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Intentional Binding Is Unrelated to Action Intention

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The present study examined the role of voluntary motor commands in the subjective temporal attraction between an action and its sensory consequence termed as *intentional binding*. Participants either pressed a key voluntarily or involuntarily while seeing a rotating clock hand. The key press was followed by a short beep tone in some blocks of trials. Then, the position of the clock hand at action or tone occurrence was judged. Trials in which key presses and tones occurred separately provided baseline measures. A direct comparison of baseline uncorrected estimates between both action conditions indicated less binding for involuntary than for voluntary movements as reported by previous studies. However, this effect disappeared after a baseline correction and when we controlled for the temporal predictability of critical events. These results cast substantial doubts on a close link between action intention and intentional binding, but instead highlight the role of causal inference and multisensory integration processes.

Public Significance Statement
In contrast to previous research, this study suggests that the subjective temporal attraction between an action and its sensory effect previously termed as intentional binding is not related to the intentionality of the actor.

Keywords: action and perception, intentional binding, temporal binding

The delay between a voluntary action and its sensory consequence is perceptually compressed: The perceived time of the action shifts toward its sensory effect, whereas the perceived time of the effect shifts toward the time of the action (Haggard, Clark, & Kalogeras, 2002). The origin of this temporal attraction, or binding, is supposed to be related to action intention as it is either not observed or diminished with involuntary actions (Borhani, Beck, & Haggard, 2017; Caspar, Cleeremans, & Haggard, 2015; Engbert, Wohlschläger, & Haggard, 2008; Engbert, Wohlschläger, Thomas, & Haggard, 2007; Haggard et al., 2002; Moore, Wegner, & Haggard, 2009; Nolden, Haering, & Kiesel, 2012; Tsakiris & Haggard, 2003; Wohlschläger, Engbert, & Haggard, 2003). Accordingly, the phenomenon has been termed *intentional binding* and has been used as an implicit marker of the sense of agency (e.g., Haggard, 2017).

Notwithstanding this definition and the proposed link to agency, we believe that there is no unequivocal evidence for the contribution of voluntary motor commands, a key component of action intention and agency, to intentional binding (cf. also Buehner, 2012; Hughes, Desantis, & Waszak, 2013). This conclusion is based on a close assessment of the studies that compared voluntary with involuntary actions, which reveals a number of confounding variables. In particular, in most studies the onsets of involuntary actions were unpredictable for the participants, because they were unpredictably induced manually, mechanically, or electromagnetically by the experimenter. By contrast, participants could well predict the onsets of (their own) voluntary actions. Accordingly, the often observed decrease in binding in involuntary compared with voluntary actions might be caused by differences in temporal prediction rather than in action intention (cf. e.g., Pariyadath & Eagleman, 2007).

Two previous studies controlled for the predictability of the action onset for involuntary movements by using a constant time interval between the start of the trial and the onset of action (Nolden et al., 2012) or by presenting a warning cue (Exp. 3 in Engbert et al., 2007). The former study did not find differences in binding between the voluntary and involuntary conditions for a short action effect interval of 250 ms, which is often used in intentional binding studies, although it did find an effect for a longer interval (600 ms). The latter study, in contrast, reported stronger binding effects for voluntary as compared with involuntary actions using short action effect intervals (200, 250, and 300 ms).

These studies should be considered with caution, however, because of another methodical issue. The authors focused on estimates of action-effect intervals, rather than on estimates of time

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points of individual events. This opens the possibility that participants based the estimate of intervals on different event cues in the voluntary condition (e.g., time of key press) as compared with the involuntary condition (e.g., onset of finger movement). Note that such a difference in the use of event cues would not pertain to the supposed temporal compression between an action and its sensory consequence. For example, the observed decrease in perceived interval duration for the voluntary as compared with the involuntary actions would arise because voluntary actions are perceived as occurring later than involuntary actions whether or not a sensory effect follows (cf. Wohlschläger, Haggard, Gesierich, & Prinz, 2003). Thus, it is possible that the reported effects reflect differences in binding of involuntary versus voluntary actions with their effects. But estimates in the voluntary and involuntary conditions may have differed as well because participants based their estimates on different events. The necessary baseline conditions to control for such confounding variables were missing. The same argument can be applied to other studies as well where conditions including voluntary movements were directly compared with conditions including involuntary movements (Caspar et al., 2015; Engbert et al., 2008; Moore et al., 2009).

