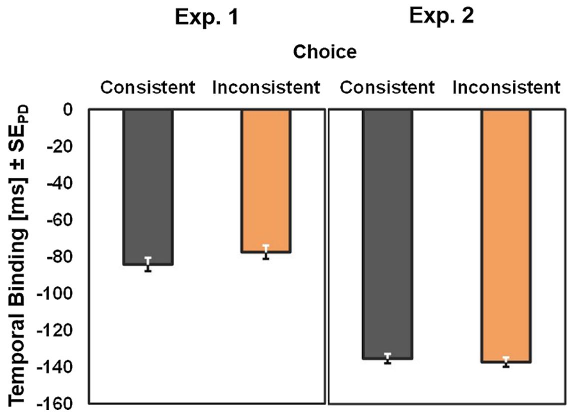

Fig. 3. Temporal binding as a function of choice consistency in Experiments 1 and 2. Data analysis suggested a non-significant trend for the effect of choice consistency on temporal binding in Experiment 1. However, this association was not confirmed by our high-powered replication study (Experiment 2). Error bars depict standard errors of paired differences (SE_{PD}; Pfister & Janczyk, 2013).

2.2.2. Temporal binding

We observed a strong temporal binding effect with tones being estimated to appear almost 100 ms earlier in the operant condition (O) than in the baseline condition (B), $M_O = -81$ ms, $M_B = 12$ ms, $t(42) = 6.30$, $p < .001$, $d_z = 0.96$ ($N = 39$, $M_O = -87$ ms, $M_B = 12$ ms, $t(38) = 6.11$, $p < .001$, $d_z = 0.98$).

2.2.3. Action-Effect binding and temporal binding

Fig. 3 shows temporal binding effects as a function of choice consistency. We found a descriptive but non-significant trend in the predicted direction with temporal binding being slightly stronger when the participants' response to the second tone (probe segment) was consistent (C) with the previous keypress–tone association (prime segment) than when their response choice was inconsistent (I), $M_C = -84$ ms, $M_I = -78$ ms, $t(42) = 1.91$, $p = .064$, $d_z = 0.29$ ($N = 39$, $M_C = -90$ ms, $M_I = -83$ ms, $t(38) = 1.97$, $p = .057$, $d_z = 0.32$). Bayes factor analysis indicated that the absence of a clear effect in our analysis might not be based on a true absence of any effect of choice consistency on temporal binding, but might instead be a problem of statistical power, directional $BF_{01} = 0.61$ (nondirectional $BF_{01} = 1.16$).

2.3. Discussion

Our analyses revealed strong temporal binding as well as short-term action-effect binding indicating that our paradigm was suited to study the effects of action-effect binding on temporal binding. The critical test, however, revealed only a marginally significant association of action-effect binding and temporal binding, although in the predicted direction, i.e., consistent choices were associated with stronger temporal binding effects than inconsistent choices. Bayesian analysis revealed that this lack of a statistical evidence for an effect of choice consistency on temporal binding might be due to a lack of statistical power, possibly because the actual effect size is smaller than we previously assumed. We therefore chose to replicate this study in a second experiment with more participants and an optimized experimental design to increase the statistical power of our critical test.

3. Experiment 2

All raw data and analyses scripts are available at the corresponding project repository (https://osf.io/dtx6k/).

3.1. Methods

3.1.1. Participants

For the replication experiment, we recruited 61 new participants (mean age = 26.5 years, range 20–66; 42 females, 48 right-handed). Sample size ensured a power of 0.80 even for small effects of $d_z = 0.31$ (as indicated by our first experiment) for directional hypotheses (one-sided tests). Participants gave informed consent prior to the experiment and received course credit or monetary compensation for participation. Five participants were excluded because of technical issues or because they did not perform the task correctly.

