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The Time Course of Intentional Binding for Late Effects

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Abstract

Stimuli elicited by one's own actions (i.e., effects) are perceived as temporally earlier compared to stimuli not elicited by one's own actions. This phenomenon is referred to as intentional binding (IB), and is commonly used as an implicit measure of sense of agency. Typically, IB is investigated by employing the so-called clock paradigm, in which participants are instructed to press a key (i.e., perform an action), which is followed by a tone (i.e., an effect), while presented with a rotating clock hand. Participants are then asked to estimate the position of the clock hand at tone onset. This time point estimate is compared to a baseline estimate where the tone is presented without any preceding action. In the present study, we investigated IB for effects occurring after relatively long delay durations (500 ms, 650 ms, 800 ms), while manipulating the temporal predictability of the delay duration. We observed an increase of IB for longer delay durations, whereas the temporal predictability did not significantly influence the magnitude of IB. This extends previous findings obtained with the clock paradigm, which have shown an increase of IB for very short delay ranges (<250 ms), but a decrease for intermediate delay ranges up to delay durations of 650 ms. Our findings, thus, indicate rather complex temporal dynamics of IB that might look similar to a wave-shaped function.

Keywords

Intentional binding, temporal binding, effect delay duration, action–effect interval, temporal predictability, causality, clock method

1. The Time Course of Intentional Binding for Late Effects

We perceive the temporal occurrence of an effect that we have elicited by our action earlier, compared to the temporal occurrence of a stimulus we did not cause by our action (Haggard *et al.*, 2002a; for a review see Moore and Obhi, 2012). There is an increasing number of studies investigating this temporal bias which is typically referred to as temporal, or intentional binding (IB; e.g., Haggard *et al.*, 2002b). As this temporal bias occurs selectively for effects we caused in an intentional

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manner by our actions (e.g., Haggard *et al.*, 2002b, 2009), it is employed as an implicit measure for sense of agency in many studies (e.g., Moore, 2016; Moore *et al.*, 2009; Ruess *et al.*, 2017a). However, some previous studies (e.g., Buehner, 2012, 2015; Buehner and Humphreys, 2009; Dewey and Knoblich, 2014) called that view into question. For example, in a study by Buehner (2015) he observed IB not only with voluntary actions, but also with passively induced causing actions.

An important factor affecting the magnitude of IB is the duration of the effect's delay, that is, the time elapsed between action (e.g., key press) and corresponding effect (e.g., tone). Indeed, in a considerable number of studies (e.g., Cravo *et al.*, 2011; Haggard *et al.*, 2002b; Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Ruess *et al.*, 2017b, in press; Wen *et al.*, 2015) it was investigated whether and how the delay duration of an effect impacts the sense of agency, assessed by IB for said effect. Yet, results are diverging, resulting in an ongoing debate on how the duration of the effect's delay influences IB.

Several studies have investigated the influence of delay duration on IB by employing the so-called clock paradigm (Haggard *et al.*, 2002b; Ruess *et al.*, 2017b, in press). In these studies, the participants press a key (i.e., action) that causes a tone (i.e., effect), while watching a rotating clock hand. Afterwards, participants are asked to estimate the position of the clock hand at the moment they perceived the tone. This time point estimate is compared to a time point estimate from a condition where the tone is presented without any causing action. In this clock paradigm, IB is considered present when the point estimate of the tone caused by the action is estimated earlier than the point estimate of a tone not caused by an action. Employing this classic version of the clock paradigm with delay durations of 250 ms, 450 ms, and 650 ms, Haggard *et al.* (2002b) observed a decrease of IB for longer delay durations compared to shorter delay durations. Ruess *et al.* (2017b) found a similar decrease for delay durations from about 250 ms to 400 ms, however, they observed an initial increase of IB for very short delay durations between about 100 ms to 250 ms, using the classic clock paradigm.

A common alternative measure of IB employs a delay duration measure (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012). In these studies, delay durations have to be estimated in an active and in a passive condition. In the active condition, participants press a key that causes an effect and they are asked to estimate the duration of the delay between action and effect, instead of the time point of the effect. In the passive condition, a delay between a passive stimulation and an effect of this stimulation is asked to be estimated. These studies interpret IB as an underestimation of the delay duration in the active compared to the passive condition (i.e., shorter delay duration estimate for the active compared to the passive condition). Employing this alternative IB measure and using delay durations ranging from 100 ms up to 1000 ms, an increase of IB for longer compared to shorter delay durations has been observed. Yet, IBs concerning different short delay durations (<500 ms) did not differ from each other (Wen *et al.*, 2015). In fact, the most prominent study by Humphreys and Buehner (2009) employed different ranges of delay durations (ranging from 0 ms up to 4000 ms) and observed IB to increase up to delay durations of 4000 ms, yet, failed to report single contrast analyses.

In summary, results on the influence of delay duration on IB are markedly divergent depending on whether IB is measured as time point estimate (e.g., Haggard *et al.*, 2002b; Ruess *et al.*, 2017b) or as delay duration estimate (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Wen *et al.*, 2015). Whereas studies employing time point estimates observed IB to decrease for longer delay durations, studies using delay duration estimates observed IB to increase for longer delay durations.

This could be a result of the employed measures of IB (i.e., time point estimates vs. delay duration estimates). Alternatively, the observed diverging results could be due to different ranges of delay durations employed in the studies using the two methods. The studies investigating the influence of delay duration on IB measured as time point estimates employed delay durations only up to 650 ms (Haggard *et al.*, 2002; Ruess *et al.*, 2017b), whereas the studies investigating the influence of delay duration on IB measured as delay duration estimates employed delay durations up to 4000 ms (Humphreys and Buehner, 2009). Thus, in order to systematically examine the possible explanations for diverging findings, we employed the so-called clock paradigm and investigated how different long delay durations influence IB if measured as time point estimates. This helps to clarify, whether the decrease of IB so far observed for longer delay durations (i.e., up to delay durations of maximal 450 ms and 650 ms; Haggard *et al.*, 2002b) if measured as time point estimates holds true also for different long delay durations (500 ms, 650 ms, and 800 ms).