Another critical issue concerns the role of causality in intentional binding. As noted by Buehner (2012), many studies "have confounded intentionality and causality" (p. 1491). The core argument here is that two events, such as a key press and a tone, are subjectively compressed in time basically because the former is considered as the cause of the latter. This argument is based on studies indicating temporal binding for causally linked events even when action intention was controlled for or when it was not involved (Buehner, 2012; Buehner & Humphreys, 2009). Buehner and Humphreys (2009), for example, examined two conditions, in which voluntary actions were followed by an external sensory event. The specific experimental setup causally linked actions to the sensory event in one condition, but not in another condition. In the former condition, the perceived times of actions and sensory events shifted to each other as compared with the latter condition, suggesting that binding depends on the assumed causal relation of action and effect. Accordingly, differences in binding between voluntary and involuntary actions can result from differences in participants' belief about the causal relation between the critical events, rather than from differences in intention. For example, with voluntary action one event (e.g., the keypress) can be construed as the cause of the other event (e.g., the tone), whereas in involuntary action one event (keypress) is, under certain conditions, not construed as the cause for another event (tone), but both events are construed as being independent from one another (Buehner, 2012, 2015). This could explain the reported decrease in binding for the involuntary as compared to the voluntary condition.

It has also been suggested that binding is a consequence of the statistically optimal integration of multimodal cues, that is of information about action and its sensory outcome, and of prior expectations about their relation (Moore & Fletcher, 2012; Moore & Haggard, 2008; Wolpe, Haggard, Siebner, & Rowe, 2013). This idea has been derived from established models of human perception (e.g., Ernst, 2006; Landy, Maloney, Johnston, & Young, 1995) and adapted to the temporal perception of actions and their effects. Crucially, internal motoric cues such as efference copy might be one such cue which is also integrated with subsequent events (e.g., Moore, Wegner, & Haggard, 2009). However, this specific claim is empirically not well supported as we argue in this article. Moreover, multisensory integration can in principle occur for various sensory events, such as tactile and auditory effects of a keypress, and it is therefore not reliant upon efferent motoric cues. Thus, although this approach provides a promising theoretical framework to explain and to model intentional binding and related phenomena, the issue on the role of efferent signals remains an empirical endeavor.

It is worth noting that the assumed cue integration rests on causal inference as well, though in a different way than proposed by the causal interpretation of binding. Multimodal signals are assumed to be integrated to the extent that observers consider them to originate from the same object or event and they are segregated to the extent observers consider them to be caused by independent objects or events (e.g., Deroy, Spence, & Noppeney, 2016; Ernst, 2006; Rohde, van Dam, & Ernst, 2016). This basic assumption implies that binding (i.e., crossmodal integration) should occur as long as two signals, such as tactile feedback from a key press and auditory stimulation, are believed to be different aspects of a single event. This is a small but theoretically important difference to the strict causal perspective. The causal perspective assumes that binding occurs when a preceding sensory signal is perceived as the cause for the subsequent sensory signal (Buehner, 2012; Buehner, 2015), whereas the multisensory approach suggests that two signals are integrated more likely if they are supposed to belong to a common object or event, and thus to jointly originate from that same object or event.

To recap, several studies on intentional binding have indicated a close relation of this phenomenon to the human motor system in general and to action intention in particular (*motor approach* hereafter). However, direct evidence for this claim is lacking insofar as previous comparisons of voluntary and involuntary actions either suffered from a lack of appropriate baseline conditions or did not control for confounding factors such as for the higher temporal predictability of voluntary actions compared to involuntary actions. Moreover, binding was observed for causally linked sensorimotor events even though action intention was held constant or not involved at all. These results were used to suggest that binding is attributable to principles of causation rather than to intentional action (*causal approach* hereafter). Another approach is based on the idea that intentional binding results from the integration of redundant sensory cues that relate to a common event (*cue integration approach* hereafter). Although internal motoric signals have been suggested to enter the assumed integration process by some researchers, this approach does not require the assumption of any efferent cues (i.e., voluntary motor command, intention, efference copy etc.) to explain temporal attraction, so as the original motor approach does. Also, it does not require the assumption of a direct causal link of a preceding event to a subsequent event, so as the causal approach does.