3.1.2. Stimuli and procedure

Stimuli and experimental procedure were exactly as described in Experiment 1, with two exceptions: We chose to switch one baseline block with another operant block, resulting in a block sequence of BOO OOO, to increase power for our critical test (comparison of temporal binding effects between trials with consistent and inconsistent choices – note that the individual baseline scores are irrelevant for this comparison because they are subtracted from consistent and inconsistent choice alike). Moreover, catch trials now stopped 1500–2000 ms after a tone would have been presented in the normal probe segments to mimic the trial timing of regular trials in the operant condition more accurately.

3.1.3. Data analysis

Data analysis was performed as detailed for Experiment 1. Catch trials (10.7%), practice trials (2.4%) and trials during which an error occurred (4.9%) were again excluded from all data analyses. For the calculation of estimation errors, 2.0% of trials were excluded as outliers.

3.2. Results

In addition to the five excluded participants (see Methods), a further five participants showed almost no variation in their response patterns, similarly to Experiment 1. As these data may be statistically unreliable, we again performed additional analyses without these participants to ensure that they did not fundamentally affect our results. Results without these participants are reported in parentheses (see Fig. A1 in the Appendix A for individual data).

3.2.1. Response repetitions

Response repetitions as a function of tone sequence are shown in Fig. 2. As in Experiment 1, response repetitions were more frequent after tone repetitions (TR) than after tone switches (TS), $M_{TR} = 37.96\%$, $M_{TS} = 33.11\%$, $t(55) = 3.54$, $p = .001$, $d_z = 0.47$ ($N = 51$, $M_{TR} = 39.59\%$, $M_{TS} = 34.21\%$, $t(50) = 3.64$, $p = .001$, $d_z = 0.51$). These results indicate that short-term action-effect binding within trials occurred during the experiment.

3.2.2. Temporal binding

Again, we found strong temporal binding effects with tones in the operant condition (O) being perceived as appearing about 140 ms earlier than in the baseline condition (B), $M_O = -137$ ms, $M_B = 9$ ms, $t(55) = 10.81$, $p < .001$, $d_z = 1.44$ ($N = 51$, $M_O = -140$ ms, $M_B = 7$ ms, $t(50) = 11.42$, $p < .001$, $d_z = 1.60$).

3.2.3. Action-Effect binding and temporal binding

Fig. 3 shows temporal binding effects as a function of choice consistency. Here, we found no indication of an association of choice consistency and temporal binding, $M_C = -135$ ms, $M_I = -137$ ms, $t(55) = 0.74$, $p = .460$, $d_z = 0.10$ ($N = 51$, $M_C = -139$ ms, $M_I = -141$ ms, $t(50) = 0.93$, $p = .357$, $d_z = 0.13$). In contrast to Experiment 1, Bayes factor analysis points to a clear absence of an effect of choice consistency on temporal binding, directional $BF_{01} = 11.14$ (nondirectional $BF_{01} = 5.28$).

3.3. Results – Combined data

As trial procedure and stimuli were the same in both experiments, we chose to analyze all collected data together for a maximum of statistical power ($N = 99$, power = 0.90 given a small effect size of $d = 0.30$, directional hypotheses). Statistical values in parentheses again reflect analyses without participants showing almost no variation in their response patterns, as in the separate analyses of Experiments 1 and 2.

3.3.1. Response repetitions

Overall, we found strong evidence for the establishment of short-term action-effect bindings, as indicated by a higher percentage of response repetitions (TR) than after tone switches (TS), $M_{TR} = 35.31\%$, $M_{TS} = 31.14\%$, $t(98) = 4.54$, $p < .001$, $d_z = 0.46$ ($N = 90$, $M_{TR} = 37.57\%$, $M_{TS} = 32.92\%$, $t(89) = 4.69$, $p < .001$, $d_z = 0.49$).

3.3.2. Temporal binding

Participants perceived tones to appear about 120 ms earlier overall in the operant condition (O) compared with the baseline condition (B), $M_O = -113$ ms, $M_B = 10$ ms, $t(98) = 11.98$, $p < .001$, $d_z = 1.20$ ($N = 90$, $M_O = -117$ ms, $M_B = 9$ ms, $t(89) = 12.16$, $p < .001$, $d_z = 1.28$).