If IB, measured as time point estimate, would decrease for different long delay durations (500 ms, 650 ms, and 800 ms), this would be a first hint that the method to assess IB, that is, time point estimates in contrast to duration estimates, determines whether IB decreases or increases with long delay durations. If, however, IB measured as time point estimates would increase for the employed long delay durations (500 ms, 650 ms, and 800 ms), the observed diverging results between time point estimates and delay duration estimates (e.g., Haggard *et al.*, 2002b; Humphreys and Buehner, 2009) would be restricted to rather intermediate delay durations (between about 250 ms up to 450 ms). Thus, the impact of delay duration on IB would depend on the specific range of delay duration. In the present study, we aim to disentangle these explanations.

There is an additionally important component that needs to be considered when investigating the influence of delay duration on IB measured as time point estimates with the clock paradigm: the temporal predictability of the effect, that is, whether the effect follows the causing action always after the same, temporally predictable delay, or after different, temporally unpredictable delays. IB has been shown to be generally weaker for temporally unpredictable in comparison to temporally predictable effects (Haggard *et al.*, 2002b). Importantly, however, this influence of temporal predictability interacted with the duration of the effect's delay in the sense that the decrease of IB for longer delay durations was more pronounced for temporally predictable in comparison to temporally unpredictable effects (Haggard *et al.*, 2002b; Ruess *et al.*, 2017b). Yet, this interaction of delay duration and temporal predictability was only found for a large range of temporal unpredictability. More precisely, the decrease of IB for temporally predictable compared to unpredictable effects was more pronounced only if the temporally unpredictable effect delays varied within a large range (i.e., +/− 150 ms), but not if the temporally unpredictable effect delays varied within a small range (i.e., +/− 50 ms) around the delay duration of the temporally predictable effect (Ruess *et al.*, 2017b).

Consequently, to investigate the influence of different long delay durations on the magnitude of IB, we presented three different delay durations (500 ms, 650 ms, and 800 ms). Thus, comparable to the study by Ruess *et al.* (2017b), the employed three delay durations varied within a large range (650 ms +/− 150 ms). We assessed IB in two separate sessions. In one session, the three delay durations were presented in temporally predictable manner, that is, each of them (500 ms, 650 ms, and 800 ms) was presented in a separate block. In the other session, delay durations were temporally unpredictable, that is, all three delay durations were presented randomly intermixed within a block.

It has to be noted that IB measured with the clock paradigm is, additionally to the earlier time point estimate of an effect stimulus that was elicited by an action (i.e., effect IB), indicated by a second component. This second component refers to the temporal perception of the action, that is, the time point estimate of an action that elicited an effect is estimated later compared to the time point estimate of an action that did not elicit an effect (i.e., action IB; Haggard *et al.*, 2002a). This action IB is, however, less pronounced than the effect IB (e.g., Ruess *et al.*, 2017b). Nevertheless, there are first investigations of whether the duration of the effect's delay influences action IB with somewhat intermixed results (Ruess *et al.*, 2017b). Thus, we also considered the action IB.

2. Method

The experiment consisted of experimental conditions in which participants pressed a key (i.e., the action) to produce an effect tone and of baseline conditions in which only an action was required or only the tone was presented. In all trials, participants saw a clock with a rotating clock hand. In the experimental conditions, participants were asked to press — at freely chosen points in time — one of two possible response keys which contingently produced one of two possible effect tones (e.g., Barlas and Obhi, 2013; Barlas *et al.*, 2017a, b). The tones occurred after a delay duration of either 500 ms, 650 ms, or 800 ms and these delay durations varied either block-wise or trial-wise, so that the delay duration of an effect was either temporally predictable (varying block-wise, i.e., the same delay duration within each block) or temporally unpredictable (varying trial-wise, i.e., all three delay durations within each block). In some blocks, participants were asked to estimate the clock hand's position at the moment when they had pressed the response key (i.e., action experimental). In other blocks, they were asked to estimate the hand's position when they heard the effect tone (i.e., effect experimental). In the baseline conditions, only an action was required, without a following tone (action baseline), or the tone occurred without preceding action (effect baseline) and participants were asked to estimate the respective points in time by indicating the clock hand's position. IB was computed as the difference between experimental conditions (action/ effect) compared to the respective baseline conditions (action/ effect; cf. Haggard *et al.*, 2002b).

2.1. Participants

Based on effect sizes in previous studies (Haering and Kiesel, 2012), 48 participants (25 females; mean age = 25, SD = 4.31, range 19–39 years; 44 right-handed) were tested and received 15 Euros or course credit for compensation.

2.2. Apparatus and Stimuli

The experiment was run using the E-Prime 2.0 software (Schneider *et al.*, 2012) and it was presented on a standard PC with a 20" LCD screen (1600 pixels × 1200 pixels, 60 Hz refresh rate). For the action, two separate response keys were operated with the index and middle finger of the left hand. Please note, that we decided to employ two action alternatives (and two action-contingent effect tones) similar to the study by Ruess *et al.* (2017b), whereas Haggard *et al.* (2002b) employed only one action alternative (and one single effect tone). Stronger IB in conditions with multiple action alternatives compared to only one action has been reported in previous studies (e.g., Barlas and Obhi, 2013; Barlas *et al.*, 2017a, b). As, so far, a decrease of IB for longer delay durations has been observed with the clock paradigm (Haggard *et al.*, 2002b), we decided to increase the probability of observing IB by employing two action alternatives. For the effects, two sinusoidal tones (400 Hz or 800 Hz) were presented by Auna Base DJ 10014216 headphones for 150 ms. Tones were mapped to response keys in a SMARC compatible manner (Mudd, 1963), thus, left key to 400 Hz, and right key to 800 Hz. As reference for participants' time point estimates, the Libet Clock (Libet *et al.*, 1983; Wundt, 1887; see Fig. 1) was employed. It involves the visual display of an analogue clock with 12 marked 'five minute' intervals and a clock hand revolving over the dial at a continuous pace (centrally presented with diameter 6.3 cm, clock hand 2.2 cm, 2560 ms/full rotation). Participants entered time point estimates with their right hand using the number pad of the standard computer keyboard (1–9) and the next trial started when participants confirmed the time point estimate using the enter key.