Given this inconclusive state of affairs the primary goal of the present study was to reappraise the role of intentionality in intentional binding. In particular, we were interested in whether voluntary and involuntary actions differ with respect to the magnitude of intentional binding. Importantly, in extending previous research we tried to equalize voluntary and involuntary movements with respect to possible confounding variables as far as possible by using appropriate baseline conditions and by controlling for temporal prediction.

While seeing a rotating clock hand participants either voluntarily pressed a key or experienced involuntary key presses which were followed by a tone in the experimental (or "operant") blocks of trials. Then, they judged the position of the clock hand at action or tone occurrence. These judgments were compared with judgments collected in baseline blocks where key presses and tones were separately presented. In one session, neither the time-point of the involuntary key press nor the time-point of the tone in the baseline blocks was predictable. This session resembles experimental situations which have often been used in previous studies (e.g., Haggard et al., 2002). In another session, we introduced a warning cue that made the events in all conditions predictable.

If action intention is in fact critical for the binding effect to occur as the motor approach suggests, then we should observe a binding effect for the voluntary but not for the involuntary key presses, or the effect should at least be reduced for involuntary as compared with voluntary movements. Moreover, the same pattern should be observed irrespective of the predictability of events (i.e., of session). If, however, an action intention is not critical, as predicted by the cue integration framework, binding of a comparable magnitude should be observed for both voluntary and involuntary key presses, at least if a possible impact of temporal prediction is held constant. According to the strict causal perspective both outcomes are possible depending on what participants believe about the causal structure of the critical events. If the involuntary key press and the tone are considered as being independent from one another rather than to be a sequence of a cause and its effect, no or less binding should occur in the involuntary as compared with the voluntary condition. In contrast, if the key press, be it voluntary or involuntary, is assumed to cause the tone, then binding should occur for both the voluntary and the involuntary conditions.

Method

Participants

Forty participants participated in the study. The sample included 30 females and 10 males ($M_{age} = 25$, $SD = 5$). Thirty-six participants reported to be right-handed, three left-handed, and one ambidextrous. The participants gave their written informed consent for the procedures and received monetary compensation or course credit for their participation. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision. The sample size was determined a priori based on prior research and ensured a power of $1 - \beta = 0.95$ for effect sizes of $d_z = 0.593$ (as estimated from Experiment 1 in Engbert et al., 2008; cf. also Borhani et al., 2017, who used the same sample size).

The study was conducted in accordance with German Psychological Society (DGPs) ethical guidelines (2004, CIII) which do not require Institutional Review Board approval for the experiments reported in this article.

Apparatus

The study was performed in a dim experimental room. Stimuli were displayed on a CRT monitor (19″ Samsung Samtron 96 B, Samsung), with a resolution of 1280 × 1024 pixels and a refresh rate of approximately 75 Hz. Observers were seated at a distance of 65 cm from the screen with their head supported by a combined chin-and-forehead rest. The middle of the monitor was slightly above the participants' eye level. Participants' dominant hand was below a cover plate and was thus not visible. Participants' index finger of the dominant hand was tied to a key-device by means of a string. When an electric motor integrated in the device was turned on, it pulled the string and consequently the participant's finger down until the button was pressed. The key could also be easily pressed by moving the index finger actively. The key displacement was about 1.5 mm. Acoustic signals were presented via sound absorbing headphones (Vic Firth SIH1). One critical event was a short beep tone (1000 Hz, 50 ms). We also presented white noise to reduce a possible impact of noise from the key-device (from trial beginning until time estimation). Time estimates were done by pressing the arrow keys and the enter key on a keyboard using the nondominant hand.[1]

Stimuli and General Trial Procedure

The main stimulus was a clock presented on a gray background and consisting of a central cross (line length 2 mm), a clock hand (11 mm), a circle (30 mm in diameter) subdivided in 12 parts by strips (2 mm), and digits between "5" and "60" (2 mm). The clock hand was black, red, or green. The rest of the clock except for the cross was always black. The clock face and the central cross were presented throughout the trial (see Figure 1). The general trial procedure started with a central cross presented in yellow for 400 ms. Then it was turned from yellow to black, the clock hand appeared and began to rotate with a period of 2560 ms. The initial position of the clock hand was random. Following the critical events which are described below, the clock hand continued to rotate for 1000, 1500, or 2000 ms. After a delay period of 1000 ms, the clock hand reappeared in the color green. Pressing the right and the left arrow keys on a keyboard caused the clockwise and the anticlockwise movement of the clock hand. The task was to adjust the clock time to the time of the critical event (i.e., to place the clock hand at the position at which a critical event occurred). The initial start position of the clock hand randomly varied between 45° and 60° in the clockwise and anticlockwise direction with respect to the real time of the event. The judgment was confirmed by pressing the enter key of the keyboard. Then, the clock hand disappeared and following 100 ms the next trial began.