3.3.3. Action-Effect binding and temporal binding

Similarly to Experiment 2, choice consistency did not affect temporal binding when analyzing the combined data sets (C, consistent; I, inconsistent), $M_C = -113$ ms, $M_I = -111$ ms, $t(98) = 0.86$, $p = .393$, $d_z = 0.09$ ($N = 90$, $M_C = -118$ ms, $M_I = -116$ ms, $t(89) = 0.95$, $p = .345$, $d_z = 0.10$). Similarly to Experiment 2, Bayes factor analysis points to a true absence of an effect, directional $BF_{01} = 3.90$ (nondirectional $BF_{01} = 6.28$).

3.4. Discussion

Data analysis of Experiment 2 as well as of the combined data of Experiments 1 and 2 suggest that short-term action-effect binding is not associated with temporal binding. Although both, short-term action-effect binding and temporal binding, were induced in Experiment 2 (and also present in the analysis of both data sets), we found no statistical evidence for an association of both effects. To the contrary, Bayes analyses indicate a true absence of such an effect in the Experiment 2 data as well as in the combined data set.

Furthermore, mean repetition rates were consistently lower than 50% across both experiments. Even though the latter value might be expected for a random selection between both options, choice reaction tasks readily give rise to either repetition or alternation biases. While the direction of this bias towards repetition or towards alternation hinges on expectancy effects – which are based on the statistical and temporal structure of the task, in turn (Soetens, Boer, & Hueting, 1985) –, an alternation bias such as the present one is also routinely observed in studies using the present prime-probe design (e.g., Dutzi & Hommel, 2009; Schwarz, Pfister, et al., 2018). In addition to general expectancy effects, a second explanation for this bias might also be that tone switches exert a stronger bias towards response switches than tone repetitions bias towards response repetition (see Dutzi & Hommel, 2009, for a tentative proposal along this line). Such a mechanism would yield response repetition rates of less than 50% on average; however, it would predict repetition rates of at least 50% for tone repetitions if no additional expectancy effects were at play, The present data as well as other recent observations (Moeller, Pfister, Kunde, & Frings, in press) yielded rather low repetition rates also in this condition so that we prefer an account in terms of general expectancies for the time being.

4. General discussion

The present experiments aimed at the question of whether basic action control mechanisms such as short-term action-effect bindings are associated with temporal binding – a measure that is often seen as an implicit measure for agency. This research question was based on our previous work showing evidence for an association of such short-term action-effect bindings and explicit judgments of agency (Schwarz, Burger, et al, 2018); an association that could have been explained by a conceptual as well as temporal integration of action and effect during the action, leading to action-effect binding and temporal binding alike.

To study the association of short-term action-effect bindings and temporal binding, we employed a two-step paradigm designed to test for action-effect bindings (Dutzi & Hommel, 2009; Janczyk et al., 2012; Moeller et al., 2016, in press), and incorporated a time estimation of the participant's action effect to test for temporal binding and an interaction of both phenomena. Experiment 1 revealed strong evidence for action-effect binding and temporal binding alike, suggesting that the paradigm was suitable to study both effects. However, we found only a marginal association of both phenomena with Bayes Factor analysis indicating that this lack of clear evidence for or against our hypothesis might be due to a lack of power. Thus, we ran a replication experiment (Experiment 2) with the same basic trial structure to allow a combined data analysis and only a slightly adjusted experimental procedure to maximize statistical power. This replication experiment revealed convincing evidence that, contrary to our hypothesis and the potential association seen in Experiment 1, there is no association of action-effect binding and temporal binding, as confirmed by Bayes Factor analysis. Analysis of all data combined further supported this conclusion. This indicates that short-term action-effect binding and temporal binding are two separate and unrelated processes. By extension, this suggests that the association of short-term action-effect binding and explicit judgements of agency is not mediated by perceptual biases such as temporal binding.