2.3. Procedure

The experiment was conducted in two separate sessions on two different days: in one session, the three effect delay durations varied between blocks (temporally predictable effects), whereas the three delay durations varied within blocks in the other session (temporally unpredictable effects). The order of sessions was counterbalanced across participants and each session lasted about one hour.

2.3.1. Trial Procedure

We employed the clock paradigm (Haggard *et al.*, 2002b): At trial start, the clock was presented on the screen and the clock hand immediately started to rotate at a random position. Participants were asked to press one of the two response keys at a freely chosen point in time, but to wait until the clock hand had revolved at least once. Further, they were instructed not to press at a pre-planned point in time or clock position, to randomly choose which of the two keys to press, while trying to press both keys roughly equally often. In the experimental conditions, the action (i.e., key press) was followed by the effect, a tone, after a delay duration of either 500 ms, 650 ms, or 800 ms. In the action

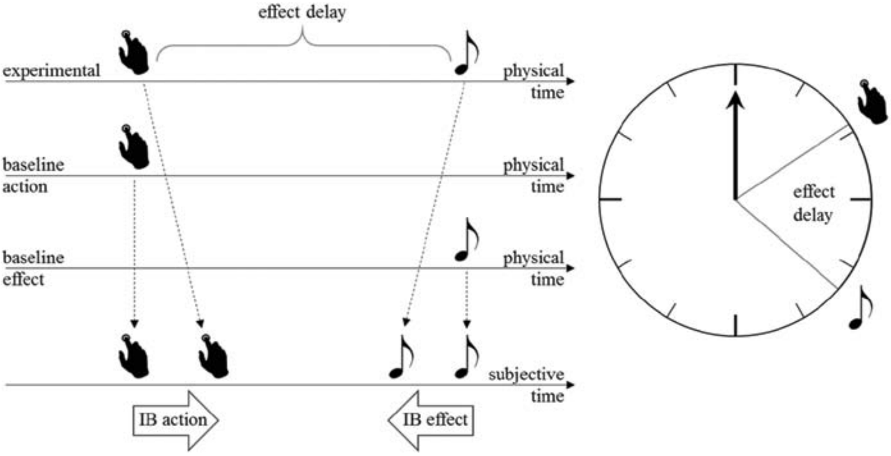

Figure 1. Clock paradigm (Haggard *et al.*, 2002b). Participants saw a clock with a rotating clock hand. In experimental conditions, they were asked to press a key that was followed by a tone. In the action baseline condition, the key press was not followed by the tone, and, in the effect baseline condition, the tone was presented without any preceding action. After a random additional 2 s to 3 s of rotation, the clock hand stopped and participants were asked to estimate the position of the clock hand at the moment they pressed the key (action experimental and action baseline conditions) or at tone onset (effect experimental and effect baseline conditions). Intentional binding (IB) was calculated as the difference between mean estimate in experimental and baseline conditions, separately for action and effect estimates.

baseline condition, no tone followed after action execution, whereas in the effect baseline condition, no action was required and one of the two tones was presented randomly 2560 ms to 5120 ms after the clock hand rotation had started. In all conditions, the clock disappeared randomly 2000 ms to 3000 ms after the tone (or the action execution in the action baseline condition) had occurred. In the action experimental and action baseline conditions, participants were asked to estimate the position of the clock hand at the moment they had pressed the key. Comparably, in the effect experimental and effect baseline conditions, participants were asked to estimate the position of the clock hand at tone onset (in minutes 1–60; e.g., 6 if they perceived the clock hand to have been at the bottom of the clock face at the moment they heard the tone onset).

2.3.2. Block Procedure

Each session started with three training trials for each of all four conditions, that is, action baseline, effect baseline, action experimental, and effect experimental. The training trials were followed by one action baseline block (i.e., key press not followed by tone) and one effect baseline block (i.e., tone without preceding key press), and by six experimental blocks in which time point estimates for action and effect alternated block-wise. Another action baseline block and one effect baseline block followed. The order of whether action or effect estimates were required first was counterbalanced across participants (in both, the baseline and experimental condition blocks). Each baseline block consisted of 21 trials (21 trials * 2 blocks = 42 trials) and each experimental block consisted of 42 trials (unpredictable session: 14 trials per delay duration * 3 blocks = 42 trials per delay duration overall per session). The three delay durations (i.e., 500 ms, 650 ms, and 800 ms) were presented randomly in the experimental blocks of the temporally unpredictable session. In the temporally predictable session, the same delay duration was presented in two consecutive experimental blocks (i.e., one block with action estimation and one block with effect estimation) and the order of the delay durations was counterbalanced across participants.

2.4. Data Analysis

For IB analyses of the effect estimation conditions, we discarded the data of two participants, and for IB analyses of the action estimation conditions, we discarded the data of seven participants, due to misunderstanding of the instructions in some of the blocks (estimation of action instead of effect, or vice versa, for a similar procedure, see also Ruess *et al.*, 2017b).

First, for each participant, the differences between estimated and actual positions of the clock hand were computed trial-wise and these angle differences were transformed into temporal differences (angle difference * 2560 ms/60). The temporal differences were then averaged separately for each condition (baseline vs. experimental condition, action vs. effect condition, predictable vs. unpredictable session, delay duration 500 ms, 650 ms, or 800 ms). If the trial-wise temporal differences deviated more than +/− 2.5 SD from the participant's mean temporal difference in the respective condition, this trial was discarded (on average 2.73% for each participant; for a similar screening procedure, see Haering and Kiesel, 2014). Finally, IB was calculated as the difference between mean temporal differences in the baseline compared to experimental conditions (separately for action vs. effect condition, predictable vs. unpredictable session, and delay duration 500 ms, 650 ms, or 800 ms). The differences were computed in such a way that both measures, that is, effect IB and action IB, had positive values if IB occurred. Therefore, results are reported as experimental minus baseline condition values for action estimates and as baseline minus experimental condition values for effect estimates. Thus, positive values for action IB mean a bias of the action toward the effect, that is, the action was perceived later if it was followed by an effect compared to if it was not followed by an effect. Positive values for effect IB mean a bias of the effect toward the action, that is, the effect was perceived earlier if it was elicited by a preceding action compared to if it was not elicited by an action. Greenhouse–Geisser-corrected statistics are reported, where appropriate.

