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ORIGINAL ARTICLE

Intentional binding of two effects

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Abstract An action that produced an effect is perceived later in time compared to an action that did not produce an effect. Likewise, the effect of an action is perceived earlier in time compared to a stimulus that was not produced by an action. Despite numerous studies on this phenomenon—referred to as Intentional Binding effect (IB)—the underlying mechanisms are still not fully understood. Typically, IB is investigated in settings where the action produces just one single effect, whereas in everyday action contexts, it rather causes a sequence of effects before leading to the desired outcome. Therefore, we investigated IB of two consecutive effects. We observed substantially more IB of a first effect tone compared to a second tone. This pattern was observed for second tones that were temporally predictable (Exp. 1) or not (Exp. 2 and 3). Interestingly, the second tone yielded stronger IB when it was less delayed (Exp. 4). Thus, also an event occurring later in an unfolding action–effect sequence can be bound to its causing action, but it might be less bound to the action than a first effect. Instead of the fact that it is the second of two consecutive effects, this, however, rather seems to be influenced by the longer delay of a second and, therefore, later occurring effect.

Raw data are available in Open Science https://osf.io/y85wr/?view_only=e0017be09ffb4e64aa970110200926bb.

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Introduction

If we want to succeed in achieving certain goals, like getting ice from an ice machine, we need to interact with our environment, that is, execute actions to cause intended effects. In this case, we need to insert money into the machine and press the start button. This is followed by a characteristic sequence of perceivable effects that lead to the desired outcome: the crunching sound of the cup falling down, the clinking sound of the ice machine cutting the ice cubes, and finally the cubes plopping into the cup.

A number of studies (e.g., Haering & Kiesel, 2014; Moore, Lagnado, Deal, & Haggard, 2009; Moore, Middleton, Haggard, & Fletcher, 2012; Ruess, Thomaschke, & Kiesel, 2017; Wenke, Waszak, & Haggard, 2009) has shown that actions producing intended effects are temporally biased in the sense that we perceive them later than actions without following effects. The effects that we produce by our actions are, in turn, perceived earlier than stimuli that we do not produce by our actions (Haggard, Aschersleben, Gehrke, & Prinz, 2002). This temporal bias is termed temporal binding or intentional binding (IB) of actions and IB of effects, respectively.

Typically, IB is investigated in settings where participants have to press a key followed by a tone. Afterwards, they have to indicate the position of a rotating clock hand they saw at the moment they pressed the key or heard the tone (Haggard, Clark, & Kalogeras, 2002). These estimates are compared to clock hand estimates of baseline conditions, where only one of these events occurs: the action, or

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in other blocks a single tone. Yet, this typical laboratory setting deviates considerably from most of our everyday action contexts, like the one described above. Instead of being confined to just one single effect, most of our actions produce a sequence of effects. Accordingly, pressing the start button on the ice machine produces not just the crunching sound of the cup falling down, but it is typically also followed by a cascade of perceivable effects, culminating in the final goal: the ice cubes plopping into the cup.

Consequently, it is necessary to investigate IB in settings that are more complex and that more closely match real everyday action contexts. A previously neglected, but nevertheless very important, question is whether both effects, the first and second of two consecutive effects, are subject to IB. Thus, we devised an extension of the classic IB design (Haggard, Clark, et al., 2002), including two successive effects.

The challenge in investigating not just one, but two effects, is that the second effect is inevitably more delayed than the first effect. Yet, the temporal relationship between action and effect is an intensely investigated factor that has been shown to substantially influence IB. More precisely, IB greatly depends on the temporal contiguity of the effect (i.e., effect delay; e.g., Haggard, Clark, et al., 2002; Humphreys & Buehner, 2009; Nolden, Haering, & Kiesel, 2012; Ruess et al., 2017; Wen, Yamashita, & Asama, 2015), and this effect delay interacts with the temporal predictability of the effect (i.e., temporal variability of the effect delay; Haggard, Clark, et al., 2002; Ruess et al., 2017). Using the classic clock procedure, Haggard, Clark, et al. (2002) observed less IB of effects that were longer delayed, and also temporally unpredictable, compared to effects that were shorter delayed, and also temporally predictable. Furthermore, this depends on whether the delays vary within small or large ranges (Ruess et al., 2017). Yet, effect delay is always confounded with the position the effect has in a sequence. The second effect is necessarily more delayed than the first one and should inevitably show less IB than the earlier occurring first effect. Consequently, effect delay and temporal predictability of the effect are two important factors that have to be considered when investigating IB of two consecutive effects.

To properly account for potential confounds from effect delay and temporal predictability, we conducted several experiments in our investigation of IB of two effects. In the first experiment, the delay between action execution and first effect, and the delay between first and second effect were both predictable (500 ms). In Experiment 2 and Experiment 3, we made the modification that, on average, the delays were still of the same duration (500 ms), but now only the first effect was temporally predictable, whereas the second effect was temporally unpredictable. More precisely, the delay of the second effect varied within a small (Experiment 2: 350 ms–650 ms) or large (Experiment 3: 200 ms–800 ms) range after the first effect occurred. In a last experiment, we took the influence of effect delay magnitude into account by employing two shorter delays of 250 ms between action and first effect and between first and second effects, respectively (both effects were temporally predictable).