A possible confound in our data preventing the emergence of the proposed association could be that in the case of tone repetitions, participants confused both tones and estimated the appearance of the second, later tone rather than the first, earlier tone. If this were the case, this would lead to less negative estimation errors in tone repetition trials compared with tone switch trials (the earlier participants perceive a tone, the more negative the estimation error). However, analysis of temporal binding (i.e., estimation errors) effects revealed that participants did not estimate the tones to appear later in tone repetition (TR) trials than in tone switch (TS) trials, $M_{TR} = -113$ ms, $M_{TS} = -112$ ms, $t(98) = 0.77$, $p = .441$, $d_z = 0.08$, directional BF = 15.19, rendering this possible confound unlikely.

Then, why do we find an association of action-effect bindings with explicit agency judgments (Schwarz, Burger, et al., 2018), but not with temporal binding? A first answer lies in the possibility that temporal binding and agency judgments do not measure implicit and explicit aspects of the same process. Indeed, several studies have investigated how temporal binding and agency judgments are associated with controversial results: while some found a correlation of both (Imaizumi & Tanno, 2019; Pyasik, Burin, & Pia, 2018), others did not (Dewey & Knoblich, 2014; Saito, Takahata, Murai, & Takahashi, 2015; Schwarz, Weller, Klaffehn, & Pfister, 2019). In a previous study of ours, we also found discrepancies in how temporal binding and explicit agency judgments respond to experimental manipulation (free vs. forced choice; Schwarz et al., 2019).

A provocative interpretation of this database is that temporal binding is related less directly to agency than initially assumed. Instead, it might be based on causality perception instead and therefore rather measures a sense of causality (Kirsch et al., 2019) which, while closely related to agency, might differ in certain situations. In the present experiments, one could argue that even though agency judgments might be affected by short-term action-effect bindings, the perception of causality does not necessarily differ as there is no action-effect contingency throughout the task. An alternative take on this issue is the assumption that temporal binding and subjective judgements are both related to agency but tap into different levels of agency (for a recent distinction of low- versus high-level goals and their relation to agency, see Gozli & Dolcini, 2018). Arguably, temporal binding might be specifically relevant for low-level goals corresponding to sensorimotor control (Wolpe, Haggard, Siebner, & Rowe, 2013) whereas subjective feelings of agency might be especially be tuned towards goals on higher levels of the hierarchy (Gozli, 2019). Crucially, this framework does not necessitate a clear relation or dependence of temporal binding and subjective judgments but rather assumes temporal binding to cover a distinct facet of agency.

However, if short-term action-effect binding and temporal binding are not associated, how do we explain our previous findings of an association of action-effect binding and explicit agency judgments? We believe that our results may be taken to question the common interpretation of protocols to measure short-term action-effect binding. This interpretation typically suggests an incidental integration of action and subsequent effect in an event file which is retrieved upon re-encountering the previous effect so that the corresponding action is activated automatically (Dutzi & Hommel, 2009; Herwig & Waszak, 2012; Janczyk et al., 2012; Moeller et al., 2016). By contrast, the robust preference for consistent choices might instead reflect strategic decision-making in the probe segment, in that participants might explicitly decide to repeat responses after tone repetitions or switch responses after tone switches (for recent findings on the role of response strategies in action-effect learning, see Vogel, Scherbaum, & Janczyk, 2018; Weller, Kunde, & Pfister, 2017). This alternative interpretation receives tentative support from comparisons between common action-effect binding protocols which focus on conscious action choices (as in the present experiments) with incidental retrieval of action-effect bindings as assessed with reaction time protocols. Studies have shown that effect sizes of action-effect binding differ dramatically dependent on which measurement is chosen (e.g., Moeller et al., 2016; $d = 1.06$ for response choices vs. $d = 0.63$ for reaction time protocols). This leads to the question if both types of measures actually capture the same phenomenon. Methodological groundwork on the topic of short-term action-effect binding is needed to elucidate this issue that potentially also affects the present results. If the above reasoning holds, however, response strategies might provide a guidance for action selection, leading to higher action selection fluency and higher agency without assuming a temporal integration of action and effect.