3. Results

3.1. Effect IB

To assess whether effect IB was significant for each respective condition, we conducted separate Bonferroni-corrected *t*-tests (corrected $\alpha = 0.0083$). For predictable conditions, IB did not significantly differ from zero for the delay duration of 500 ms: $t(45) = 1.92$, $M = 15.62$, $SE = 8.14$, $p = 0.061$; but it significantly differed from zero for delay durations of 650 ms: $t(45) = 3.11$, $M = 21.23$, $SE = 6.84$, $p = 0.003$; and of 800 ms: $t(45) = 4.50$, $M = 33.95$, $SE = 7.55$, $p < 0.001$. For unpredictable conditions, IB did not significantly differ from zero for the delay durations of 500 ms: $t(45) = 0.53$, $M = 3.19$, $SE = 5.98$, $p > 0.250$; and of 650 ms: $t(45) = 2.60$, $M = 18.95$, $SE = 7.30$, $p = 0.013$; but it significantly differed from zero for the delay duration of 800 ms: $t(45) = 3.29$, $M = 24.57$, $SE = 7.47$, $p = 0.002$ (see Appendix).

A within-subjects 3 × 2 ANOVA (delay duration and predictability) revealed that IB increased for longer delay durations, $F(2, 90) = 8.43$, $p < 0.001$, $\eta^2_p = 0.16$; 500 ms: $M = 9.40$, $SE = 5.51$; 650 ms: $M = 20.09$, $SE = 5.82$; 800 ms: $M = 29.26$, $SE = 6.19$. The temporal predictability conditions did not differ significantly,

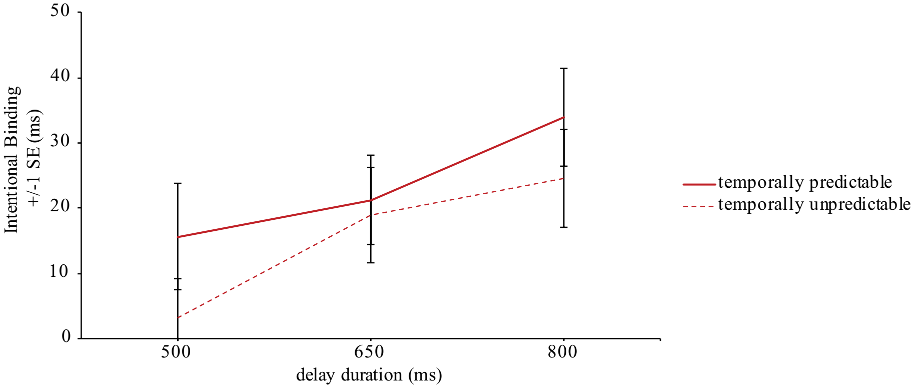

Figure 2. Intentional binding (IB) of the effect depending on effect delay duration (x-axis) and temporal predictability of the effect (separate lines) with delay durations of 500 ms, 650 ms, and 800 ms. IB of the effect is depicted on the y-axis (positive values, see Method). Error bars represent standard errors.

$F(1, 45) = 1.35$, $p > 0.250$, $\eta^2_p = 0.03$; predictable: $M = 23.60$, $SE = 5.99$; unpredictable: $M = 15.57$, $SE = 6.39$, and there was no significant interaction of delay duration × predictability, $F(2, 90) = 0.72$, $p > 0.250$, $\eta^2_p = 0.02$ (see Fig. 2). The main effect for delay duration was followed up by Bonferroni-corrected pairwise comparisons.

IB differed significantly between the delay durations of 500 ms and 800 ms, $M_{\text{Diff(500 vs. 800 ms)}} = 19.86$, $SE_{\text{Diff(500 vs. 800 ms)}} = 5.32$, $p = 0.002$, marginally between delay durations of 650 ms and 800 ms, $M_{\text{Diff(650 vs. 800 ms)}} = 9.17$, $SE_{\text{Diff(650 vs. 800 ms)}} = 4.10$, $p = 0.092$, and it did not differ between the delay durations of 500 ms and 650 ms, $M_{\text{Diff(500 vs. 650 ms)}} = 10.69$, $SE_{\text{Diff(500 vs. 650 ms)}} = 5.02$, $p = 0.116$. The effect IB in the present study did not differ for both key press alternatives (and, consequently, the two action contingent effect tones; see Note 1). Yet, the procedural differences to use two action alternatives (in the present experiment and in the Ruess *et al.*, 2017b, study) in comparison to one action alternative (in the Haggard *et al.*, 2002b, study) may have also contributed to the divergent results visible in Fig. 4 below (see Discussion).

3.2. *Action IB*

To assess whether the action IB was significant for each respective condition, we conducted separate Bonferroni-corrected t-tests (corrected $\alpha = 0.0083$). For predictable conditions, IB did not differ from zero for the delay durations of 500 ms: $t(41) = 1.84$, $M = 19.60$, $SE = 10.63$, $p = 0.073$; of 650 ms: $t(41) = 2.39$, $M = 38.56$, $SE = 16.13$, $p = 0.022$; and of 800 ms: $t(41) = 2.44$, $M = 40.10$, $SE = 16.46$, $p = 0.019$. For unpredictable conditions, IB significantly differed from zero for delay durations of 500 ms: $t(41) = 3.41$, $M = 27.77$, $SE = 8.16$, $p = 0.002$; and of 650 ms:

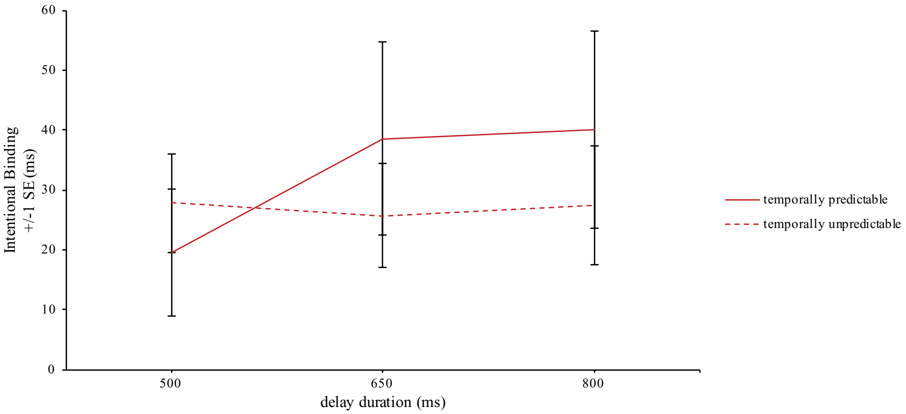

Figure 3. Intentional binding (IB) of the action depending on the effect delay duration (*x*-axis) and the temporal predictability of the effect (separate lines) with delay durations of 500 ms, 650 ms, and 800 ms. IB of the action is depicted on the *y*-axis (positive values, see Method). Error bars represent standard errors.