A recent study (Janczyk, Durst, & Ulrich, 2017) investigated for the first time effect sequences of two action–effects showing that also second action–effects can be anticipated during action selection. However, to our knowledge, no previous study has investigated how a second effect influences IB of the action, first, or second effect. Thus, we did not have any clear predictions concerning how the second effect would influence IB of these three events. However, relying on the previous research on the influence of effect delay on IB (e.g., Haggard, Clark, et al., 2002; Ruess et al., 2017), we expected generally stronger IB of the earlier occurring first effect in comparison to the necessarily later occurring second effect. In addition, we expected a generally stronger IB magnitude (for action, first effect, and second effect) in Experiment 4 with shorter effect delays compared to Experiment 1 to Experiment 3 with longer effect delays.

Experiment 1

Participants were asked to press the response key at a freely chosen point in time, to produce a first tone that followed the action execution with a delay of 500 ms, followed by a second tone after another 500 ms. During the keypress and the occurrence of the tones, the participants watched a rotating clock hand. They were asked to estimate the position of the clock hand either at the moment when they pressed the key or when they heard the first or second tones in separate blocks (experimental condition for action, first, and second tone). In baseline conditions, the action did not cause any effect tone (action baseline) or both tones were presented without preceding action (first and second tone baselines) and participants had to estimate respective points in time in relation to the rotating clock hand in separate blocks. All these baseline and experimental blocks were presented in two separate sessions. IB was measured as the difference of experimental conditions of action, first tone, and second tone compared to respective baseline conditions of action, first tone, and second tone (cf. Haggard, Clark, et al., 2002). That is, IB of the action was the difference between action estimates when the action was followed by the tones (action experimental), and action estimates when the action was not followed by the tones (action baseline). Likewise, IB of first and second tones was computed separately as the difference between respective tone estimates when they were preceded by an action (first and second tone experimental), and respective tone estimates when they were not preceded by an action (first and second tone baseline).

Method

Participants

Twenty-four participants (24 females, mean age = 20.25, *SD* = 1.98, range 18–25 years, 22 right-handed) were included as part of a course requirement.

Apparatus and stimuli

The experiment was run using the E-Prime 2.0 software (Schneider, Eschmann, & Zuccolotto, 2012) on a standard PC with a 17" CRT screen (1024 pixels × 768 pixels, 100 Hz refresh rate). Participants watched a centrally presented Libet clock (Libet, Gleason, Wright, & Pearl, 1983; Wundt, 1887; for a new open source tool see, e.g., Garaizar, Cubillas, & Matute, 2016) with 12 labeled "minute" intervals (frame 250 pixels × 250 pixels, 2560 ms/full rotation).

We asked participants to perform an action (that is to press a response key) in two different scenarios and depending on the scenario, different additional pictures were presented during each trial (scenarios and pictures uploaded in Open Science). For each scenario, different acoustic stimuli were produced using the program Audacity (Priemer, 2008) and were presented by VicFirth Isolation SIH1 headphones each for 100 ms. For one scenario, a first tone of 400 Hz and a second tone of 800 Hz were used. For the other scenario, the sound of crunching and clinking served as first and second tones (see Procedure). Thus, in each trial, two tones were presented. In the instruction prior to the experiment, we told participants that either just the first (one effect attribution) or both tones (two effects attribution) were produced by the participants' action, yet, this causality attribution[1] did not affect results and is thus not further reported here. Headphones were used to ensure that participants did not hear their key-presses as a reference for their time estimates. For the action, a separate external response key on the left side of the keyboard was operated with the index finger of the left hand. Time estimates were given with the right hand using the number pad of the keyboard (1–9). Estimates were confirmed and the next trial started with the press of the space or backspace button of the keyboard.

Procedure

The experiment consisted of two 1-h sessions conducted on two different days: In both sessions, different scenarios were used. In addition, in one session, participants were told to cause just the first of two tones (one effect attribution), whereas in the other session, they were told to cause both tones (two effects attribution). The combination of instruction and scenario and the order of scenarios were counterbalanced over participants (uploaded in Open Science).

We employed the classic clock procedure (Haggard, Clark, et al., 2002) with the Libet clock (Libet et al., 1983; Wundt, 1887) to infer IB. It consists of a visual display of an analogue clock with a hand revolving over a dial at a continuous pace. This clock was used as reference for the participants' time estimates (see Fig. 1).

Each trial started with the presentation of the clock and the pictures of the respective scenarios on the screen. The clock hand appeared at a random position and immediately started to rotate. Participants were instructed to focus on the presented clock and to press the external response key at a freely chosen point in time, but to wait until the clock hand had revolved at least once, and not to press at a pre-planned clock position or point in time. In the experimental conditions, the action was followed by the two tones. Each of the first tones followed the action after 500 ms and was followed by the respective second tones after additional 500 ms. In the baseline condition for the action, no tone followed after action execution, whereas in the baseline conditions for the tones, no action was required and the first tone was presented randomly 2560 ms–5120 ms after the trial had started followed by the second tone after an additional 500 ms. In all conditions, the clock disappeared at a random time 2 s–3 s after the second tone (or after action execution in the action baseline condition). In the experimental and baseline conditions for the action, participants had to estimate after each trial the position of the clock hand at the moment they pressed the key. In the experimental and baseline conditions for the first tone, they were prompted after each trial to estimate the position of the clock hand at onset of the first tone, whereas in the experimental and baseline conditions for the second tone, they were prompted after each trial to estimate the position of the clock hand at onset of the second tone (position estimates in minute steps between 1 and 60).