5. Conclusion

In the present experiments, we tested our hypothesis that the establishment of short-term action-effect bindings is associated with stronger temporal binding indicating a conceptual and temporal integration of action and effect at the same time and thereby affecting the participants' sense of agency. Results suggest that such an association is unlikely, and that action-effect binding and temporal binding instead seem two phenomena that are independently established but do not affect one another.

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Appendix A

See Fig. A1.

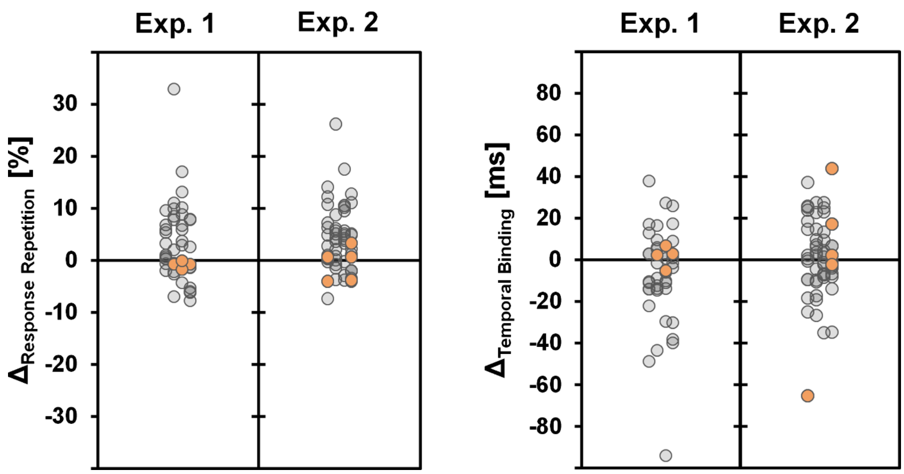

Fig. A1. Individual data for both experiments. Left panels: Data points represent individual difference scores for response repetition rates ($\Delta_{Response\ Repetition}$), calculated as the percentage of response repetitions for tone repetitions minus the percentage of response repetitions for tone switches. Right panels: Data points represent individual difference scores for temporal binding ($\Delta_{Temporal\ Binding}$), computed as the binding score for consistent choices minus the binding score for inconsistent choices. Bright orange points indicate excluded participants in the restricted analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