$t(41) = 2.98$, $M = 25.72$, $SE = 8.63$, $p = 0.005$; while it did not differ significantly from zero for the delay duration of 800 ms: $t(41) = 2.75$, $M = 27.45$, $SE = 9.99$, $p = 0.009$ (see Appendix).

In a within-subjects 3 × 2 ANOVA (delay duration and predictability) there was no significant main effect of the delay duration, $F(2, 80) = 0.96$, $p > 0.250$, $\eta^2_p = 0.02$; 500 ms: $M = 23.68$, $SE = 8.21$; 650 ms: $M = 32.14$, $SE = 10.29$; 800 ms: $M = 33.77$, $SE = 10.91$, no significant main effect of the predictability conditions, $F(1, 40) = 0.27$, $p > 0.250$, $\eta^2_p = 0.01$; predictable: $M = 32.75$, $SE = 12.04$; unpredictable: $M = 26.98$, $SE = 8.45$, and no significant interaction of delay duration × predictability, $F(2, 80) = 1.29$, $p > 0.250$, $\eta^2_p = 0.03$ (see Fig. 3). The action IB was stronger for the left compared to the right key press, that is, the action IB was stronger for the middle finger compared to the index finger key press of the left hand (Note 2). Probably, it is more effortful to use the middle compared to the index finger. Whereas results concerning an influence of effort onto the magnitude of IB are intermixed (e.g., Demanet *et al.*, 2013; Howard *et al.*, 2016), a study investigating explicit sense of agency (Damen *et al.*, 2014) observed stronger sense of agency ratings for the non-dominant compared to the dominant hand use. Thus, the influence of effort and different actions on the magnitude of action IB needs future investigations.

4. Discussion

In the present study, we employed the clock paradigm to investigate effect IB, that is, the temporal occurrence of an effect stimulus is perceived earlier if the stimulus was elicited by an action compared to if the stimulus was not elicited by an action (Haggard *et al.*, 2002a). For action–effect delay durations ranging from 500 ms to 800 ms, the effect IB increased with delay duration. There was no influence of the temporal predictability of the effect on the magnitude of IB. Additionally, the action IB, that is, the temporal occurrence of an action is perceived later if the action elicited an effect compared to if the action did not elicit an effect, was neither influenced by delay duration nor by temporal predictability of the effect.

The finding that the effect IB increases for longer delay durations is in line with results of studies investigating IB with delay duration measures. These studies (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Wen *et al.*, 2015) observed an increase of IB for longer delay durations up to delay duration ranges of 4000 ms. While the longest investigated delay duration in the present study was only 800 ms, our results, like results obtained with delay duration measures, nevertheless point into the same direction: the mechanisms contributing to IB might result in generally stronger IB for longer delay durations independently of the employed measure of IB (our time point measure vs. delay duration measure).

In previous studies (e.g., Humphreys and Buehner, 2009), the increase of IB for longer delay durations, if measured as delay duration estimates, has been interpreted in terms of the pacemaker account of human time perception. According to this account, humans have an inner pacemaker that exerts pulses in a certain frequency and the duration of an event is interpreted by accumulating the pulses exerted during event occurrence. Thus, the pacemaker account explains IB by a slowing of the speed of the inner pacemaker after action execution, resulting in less pulses exerted after an action and, thus, less pulses being accumulated between action and effect. This reduced amount of summed pulses following an action compared to a passive stimulation is assumed to be the reason for the underestimation of the delay between an action and its effect in comparison to a physically identically delay between a passive stimulation and an effect. Further, this reduced amount of summed pulses after action execution compared to the amount of summed pulses after a passive stimulation necessarily increases cumulatively the longer the delay between action and effect. Thus, the pacemaker account explains the stronger IB for longer delay durations compared to shorter delay durations by a slowing of the speed of the inner pacemaker.

Yet, this explanation of an increase of IB for longer delay durations if measured as delay duration estimates cannot explain our results. When assessing IB with the time point measure, necessarily a shift of the effect has to occur, whereas a potential slowing of the inner clock would not be able to explain this perceived shift of the effect. Consequently, it is still an open question how to explain our results of stronger IB for later effects measured with time point estimates.

Whereas the observed increase of IB for longer delay durations seems to be in line with previous results found with delay duration measures (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Wen *et al.*, 2015), it is unexpected given previous results obtained by studies investigating the influence of delay duration on IB using the clock paradigm. These studies observed a decrease of IB for longer delay durations (Haggard *et al.*, 2002b; Ruess *et al.*, 2017b). Yet, in these previous studies the longest employed delay durations were of 450 ms and 650 ms (Haggard *et al.*, 2002b). We, however, assessed IB for an even longer delay duration of 800 ms and, importantly, found an increase only between the delay duration of 400 ms and 800 ms, and a marginal increase between the delay duration of 650 ms and 800 ms. Additionally, Haggard *et al.* (2002b), employing the clock paradigm with delay durations of 250 ms, 450 ms, and 650 ms, reported no single contrast analyses. Thus, it is not clear, whether the decrease of IB for longer delay durations was driven mainly by the shorter delay durations (250 ms vs. 450 ms) or whether it was also present between the longer delay durations (450 ms vs. 650 ms).