Each of the two sessions started with three baseline blocks: one baseline block for the action, one baseline block for the first tone, and one baseline block for the second tone (each with 20 trials). The baseline blocks were

[1] The effects of the causality attribution were analyzed independently of the main analysis of an effect sequence with two effects. However, neither the main effect of causality attribution nor any interaction with this factor was significant and is, thus, not described further (uploaded in Open Science).

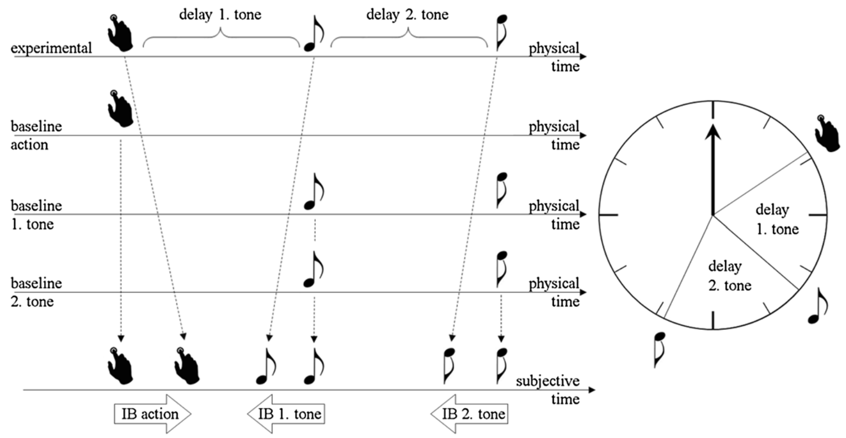

Fig. 1 Clock procedure (Haggard, Clark, et al., 2002). Participants saw a rotating clock hand, while they were asked to press a key that was followed by a first tone and a second tone (experimental conditions). In the baseline conditions, the key press was not followed by the tones (baseline action) or the first and second tones were presented without preceding action (baseline first and second tone). After the clock hand stopped, participants had to judge the position of the clock hand at action execution (experimental and baseline condition action), first, or second tone onset (experimental and baseline condition of first and second tone). Intentional binding (IB) was calculated as the difference between the mean estimate biases in experimental and baseline conditions for action, first, and second tone separately

followed by six experimental blocks (3 conditions × 2 consecutive blocks = 6 blocks) in which action, first, or second tone estimates were required in separate blocks (each with 20 trials). The experiment finished with further baseline blocks for action, first, and second tone, respectively (each with 20 trials). Both sessions started with six training blocks (each with 3 trials) for each of the three baseline, and each of the three experimental conditions, respectively. The order of action, first, or second tone estimate blocks was identical for each participant in training, baseline, and experimental blocks, but counterbalanced between participants (overall in both sessions together 480 trials + 36 training trails).

Data analysis

For each participant, the difference between estimated and actual positions of the clock hand for either action, first, or second tone was computed trial-wise and averaged separately for each condition (baseline vs. experimental, action vs. first tone vs. second tone). The angle differences were transformed into temporal differences (angle difference × 2560 ms/60). If the trial-wise differences deviated more than ± 2.5 *SD* from the participant's mean estimate in the respective condition, they were excluded (in total, 2.16% of all trials for Experiment 1 to Experiment 4 together; see Haering & Kiesel, 2014). IB was calculated as the difference between the mean shift of the perceived time in baseline and experimental conditions (separately for action vs. first tone vs. second tone). To compare IB of all three measures (action, first, and second tone), we computed the differences in the way that all three measures became positive. Therefore, results are reported as experimental minus baseline condition for action estimates and as baseline minus experimental condition for first and second tone estimates resulting in positive values for IB of all three measures. Thus, positive values for IB action mean that the action is perceived later, that is, shifted towards the tones, and positive values for IB of first and second tones mean that the tones are perceived earlier, that is, shifted towards the action.

Results

To assess whether IB was significant for action, first, and second tone, we conducted separate *t* tests to test whether the difference between mean baseline and mean experimental estimates (IB of action, first, and second tone, separately) was significantly different from zero. IB was significant for the first tone, $M = 57.58$, $SE = 6.18$, $t(23) = 9.31$, $p < .001$, marginally significant for the second tone, $M = 11.43$, $SE = 5.74$, $t(23) = 1.99$, $p = .058$, and not significant for the action, $M = 4.20$, $SE = 3.94$, $t(23) = 1.07$, $p > .250$ (see Appendix A).