References

Beck, B., Di Costa, S., & Haggard, P. (2017). Having control over the external world increases the implicit sense of agency. *Cognition, 162*, 54–60.
Blakemore, S. J., Smith, J., Steel, R., Johnstone, E. C., & Frith, C. D. (2000). The perception of self-produced sensory stimuli in patients with auditory hallucinations and passivity experiences: Evidence for a breakdown in self-monitoring. *Psychological Medicine, 30*(5), 1131–1139.
Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (2002). Abnormalities in the awareness of action. *Trends in Cognitive Sciences, 6*, 237–242.
Chambon, V., Sidarus, N., & Haggard, P. (2014). From action intentions to action effects: How does the sense of agency come about? *Frontiers in Human Neuroscience, 8*, 320.
Damen, T. G., van Baaren, R. B., & Dijksterhuis, A. (2014). You should read this! Perceiving and acting upon action primes influences one's sense of agency. *Journal of Experimental Social Psychology, 50*, 21–26.
Dewey, J. A., & Knoblich, G. (2014). Do implicit and explicit measures of the sense of agency measure the same thing? *PloS One, 9*(10), e110118.
Dutzi, I. B., & Hommel, B. (2009). The microgenesis of action-effect binding. *Psychological Research, 73*, 425–435.
Eder, A. B., & Dignath, D. (2017). Influence of verbal instructions on effect-based action control. *Psychological Research, 81*, 355–365.
Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 229–240.
Franck, N., Farrer, C., Georgieff, N., Marie-Cardine, M., Daléry, J., d'Amato, T., & Jeannerod, M. (2001). Defective recognition of one's own actions in patients with schizophrenia. *American Journal of Psychiatry, 158*(3), 454–459.
Frings, C., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Hommel, B., ... Philipp, A. (2018). *Merkmalsintegration und Abruf als wichtige Prozesse der Handlungs-steuerung – eine Paradigmen-übergreifende Perspektive [Feature integration and retrieval as core processes in action control – A cross-paradigm perspective].* Psychologische Rundschau.
Frith, C. D. (2014). Action, agency and responsibility. *Neuropsychologia, 55*, 137–142.
Gozli, D. G. (2019). *Experimental Psychology and Human Agency.* Cham, Switzerland: Springer.
Gozli, D. G., & Dolcini, N. (2018). Reaching into the unknown: Actions, goal hierarchies, and explorative agency. *Frontiers in Psychology, 9*, 266.
Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience, 18*(4), 197–208.
Haggard, P., & Tsakiris, M. (2009). The experience of agency: Feelings, judgments, and responsibility. *Current Directions in Psychological Science, 18*(4), 242–246.
Hauser, M., Knoblich, G., Repp, B. H., Lautenschlager, M., Gallinat, J., Heinz, A., & Voss, M. (2011). Altered sense of agency in schizophrenia and the putative psychotic prodrome. *Psychiatry Research, 186*, 170–176.
Herwig, A., & Waszak, F. (2012). Action-effect bindings and ideomotor learning in intention-and stimulus-based actions. *Frontiers in Psychology, 3*, 444.
Hoffmann, J., Lenhard, A., Sebald, A., & Pfister, R. (2009). Movements or targets: What makes an action in action-effect learning? *Quarterly Journal of Experimental Psychology, 62*(12), 2433–2449.
Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences, 8*(11), 494–500.
Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research, 73*, 512–526.
Hughes, G., Desantis, A., & Waszak, F. (2013). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction, and motor prediction. *Psychological Bulletin, 139*, 133–151.
Imaizumi, S., & Tanno, Y. (2019). Intentional binding coincides with explicit sense of agency. *Consciousness and Cognition, 67*, 1–15.
Janczyk, M., Heinemann, A., & Pfister, R. (2012). Instant attraction: Immediate action-effect bindings occur for both, stimulus- and goal-driven actions. *Frontiers in Cognition, 3*, 446.
Kirsch, W., Kunde, W., & Herbort, O. (2019). Intentional binding is unrelated to action intention. *Journal of Experimental Psychology: Human Perception and Performance, 45*(3), 378–385.
Kirsch, W., Pfister, R., & Kunde, W. (2016). Spatial action-effect binding. *Attention, Perception, & Psychophysics, 78*(1), 133–142.
Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 387–394.
Moeller, B., Pfister, R., Kunde, W., & Frings, C. (2016). A common mechanism behind distractor-response and response-effect binding? *Attention, Perception, & Psychophysics, 78*(4), 1074–1086.
Moeller, B., Pfister, R., Kunde, W., & Frings, C. (in press). Selective binding of stimulus, response, and effect features. Psychonomic Bulletin & Review. http://doi.org/10.3758/s13423-019-01646-1.
Moore, J. W. (2016). What is the sense of agency and why does it matter? *Frontiers in Psychology, 7*, 1272.