It has to be noted that the clock paradigm was employed in another study with longer delay durations of 250 ms, 500 ms, and 1000 ms (Ruess *et al.*, in press) and reported a decrease of IB for longer delay durations. Thus, in that study the longest delay duration (1000 ms) was even longer than the longest delay duration in our present study (800 ms). Yet, in that study, the experimental setting was quite different compared to our present study, because in each trial two effect stimuli occurred (either after 250 and 500 ms, or after 500 and 1000 ms). We conjecture that the results of almost no IB for effects after a delay duration of 1000 ms in that study might be due to the intermediate effect occurring before the effect after 1000 ms was presented instead of due to the influence of the long delay duration on IB.

Taken together, our results indicate, for the first time, that for specific long delay duration ranges there might be an increase of IB with delay duration if measured as time point estimates of the effect. One possible explanation might be that IB measured as time point estimate is extremely time-sensitive, depending on the specific delay duration. Such a time-sensitive, dynamic approach might explain an integrative conception of the seemingly contrasting results for delay duration's modulation of IB (see Fig. 4): When combining the results of several studies investigating the impact of delay duration on IB, an increase of IB with delay duration for very short delay durations has been observed (Ruess *et al.*, 2017b). This might, eventually, prevent a violation of the order principle of action and effect. Because, if IB would get increasingly stronger for shorter delay durations, effects just above 0 ms after the action would have to be experienced as occurring prior to the action. The initial increase of IB is then followed by a decrease of IB up to effect delay duration ranges of about 650 ms (Haggard *et al.*, 2002b). Thereafter, our findings indicate a second increase of IB for longer delay durations (> about 650 ms), suggesting a cyclic pattern of IB magnitude. Thus, overall, such a pattern would look like a wave-shaped function. Such a dynamical approach for explaining the influence of delay duration on IB measured as time point estimates awaits explicit

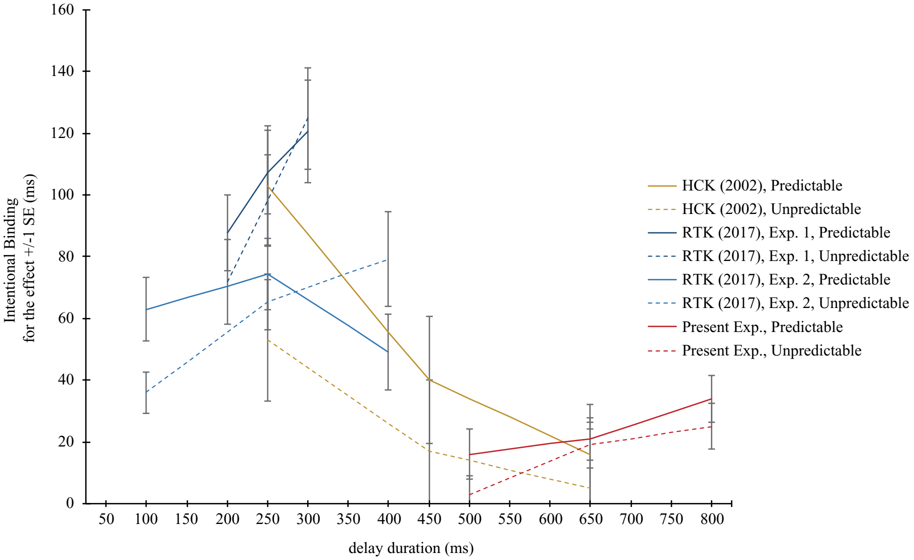

Figure 4. Intentional Binding (IB) depending on the effect delay duration (x-axis) and temporal predictability of the effect (separate lines). IB of the effect is depicted on the y-axis with positive values (see Method). Error bars represent standard errors. The integrative depiction includes all studies investigating the influence of delay duration on time point measures of IB by employing the so-called clock paradigm: Haggard *et al.*, 2002b; with delay durations of 250 ms, 450 ms, and 650 ms (depicted in yellow); Ruess *et al.*, 2017b; with delay durations of 200 ms, 250 ms, and 450 ms (Experiment 1; depicted in light blue) and delay durations of 100 ms, 250 ms, and 650 ms (Experiment 2; depicted in dark blue), and the present experiment, with delay durations of 500 ms, 650 ms, and 800 ms (depicted in red).

future investigation. A more fine-tuned investigation where delay durations from 100 ms up to 850 ms or even longer delay durations in one single within-subjects experiment is, for sure, necessary in order to confirm the so far speculative wave-shaped influence of the delay duration on the magnitude of IB.

Additionally, time point estimates investigated for effects after short effect delay durations may rely more on sensory processes, whereas duration estimates, and eventually also our investigated time point estimates for effects after long delay durations, may rather be based on inferential processes (e.g., Humphreys and Buehner, 2009). This could explain why our present results are in line with the results obtained with delay duration measures (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Wen *et al.*, 2015), but are in contradiction to previous results obtained with time point measures (Haggard *et al.*, 2002b; Ruess *et al.*, 2017b). Taken together, such an explanation would imply that processes underlying the observed IB obtained with time point estimates change from sensory processes to more inferential processes if more time elapses between an action and its elicited effect (i.e., for longer delay durations).

With regard to the temporal predictability manipulation, we did not observe any influence on IB in the present study (see Fig. 4). Some previous studies, on the contrary, found that IB was strongly influenced by the context of presentation (e.g., Jazayeri and Shadlen, 2010). Yet, taken together these seemingly contradicting findings of Fig. 4 suggest an interesting pattern: in each single experiment different ranges of delay duration have been employed. More precisely, in the present study the delay range was +/− 150 ms (i.e., 500 ms, 650 ms, and 800 ms). In Experiment 1 of Ruess *et al.* (2017b), the employed delay range was +/− 50 ms (i.e., 200 ms, 250 ms, 300 ms). These delay ranges are comparably small. In fact, both experiments did not find any influence of the context of presentation, that is, whether the delay durations were presented temporally predictably or temporally unpredictably. In addition, in both experiments an increase of the magnitude of IB for longer delay durations was observed.