A repeated-measures ANOVA (action vs. first tone vs. second tone) revealed that IB differed for action, first tone, and second tone, $F(2, 46) = 31.52$, $p < .001$, $\eta_p^2 = .58$. IB was significantly stronger for the first tone in comparison to the action, $t(23) = 7.04$, $M_{Diff} = 53.27$, $SE_{Diff} = 7.57$, $p < .001$, and the second tone, $t(23) = 6.90$, $M_{Diff} = 46.27$, $SE_{Diff} = 6.70$, $p < .001$, and there was no significant difference between IB of the second tone in comparison to the action, $t(23) = 0.93$, $M_{Diff} = 7.00$, $SE_{Diff} = 7.49$, $p > .250$ (see Fig. 2).

Experiment 2

In Experiment 1, the second of two effect tones showed less IB than the first tone. There might be, however, the possibility that two effects are perceived rather as one single effect sequence instead of being perceived as two effects caused by an action. Haggard, Aschersleben, et al. (2002) investigated time perception for stimulus sequences without a causing action and found temporal repulsion rather than attraction for two stimuli in a stimulus sequence. This means that the first of the two effect tones should have been perceived earlier, whereas the second effect would be expected to be perceived later than it actually occurred. Consequently, a potential perception of both effects in our first experiment as one effect sequence, rather than two effects caused by an action, might have led to a difference in IB of first and second tones. This might have been the reason why there was just marginal IB of the second effect tone.

In Experiment 1, the second tone followed the first tone predictably after 500 ms. However, Haggard, Clark, et al. (2002) showed IB to be less pronounced for effects that followed the action in a temporally unpredictable manner. Therefore, we investigated, in a second experiment, whether the second tone would be affected by IB if it followed the first tone with temporal unpredictability. However, the average duration of the variable delay in Experiment 2 matched the average duration of the constant one in Experiment 1 (500 ms). This unpredictable temporal delay between first and second effects in Experiment 2 makes it less likely that both effects are perceptually grouped into one stimulus sequence, and would thus render such an explanation as cause for different amounts of IB of first and second tones less plausible.

Method

Participants

Twenty-four participants (19 females, mean age = 20.25, *SD* = 2.25, range 18–27 years, 22 right-handed) were included as part of a course requirement.

Apparatus, stimuli, procedure, and data analysis

Apparatus, stimuli, procedure, and data analysis were similar to Experiment 1, except that the second tone followed the first tone with temporal unpredictability after 350 ms–650 ms (in steps of 50 ms: 350, 400, 450, 500, 550, 600, and 650 ms). The seven different delays of the second tone were presented in random order. Consequently, the second tone followed the first tone on average after 500 ms.

Results

To assess whether IB was significant for action, first, and second tone, we conducted separate *t* tests to test whether the difference between mean baseline and mean experimental estimates (IB of action, first, and second tone separately) was significantly different from zero. IB was significant for the first tone, $M = 44.12$, $SE = 12.41$, $t(23) = 3.55$, $p = .002$, marginally significant for the action, $M = 8.77$, $SE = 4.28$, $t(23) = 2.05$, $p = .052$, and not significant for the second tone, $M = 0.09$, $SE = 7.07$, $t(23) = 0.01$, $p > .250$ (see Appendix A).

A repeated-measures ANOVA (action vs. first tone vs. second tone) revealed that IB differed for action, first tone, and second tone, $F(2, 46) = 6.47$, $p = .003$, $\eta_p^2 = .22$. IB was significantly stronger for the first tone in comparison to the action, $t(23) = 2.96$, $M_{Diff} = 35.35$, $SE_{Diff} = 11.94$, $p = .007$, and the second tone, $t(23) = 2.69$, $M_{Diff} = 44.03$, $SE_{Diff} = 16.35$, $p = .013$, and there was no significant difference between IB of the second tone in comparison to the action, $t(23) = 0.89$, $M_{Diff} = 8.68$, $SE_{Diff} = 9.71$, $p > .250$ (see Fig. 2).

A repeated-measures ANOVA (action vs. first tone vs. second tone) with Experiment as between-subjects factor has been conducted to compare IB of action, first, and second tones of Experiment 1 and Experiment 2. It revealed no significant interaction of IB of action, first, and second tones and Experiment, $F(2, 92) = 0.88$, $p > .250$, $\eta_p^2 = .02$.

Experiment 3

In Experiment 2, the second tone followed the first tone unpredictably after 350 ms to 650 ms. However, the influence of temporal predictability on IB also depends on whether the delay range is small or large (Ruess et al., 2017). In that study, temporal predictability influenced IB for a large, but not for a small, delay range. Consequently, we conducted a third experiment with an extended delay range of the second tone (200 ms to 800 ms).

Method

Participants

Twenty-four participants (19 females, mean age = 20.33, *SD* = 2.26, range 18–29 years, 22 right-handed) were included as part of a course requirement.