Moore, J. W., Wegner, D. M., & Haggard, P. (2009). Modulating the sense of agency with external cues. *Consciousness and Cognition, 18*(4), 1056–1064.
Morein-Zamir, S., Soto-Faraco, S., & Kingstone, A. (2003). Auditory capture of vision: Examining temporal ventriloquism. *Cognitive Brain Research, 17*(1), 154–163.
Pfister, R. (2019). Effect-based action control with body-related effects: Implications for empirical approaches to ideomotor action control. *Psychological Review, 126*, 153–161.
Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9*(2), 74–80.
Pfister, R., Kiesel, A., & Hoffmann, J. (2011). Learning at any rate: Action-effect learning for stimulus-based actions. *Psychological Research, 75*(1), 61–65.
Pyasik, M., Burin, D., & Pia, L. (2018). On the relation between body ownership and sense of agency: A link at the level of sensory-related signals. *Acta Psychologica, 185*, 219–228.
Recanzone, G. H. (2003). Auditory influences on visual temporal rate perception. *Journal of Neurophysiology, 89*(2), 1078–1093.
Saito, N., Takahata, K., Murai, T., & Takahashi, H. (2015). Discrepancy between explicit judgement of agency and implicit feeling of agency: Implications for sense of agency and its disorders. *Consciousness and Cognition, 37*, 1–7.
Schwarz, K. A., Burger, S., Dignath, D., Kunde, W., & Pfister, R. (2018a). Action-effect binding and agency. *Consciousness and Cognition, 65*, 304–309.
Schwarz, K. A., Pfister, R., Kluge, M., Weller, L., & Kunde, W. (2018b). Do we see it or not? Sensory attenuation in the visual domain. *Journal of Experimental Psychology: General, 147*(3), 418–430.
Schwarz, K. A., Weller, L., Klaffehn, A. L., & Pfister, R. (2019). The effects of action choice on temporal binding, agency ratings, and their correlation. *Consciousness and Cognition, 75*, 102807.
Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin, 136*, 943.
Sidarus, N., Chambon, V., & Haggard, P. (2013). Priming of actions increases sense of control over unexpected outcomes. *Consciousness and Cognition, 22*(4), 1403–1411.
Sidarus, N., & Haggard, P. (2016). Difficult action decisions reduce the sense of agency: A study using the Eriksen flanker task. *Acta Psychologica, 166*, 1–11.
Sidarus, N., Vuorre, M., & Haggard, P. (2017). Integrating prospective and retrospective cues to the sense of agency: A multi-study investigation. *Neuroscience of Consciousness, 2017*(1), 1–10.
Soetens, E., Boer, L. C., & Hueting, J. E. (1985). Expectancy or automatic facilitation? Separating sequential effects in two-choice reaction time. *Journal of Experimental Psychology: Human Perception & Performance, 11*, 598–616.
Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition, 17*(1), 219–239.
Van Beers, R. J., Sittig, A. C., & Denier van der Gon, J. J. (1999). Integration of proprioceptive and visual position-information: An experimentally supported model. *Journal of Neurophysiology, 81*, 1355–1364.
Vogel, D., Scherbaum, S., & Janczyk, M. (2018). Dissociating decision strategies in free-choice tasks–A mouse tracking analysis. *Acta Psychologica, 190*, 65–71.
Voss, M., Moore, J., Hauser, M., Gallinat, J., Heinz, A., & Haggard, P. (2010). Altered awareness of action in schizophrenia: A specific deficit in predicting action consequences. *Brain, 133*, 3104–3112.
Wegner, D. M. (2003). The mind's best trick: How we experience conscious will. *Trends in Cognitive Sciences, 7*(2), 65–69.
Wegner, D. M., & Wheatley, T. (1999). Apparent mental causation: Sources of the experience of will. *American Psychologist, 54*(7), 480–492.
Weiss, C., Herwig, A., & Schütz-Bosbach, S. (2011). The self in action effects: Selective attenuation of self-generated sounds. *Cognition, 121*, 207–218.
Weller, L., Kunde, W., & Pfister, R. (2017). Non-action effect binding: A critical re-assessment. *Acta Psychologica, 180*, 137–146.
Weller, L., Schwarz, K. A., Kunde, W., & Pfister, R. (2017). Was it me?–Filling the interval between action and effects increases agency but not sensory attenuation. *Biological Psychology, 123*, 241–249.
Wenke, D., Fleming, S. M., & Haggard, P. (2010). Subliminal priming of actions influences sense of control over effects of action. *Cognition, 115*(1), 26–38.
Wolfensteller, U., & Ruge, H. (2011). On the timescale of stimulus-based action–effect learning. *The Quarterly Journal of Experimental Psychology, 64*(7), 1273–1289.
Wolpe, N., Haggard, P., Siebner, H. R., & Rowe, J. B. (2013). Cue integration and the perception of action in intentional binding. *Experimental Brain Research, 229*(3), 467–474.
Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science, 269*, 1880–1882.