On the contrary, in Experiment 2 of Ruess *et al.* (2017b), the employed delay range was +/− 150 ms (i.e., 100 ms, 250 ms, and 400 ms) and likewise in the study of Haggard *et al.* (2002b) the employed delay range was +/− 200 ms (i.e., 250 ms, 450 ms, and 650 ms). Thus, in these two last experiments the delay range was relatively large in comparison to the overall delay durations. In both experiments an influence of the temporal predictability manipulation has been observed (i.e., an interaction delay duration × temporal predictability in Experiment 2 of Ruess *et al.* 2017b, and an additional main effect of delay duration in the study of Haggard *et al.*, 2002b). Interestingly, these two latter studies found no increase of the magnitude of IB with delay duration, but a turning from an increase to a decrease (Ruess *et al.*, 2017b) or a monotonous decrease (Haggard *et al.*, 2002b) of the magnitude of IB for longer delay durations.

Thus, overall, this patter suggests that the context of presentation is only important in the case that the delay range is relatively large. Indeed, so far, we cannot be sure to what degree it may also be the magnitude of the delay range that influences whether IB increases (i.e., for smaller delay ranges) or decreases (i.e., for larger delay ranges) for longer delay durations.

For reasons of completeness, we assessed action IB. Yet, as this measure was neither influenced by the delay duration nor by the temporal predictability of the delay duration, it is possible that the action IB is, in the investigated range of delay durations, neither influenced by the delay duration nor by the temporal predictability of the effect. However, given that in a previous study some influence of delay duration on IB was observed (Ruess *et al.*, 2017b), more research is required to investigate a potential influence of the delay duration on action IB depending on different ranges of delay duration.

Such investigations may be especially relevant concerning a comparison of the influence of delay duration on different measurement methods of IB. Whereas delay duration measures (e.g., Humphreys and Buehner, 2009) may be due to both, a shift of the action and a shift of the effect, the time point measures (e.g., Haggard *et al.*, 2002b) separates a potential shift of the action in terms of an action IB and a potential shift of the effect in terms of effect IB. Thus, when comparing the influence of the delay duration on delay duration measures compared to time point measures, both the action IB and effect IB of the time point measure need to be considered. Nevertheless, our non-significant results of any influence of the delay duration on action IB rule out an alternative explanation. Namely that the delay duration measure revealed an increase of IB for longer delay durations (e.g., Humphreys and Buehner, 2009; Nolden *et al.*, 2012; Wen *et al.*, 2015) that would be reflected by a relatively larger increase of the absolute action IB compared to the effect IB.

Further, we conjecture it interesting that the action IB was not influenced by the delay duration, whereas the effect IB increased for longer delay durations. These findings are in line with some studies suggesting distinct underlying mechanisms that may contribute to the action IB and to the effect IB, concluding to investigate both measures separately (Wolpe *et al.*, 2013).

Overall, our results are a first indication that IB might increase for longer delay durations when measured as time point estimates by employing the clock paradigm. This is a fist hint that the relationship of delay duration and IB is more complex than has been previously assumed. Future investigation is needed to clarify, under which circumstances IB reaches its maximum for certain delay durations, how this differs for time point in comparison to delay duration measures of IB, and, what underlying mechanisms might contribute to these findings.

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Raw data are available at Open Science: https://osf.io/a2xtj/

Notes

1. A repeated measures ANOVA of the effect IB with the factors chosen action (i.e., left vs. right key press, means contingent low resp. high pitch tone), delay duration, and temporal predictability has been conducted to investigate whether the chosen action influenced the IB magnitude. Yet, neither the main effect of chosen action, left key press, $M = 18.46$, $SE = 5.24$; and right key press, $M = 20.81$, $SE = 5.39$; $F(1, 44) = 1.33$, $p > 0.250$, $\eta^2_p = 0.029$; nor the interaction of chosen action × delay duration, $F(2, 88) = 0.58$, $p > 0.250$, $\eta^2_p = 0.013$, nor the interaction of chosen action × temporal predictability, $F(1, 44) = 0.29$, $p > 0.250$, $\eta^2_p = 0.007$, nor the three-way interaction chosen action × delay duration × temporal predictability, $F(2, 88) = 0.94$, $p > 0.250$, $\eta^2_p = 0.021$, were significant.

2. A repeated measures ANOVA of the action IB with the factors chosen action (i.e., left vs. right key press, means contingent low resp. high pitch tone), delay duration, and temporal predictability has been conducted to investigate whether the chosen action influenced the action IB magnitude. There was a significantly stronger action IB for the left, $M = 32.80$, $SE = 8.70$, compared to the right $M = 25.83$, $SE = 9.16$, key press, $F(1, 40) = 11.65$, $p < 0.001$, $\eta^2_p = 0.226$. Yet, neither the interaction of chosen action × delay duration, $F(2, 80) = 1.65$, $p = 0.199$, $\eta^2_p = 0.040$, nor the interaction of chosen action × temporal predictability, $F(1, 40) = 0.30$, $p > 0.250$, $\eta^2_p = 0.007$, nor the three-way interaction chosen action × delay duration × temporal predictability, $F(2, 80) = 0.47$, $p > 0.250$, $\eta^2_p = 0.012$, were significant.

References

Barlas, Z. and Obhi, S. S. (2013). Freedom, choice, and the sense of agency, *Front. Hum. Neurosci.* **7**, 514. doi: 10.3389/fnhum.2013.00514.

Barlas, Z., Hockley, W. E. and Obhi, S. S. (2017a). Effects of free choice and outcome valence on the sense of agency: Evidence from measures of intentional binding and feelings of control, *Exp. Brain Res*. **2017**. doi: 10.1007/s00221-017-5112-3.

Barlas, Z., Hockley, W. E. and Obhi, S. S. (2017b). The effects of freedom of choice in action selection on perceived mental effort and the sense of agency, *Acta Psychol.* **180**, 122–129.

Buehner, M. J. (2012). Understanding the past, predicting the future: Causation, not intentional action, is the root of temporal binding, *Psychol. Sci.* **23**, 1490–1497.

Buehner, M. J. (2015). Awareness of voluntary and involuntary causal actions and their outcomes, *Psychol. Conscious.* (*Wash. D C*) **2**, 237–252.

Buehner, M. J. and Humphreys, G. R. (2009). Causal binding of actions to their effects, *Psychol. Sci.* **20**, 1221–1228.