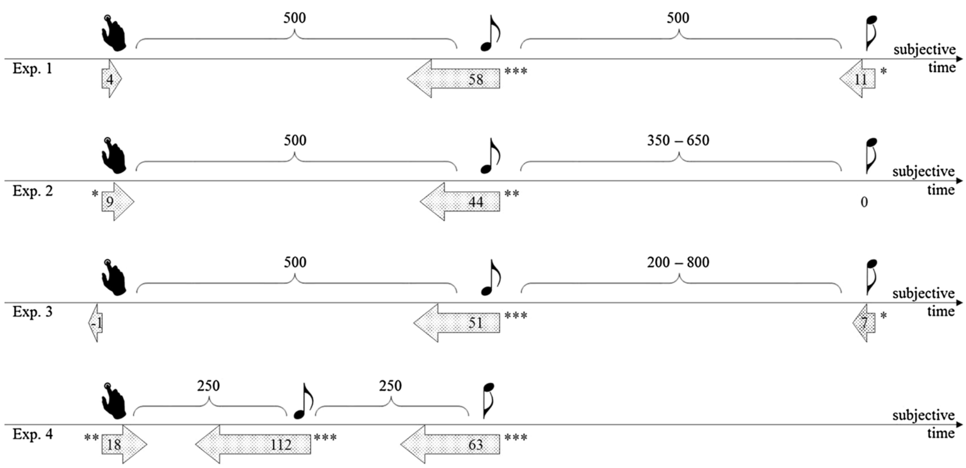

Fig. 2 Intentional binding (IB) in Experiment 1 to Experiment 4 of action, first, and second tone. The first tone followed the action and the second tone followed the first tone according to the indicated delays (depending on Experiment). IB is depicted as hatched arrows. All time indications are displayed in ms. *Asterisks* behind IB arrows indicate significant IB at significance level of $^{*}p < .10$, $^{**}p < .01$, and $^{***}p < .001$. Please note that IB of the action and tones is depicted with positive values (see Method)

Apparatus, stimuli, procedure, and data analysis

Apparatus, stimuli, procedure, and data analysis were similar to Experiment 1 and Experiment 2, except that the second tone followed the first tone with temporal unpredictability after 200 ms to 800 ms (in steps of 150 ms: 200, 350, 500, 650, and 800 ms). The five different delays of the second tone were presented equally often in random order. On average, comparable to Experiment 1 and Experiment 2, the second tone followed the first tone after 500 ms.

Results

To assess whether IB was significant for action, first, and second tone, we conducted separate *t* tests to test whether the difference between mean baseline and mean experimental estimates (IB of action, first, and second tone separately) was significantly different from zero. IB was significant for the first tone, $M = 50.94$, $SE = 10.86$, $t(23) = 4.69$, $p < .001$, marginally significant for the second tone, $M = 7.20$, $SE = 3.79$, $t(23) = 1.90$, $p = .070$, and not significant for the action, $M = -0.95$, $SE = 1.76$, $t(23) = 0.54$, $p > .250$ (see Appendix A).

A repeated-measures ANOVA (action vs. first tone vs. second tone) revealed that IB differed for action, first tone, and second tone, $F(2, 46) = 18.41$, $p < .001$, $\eta_p^2 = .45$. IB was significantly stronger for the first tone in comparison to the action, $t(23) = 4.76$, $M_{\text{Diff}} = 51.89$, $SE_{\text{Diff}} = 10.89$, $p < .001$, and the second tone, $t(23) = 4.10$, $M_{\text{Diff}} = 43.75$, $SE_{\text{Diff}} = 10.68$, $p < .001$, and there was no significant difference between IB of the second tone in comparison to the action, $t(23) = 1.77$, $M_{\text{Diff}} = 8.15$, $SE_{\text{Diff}} = 4.60$, $p = .090$ (see Fig. 2).

A repeated-measures ANOVA (action vs. first tone vs. second tone) with Experiment as between-subjects factor has been conducted to compare IB of action, first, and second tones of Experiment 2 and Experiment 3. It revealed no significant interaction of IB of action, first, and second tones and Experiment, $F(2, 92) = 0.73$, $p > .250$, $\eta_p^2 = .02$.[2]

Experiment 4

In Experiment 1 to Experiment 3, IB was stronger for the first of two tones that were triggered by action execution. Yet, different studies have shown that IB mainly depends on the delay of the effect (e.g., Haggard, Clark, et al., 2002; Humphreys & Buehner, 2009; Nolden et al., 2012; Ruess et al., 2017; Wen et al., 2015). Whereas Humphreys and Buehner (2009) used duration estimates as the measure for IB and showed IB up to effect delays of 4 s, Haggard, Clark, et al. (2002), however, employed the same classic clock procedure as we did and showed that IB decreases for longer effect delays. In Experiment 1 to Experiment 3, the first tone followed the action after 500 ms and the second tone followed the first tone after (on average) 500 ms and, thus, overall (on average) 1000 ms after action execution. Consequently, it is not clear whether the second of two tones that follows an action is less prone to IB. Rather, the results of Experiment 1 to Experiment 3 might alternatively

[2] Furthermore, a repeated-measures ANOVA (action vs. first tone vs. second tone) with Experiment as between-subjects factor has been conducted to compare IB of action, first, and second tones of Experiment 1 and Experiment 3. It revealed no significant interaction of IB of action, first, and second tones and Experiment, $F(2, 92) = 0.02$, $p > .250$, $\eta_p^2 = .00$.

be solely interpreted as a consequence of effect delay. To investigate IB of the second tone when it occurs earlier, we conducted a fourth Experiment. In this Experiment, the first tone was presented 250 ms after the action and the second tone 250 ms after the first tone. Thus, the second tone overall occurred temporally predictably 500 ms after action execution and, therefore, after the same delay as the first tone in Experiment 1 to Experiment 3.

Method

Participants

Twenty-four participants (18 females, mean age = 27.25, *SD* = 5.83, range 20–46 years, 20 right-handed) were included as part of a course requirement.

Apparatus, stimuli, procedure, and data analysis

Apparatus, stimuli, procedure, and data analysis were similar to Experiment 1, except that the first tone followed the action after 250 ms and the second tone followed the first tone with temporal predictability after another 250 ms. Consequently, comparable to the first tone of Experiment 1 to Experiment 3, the second tone followed the action predictably after 500 ms.

Results

To assess whether IB was significant for action, first, and second tone, we conducted separate *t* tests to test whether the difference between mean baseline and mean experimental estimates (IB of action, first, and second tone separately) was significantly different from zero. IB was significant for the first tone, $M = 112.14$, $SE = 18.72$, $t(23) = 5.99$, $p < .001$, the second tone, $M = 63.21$, $SE = 13.74$, $t(23) = 4.60$, $p < .001$, and the action, $M = 18.06$, $SE = 5.92$, $t(23) = 3.05$, $p = .006$ (see Appendix A).

A repeated-measures ANOVA (action vs. first tone vs. second tone) revealed that IB differed for action, first tone, and second tone, $F(2, 46) = 12.74$, $p < .001$, $\eta_p^2 = .36$. IB was significantly stronger for the first tone in comparison to the action, $t(23) = 4.27$, $M_{Diff} = 94.07$, $SE_{Diff} = 22.04$, $p < .001$, and the second tone, $t(23) = 2.98$, $M_{Diff} = 48.93$, $SE_{Diff} = 16.42$, $p = .007$, and IB was also significantly stronger for the second tone in comparison to the action, $t(23) = 2.67$, $M_{Diff} = 45.15$, $SE_{Diff} = 16.94$, $p = .014$ (see Fig. 2).

To investigate whether IB was significantly stronger in Experiment 4 with shorter delays compared to Experiment 1 to Experiment 3, a repeated-measures ANOVA (action vs. first tone vs. second tone) with Experiment as between-subjects factor has been conducted. It revealed a significant interaction of IB of action, first, and second tones and Experiment, $F(6, 184) = 2.35$, $p = .033$, $\eta_p^2 = .07$.

General discussion

The growing number of studies investigating IB (e.g., Fereday & Buehner, 2015; Haering & Kiesel, 2014; Haggard, Poonian, & Walsh, 2009; Moore et al., 2012; Obhi & Hall, 2011; Wolpe, Haggard, Siebner, & Rowe, 2013) shows that we perceive actions that cause effects later and the effects they cause earlier compared to actions that do not cause an effect or stimuli that are not caused by actions (Haggard, Aschersleben, et al., 2002). To the best of our knowledge, however, the previous studies have neglected the fact that our everyday actions usually produce not just one, but rather sequences of effects. No study has investigated so far whether a second effect would also be subject to IB, and whether the existence of a second effect influences the IB of the first effect, and for the action. Hence, to investigate IB in a context that more closely resembles everyday action contexts, we conducted four experiments where the action produced two consecutive effects.

In all four experiments (see Fig. 2), we observed stronger IB of the first tone than of the second tone and of the action. In addition, second tones were less bound to the action when they were temporally predictable (Experiment 1) as well as when they were temporally unpredictable (Experiment 2 and Experiment 3). Most interestingly, however, the reduction of the delays for the first (250 ms) and the second tone (500 ms; from now on, we refer to the delay of the second tone as its overall delay, i.e., from action execution till occurrence of the second tone), led to stronger IB of the action, the first, and the second tone (Experiment 4).

The finding that the action showed less IB compared to the effects, that is, the first (Experiment 1 to Experiment 4) and the second tone (Experiment 4), is a typical finding in IB research (Ruess et al., 2017). Therefore, we do not further consider IB of the action. However, more interestingly, concerning the difference in IB magnitude between two consecutive effect tones, it might be speculated that it was due to the existence of the first tone diminishing the IB magnitude for the second tone. This would mean that the second tone was less bound to the action, just because it was the second instead of the first tone in an effect sequence.

However, especially the results of Experiment 4 reveal that this interpretation might be considered too narrow. The strong IB not just for the first, but also for the second tone for shorter delays (first tone 250 ms, second tone 500 ms) is in line with the previous research using the clock method to investigate the influence of effect delay on IB (Haggard, Clark, et al., 2002). They showed more IB of tones occurring after shorter delays compared to tones after longer delays (employed delays: 250 ms vs. 450 ms vs. 650 ms). Accordingly, tones that followed the action after very long delays should show almost no IB. This is exactly what we found for the second tone in the initial three experiments where the second tone followed the action after (on average) 1000 ms. In addition, the—by definition later—second tone should always be less bound to the action than the earlier occurring first tone (in accordance with Experiment 1 to Experiment 4). Thus, the finding of less IB of the second compared to the first tone (Experiment 1 to Experiment 4) might alternatively be due to the longer delay of the inevitably later second tone.