Cravo, A. M., Claessens, P. M. E. and Baldo, M. V. C. (2011). The relation between action, predictability and temporal contiguity in temporal binding, *Acta Psychol.* **136**, 157–166.

Damen, T. G. E., Dijksterhuis, A. and van Baaren, R. B. (2014). On the other hand: Nondominant hand use increases sense of agency, *Soc. Psychol. Personal. Sci.* **5**, 680–683.

Demanet, J., Muhle-Karbe, P. S., Lynn, M. T., Blotenberg, I. and Brass, M. (2013). Power to the will: How exerting physical effort boosts the sense of agency, *Cognition* **129**, 574–578.

Dewey, J. A. and Knoblich, G. (2014). Do implicit and explicit measures of the sense of agency measure the same thing? *PLoS One* **9**, e110118. http://doi.org/10.1371/journal.pone.0110118.

Haering, C. and Kiesel, A. (2012). Mine is earlier than yours: Causal beliefs influence the perceived time of action effects, *Front. Psychol.* **3**, 393.

Haering, C. and Kiesel, A. (2014). Intentional binding is independent of the validity of the action effect's identity, *Acta Psychol.* 109–119.

Haggard, P., Aschersleben, G., Gehrke, J. and Prinz, W. (2002a). Action, binding, and awareness, in: *Common Mechanisms in Perception and Action: Attention and Performance*, W. Prinz and B. Hommel (Eds), pp. 266–285. Oxford University Press, Oxford, UK.

Haggard, P., Clark, S. and Kalogeras, J. (2002b). Voluntary action and conscious awareness, *Nat. Neurosci.* **5**, 382–385.

Haggard, P., Poonian, S. K. and Walsh, E. (2009). Representing the consequences of intentionally inhibited actions, *Brain Res.* **1286**, 106–113.

Howard, E. E., Edwards, S. G. and Bayliss, A. P. (2016). Physical and mental effort disrupts the implicit sense of agency, *Cognition* **157**, 114–125.

Humphreys, G. R. and Buehner, M. J. (2009). Magnitude estimation reveals temporal binding at super-second intervals, *J. Exp. Psychol. Hum. Percept. Perform.* **35**, 1542–1549.

Jazayeri, M. and Shadlen, M. N. (2010). Temporal context calibrates interval timing, *Nat. Neurosci.* **13**, 1020–1026.

Libet, B., Gleason, C. A., Wright, E. W. and Pearl, D. K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (readiness potential). The unconscious initiation of a freely voluntary act, *Brain* **106**, 623–642.

Moore, J. W. (2016). What is the sense of agency and why does it matter, *Front. Psychol.* **7**, 1272. http://doi.org/10.3389/fpsyg.2016.01272.

Moore, J. W. and Obhi, S. S. (2012). Intentional binding and the sense of agency: A review, *Consc. Cogn.* **21**, 546–561.

Moore, J. W., Wegner, D. M. and Haggard, P. (2009). Modulating the sense of agency with external cues, *Consc. Cogn.* **18**, 1056–1064.

Mudd, S. A. (1963). Spatial stereotypes of four dimensions of pure tone, *J. Exp. Psychol.* **66**, 347–352.

Nolden, S., Haering, C. and Kiesel, A. (2012). Assessing intentional binding with the method of constant stimuli, *Consc. Cogn.* **21**, 1176–1185.

Ruess, M., Thomaschke, R. and Kiesel, A. (2017a). Earlier effects are more often perceived as one's own action effects, *Timing Time Percept.* **5**, 228–243.

Ruess, M., Thomaschke, R. and Kiesel, A. (2017b). The time course of intentional binding, *Atten. Percept. Psychophys.* **79**, 1123–1131.

Ruess, M., Thomaschke, R., Haering, C., Wenke, D. and Kiesel, A. (in press). Intentional binding of two effects, *Psychol. Res.* 1–11. doi: 10.1007/s00426-017-0892-4.

Schneider, W., Eschmann, A. and Zuccolotto, A. (2012). *E-Prime User's Guide*. Psychology Software Tools, Inc., Pittsburgh, PA, USA.

Wen, W., Yamashita, A. and Asama, H. (2015). The sense of agency during continuous action: Performance is more important than action-feedback association, *PLoS One* **10**, e0125226. doi: 10.1371/journal.pone.0125226.

Wolpe, N., Haggard, P., Siebner, H. R. and Rowe, J. B. (2013). Cue integration and the perception of action in intentional binding, *Exp. Brain Res.* **229**, 467–474.

Wundt, W. (1887). *Grundzüge der physiologischen Psychologie*, 3rd ed. Wilhelm Engelman, Leipzig, Germany.

Appendix: Mean Baseline and Experimental Estimates and Resultant Intentional Binding

Table A.

Mean estimated time points (relative to true event time) in baseline (BL) and experimental (main) conditions and resultant intentional binding (IB).

		Delay Duration	BL *M*	Main *M*	IB *M*
IB Effect	Temporally Predictable				
			35 (9.11)		
		500 ms	/	19 (11.79)	16 (8.14)
		650 ms	/	14 (9.44)	21 (6.84)
		800 ms	/	1 (8.86)	34 (7.55)
	Temporally Unpredictable				
			38 (9.05)		
		500 ms	/	35 (10.70)	3 (5.98)
		650 ms	/	19 (10.81)	19 (7.30)
		800 ms	/	14 (10.67)	25 (7.47)
IB Action	Temporally Predictable				
			7 (12.46)		
		500 ms	/	27 (15.53)	20 (10.63)
		650 ms	/	46 (20.04)	39 (16.13)
		800 ms	/	48 (20.50)	40 (16.46)
	Temporally Unpredictable				
			18 (10.76)		
		500 ms	/	46 (14.35)	28 (8.16)
		650 ms	/	44 (14.70)	26 (8.63)
		800 ms	/	46 (14.53)	27 (9.99)

Note. Three different delay durations between action and effect were employed, that is, 500 ms, 650 ms, and 800 ms. All numbers are displayed in ms. Please note that IB of the effect is displayed by positive values (see Method). Numbers in parentheses behind the mean estimates refer to the standard error.