This interpretation is further supported by the results of Experiment 4. The overall reduction of the delay between action and first (250 ms), and second tone (500 ms) led to a substantial increase of IB of both tones compared to IB in Experiments 1 to Experiment 3. Nevertheless, in line with its longer delay, the second tone showed less IB than the first tone. The delay of the first tone (250 ms) was in the range of delays (about 250 ms to 400 ms) which recently has been shown where IB becomes maximal (Ruess et al., 2017). Therefore, it is not surprising that we found stronger IB of the first tone compared to the second tone. In addition, it is remarkable that IB did not differ for tones occurring after a delay of 500 ms, independently of whether they were the first (Experiment 1 to Experiment 3) or the second tone (Experiment 4) in an effect sequence.[3] Thus, these results underpin the conclusion that second effects might be bound to the action; it is, however, important to consider their delay which is always longer than the delay of the first tone.

Further, another alternative explanation could be that the first tone might have been perceived not just as an effect of the action, but also as a cause of the second tone, whereas the second tone was just an effect, without causing a further effect. This might have been an alternative reason why different amounts of IB of first and second effects were found. However, this is not supported by our findings, because for one and the same delay (i.e., 500 ms), IB did not differ between a situation where it was the first of two effect tones (Experiment 1 to Experiment 3) and a situation where it was the second of two effect tones (Experiment 4)[3]. Another aspect of our results speaks against such an interpretation. A lack of temporal predictability of the second tone by the first tone (Experiment 2 and Experiment 3) should make it less plausible, that the first tone is perceived also as a cause for the second tone. We found, nevertheless, the same results pattern for second tones that were temporally unpredictable by first tones. This speaks for the conclusion, that the effect position in an effect sequence, where intermediate effects might be also perceived as causal for consecutive effects, is not decisive for the amount of IB.

In addition, the results rule out a possible alternative cause of the influence of effect delay on IB (Haggard, Clark, et al., 2002; Ruess et al., 2017). Please note that effect delay is confounded with the probability that several stimuli occur before a later effect rather than an early effect. One might, thus, assume that the probability of additional stimuli but not actual length of the effect delay determines the amount of IB. Our results clearly speak against this alternative interpretation of the influence of effect delay on IB. We observed IB independently of whether a further tone occurred in-between action and effect (second tone in Experiment 4) or not (first tone in Experiment 1 to Experiment 3)[3]. It rather was the delay of the effect (500 ms) that impacted on the magnitude of IB.

Consequently, our results show, for the first time, that also second tones can be bound to actions. However, they are less bound to actions than early occurring action–effects. However, instead of concluding that second effects are less bound to actions than first effects are bound to actions because of their position (first or second tone), rather effect delay seems to be a critical factor influencing IB. If the delay is also short for the second and, therefore, later occurring tone, also this tone can be strongly bound to the action.

Recently, it has been argued that the influence of effect delay on IB might depend on the employed method (e.g., Ruess et al., 2017). Whereas studies using duration estimates as the measure for IB showed increasingly IB up to effect delays of 4 s (Humphreys & Buehner, 2009), studies employing the same classic clock procedure as we did showed IB to decrease for longer effect delays (Haggard, Clark et al., 2002). This has been considered to be based on different time perception mechanisms targeted by both methods (Ruess et al., 2017). Consequently, it remains unclear how our results would have looked like, if duration estimates, instead of estimates using the clock method, would have been employed.

From another point of view, one might have expected even the reverse pattern of results. IB is often used as an implicit measure of sense of agency (Moore, Wegner, &

[3] IB did not differ significantly for first (Experiment 1 to Experiment 3) and second tones (Experiment 4) occurring after a delay of 500 ms, $F(3, 92) = 0.55$, $p > .250$.

Haggard, 2009). Recent studies showed stronger sense of agency for effects following the action after a delay that was continuously filled compared to a totally unfilled delay (Weller, Schwarz, Kunde, & Pfister, 2016). In our study, the delay between action and first effect could be interpreted as an unfilled delay, whereas the delay between action and second effect is filled in the sense that the first effect occured during that interval. Thus, based on this reasoning, one might have expected stronger IB of the second effect. A probably crucial difference between our investigation and the investigation by Weller et al. (2016) is, however, that the filled delay in our study was just filled by a short single tone and, thus, mainly unfilled. Yet, Weller et al. (2016) employed a continuously filled delay. Future investigations will have to clarify the exact differences of the influence of filled and unfilled delays and, more specifically, between continuously and non-continuously filled delays on both, IB and sense of agency.

A further interesting future extension of our investigation on effect sequences draws on our temporal predictability manipulation of the second effect in Experiment 2 and Experiment 3. It did not influence IB differently compared to the temporally predictable second effect in Experiment 1. However, how would the results of IB of first and second effect look like if the first instead of the second effect would be presented temporally unpredictably? Temporal predictability is said to be a cue for causality (e.g., Greville & Buehner, 2010, 2016). Would, thus, the temporal predictability of the second effect compared to the temporal unpredictability of the first effect compensate for the larger delay of the second effect? Similarly, an alternative situation might be considered, in which the action causes the first effect after a temporally unpredictable delay, whereas the second effect follows the first effect temporally predictably. Such a scenario would be possible in the ice machine example with the button press causing the start of the ice machine after a temporally unpredictable delay, whereas, as soon as the machine starts to produce the ice cubes, all the successive effects would follow each one after the other after temporally predictable delays. Future studies investigating IB of effect sequences might address the influence of different constellations of temporal predictability and unpredictability of action, first, and second effects on IB of all three events.

It is still debatable why IB occurs and the underlying mechanisms are not fully understood yet (e.g., Haering & Kiesel, 2014). According to actual, common accounts of human time perception, IB might be explained by a slowing of an internal clock after action execution that results in less perceived time that passed after action execution. Thus, action and effect are perceived as closer together in time. Wenke and Haggard (2009) investigated whether this slowing is constant or rather dynamic. They embedded two shock stimuli between action and effect and showed a lower temporal resolution in discrimination if they were presented early after action execution compared to later after action execution. Thus, they considered the dynamical approach to explain their results best: After action execution, the internal clock initially slows down followed by a compensatory but incomplete rebound acceleration. This leads to an initially strong biased time perception followed by a diminished biased time perception with more time that elapsed after action execution.

The results of Wenke and Haggard (2009) are completely in line with what we observed. Tones that occurred early after action execution showed more IB than later occurring tones (Experiment 1 to Experiment 4). If, however, the effect tones occurred too late, almost no IB was found for the second of two consecutive tones (Experiment 1 to Experiment 3). These results can be explained by the described general slowing of an internal clock directly after action execution and a diminishing of this clock slowing with elapsed time.

Moreover, our results offer first empirical indications that, probably, extensions of the ideomotor principle should be made (cf. Greenwald, 1970; Herbart, 1825; James, 2011; for more recent works see, e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; Pfister, Janczyk, & Kunde, 2013; Shin, Proctor, & Capaldi, 2010; Thomaschke, Hopkins, & Miall, 2012). According to this principle, IB is explained as action–effect learning and it is assumed that representations of actions and those of effects that follow these actions contingently are bi-directionally bound (e.g., Haering & Kiesel, 2014; Walsh & Haggard, 2013). Thus, if an effect followed an action contingently, this leads both to expectations of this effect after action execution, and, reversely, an anticipation of the effect activates the representation of the causing action itself. This bidirectional binding could be the reason why actions and their effects show IB in comparison to actions not bound to an effect or stimuli that previously have not been related to an action.

Recently, there have been speculations about an extension of this ideomotor principle (Dignath, Pfister, Eder, Kiesel, & Kunde, 2014; Haering & Kiesel, 2012; Hoffmann, Berner, et al., 2007; Hoffmann, Butz, Herbort, Kiesel, & Lenhard, 2007). These authors argued that action–effect relations might be more complex, integrating not just one single effect bound to the action, but, also further stimuli. For example, this could include situational cues offering information about contexts in which an action might lead successfully to a desired effect or not, or proprioceptive effects like muscle contraction that necessarily has to occur before culminating in the intended exteroceptive action–effect. These considerations might cautiously be interpreted in line with our findings: Not just one, but more effects that followed the action were bound to the causing action. Recent investigations showing IB to depend on the congruency of additional intermediate stimuli between the action and intended effect support these speculations (Caspar, Desantis, Dienes, Cleeremans, & Haggard, 2016). Consequently, our findings are in line with the assumption that we can bind sequences of effects to their causing actions in an ideomotor manner (see also Janczyk et al., 2017).

Overall, our results provide a first indication that IB occurs for more than one single action–effect. In situations similar to everyday action contexts, where our actions aim at producing sequences of effects, not just a first, but also a second action–effect can be subject to IB. However, the magnitude of IB seems not to be determined by its position in a sequence (i.e., first or second effects after the action), but instead, its absolute temporal distance from the action seems to be a critical factor influencing IB.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study. No animals were involved in any of the experiments.

Appendix A: mean baseline and experimental estimates and resultant intentional binding in experiment 1 to experiment 4

See Table 1.

Table 1 Results of Experiment 1 to Experiment 4: Mean estimated time points of action, first, and second tone in baseline and experimental conditions and resultant intentional binding (IB) of action, first, and second tone

	Baseline *M*	Experimental *M*	IB *M*
Experiment 1			
Action	6 (6)	10 (9)	4 (4)
Effect 1	50 (9)	−8 (9)	58 (6)
Effect 2	−27 (9)	−38 (10)	11 (6)
Experiment 2			
Action	49 (11)	58 (13)	9 (4)
Effect 1	80 (10)	36 (14)	44 (12)
Effect 2	30 (10)	29 (8)	0 (7)
Experiment 3			
Action	22 (10)	21 (10)	−1 (2)
Effect 1	58 (8)	7 (14)	51 (11)
Effect 2	42 (7)	35 (8)	7 (4)
Experiment 4			
Action	20 (11)	38 (13)	18 (6)
Effect 1	82 (16)	−30 (24)	112 (19)
Effect 2	41 (23)	−23 (28)	63 (14)

The delay between action and first tone and between action and second tone depended on Experiment. All numbers are displayed in ms. Please note that IB of the action and IB of the tones is displayed by positive values (see Method). Numbers in parentheses refer to the standard error

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