Design

Each participant took part on two separate experimental sessions on two different days. Each session included seven experimental blocks which were completed in a random order (see Table 1). In the operant blocks, a key press was always followed 250 ms later by a short beep tone. The key was either pressed voluntary by the participant (Block Type A and B), or it was pulled down by the electric motor (Block Type C and D). The task was to judge either the time point of the key press (B, D) or of the tone (A, C). In the baseline blocks, the critical events (i.e., key presses and tones) did not occur together. That is, key presses were not followed by a

[1] The ambidextrous participant used the right index finger for the button-device and the left hand for the judgments.

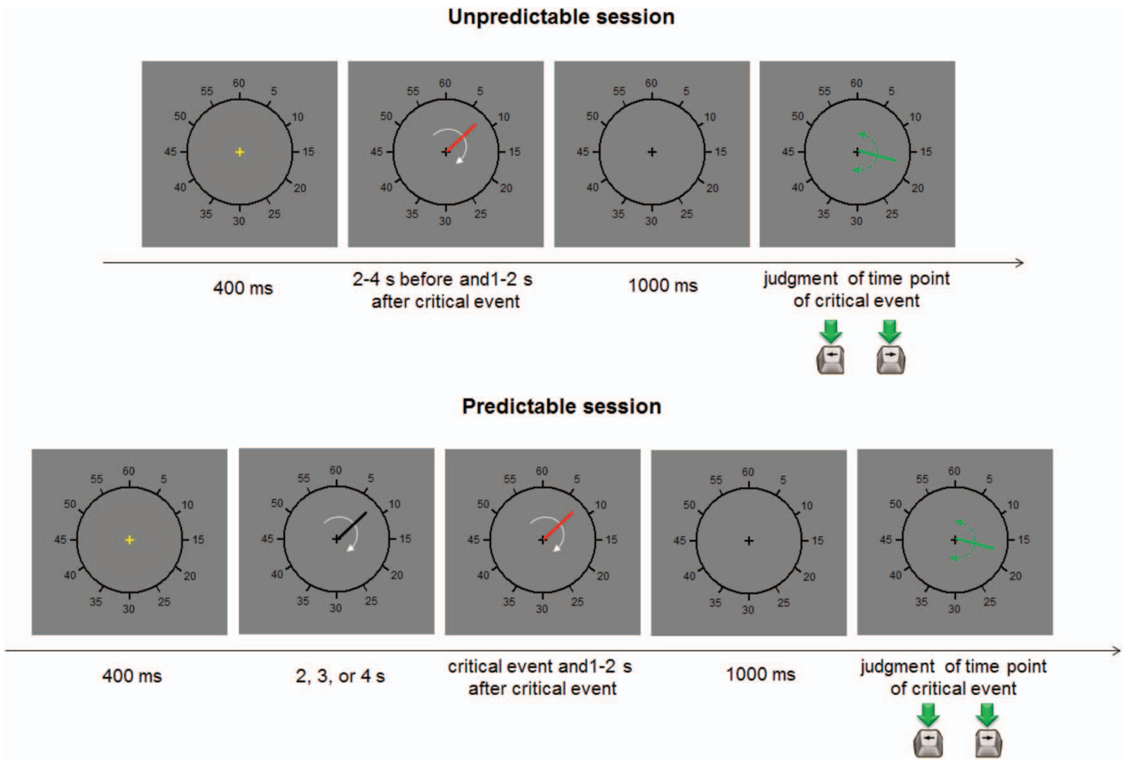

Figure 1. Main trial events of the present study. The critical event was either a key press or a short beep tone. The key press was followed by the tone in the operant blocks. In the baseline blocks, the key press and the tone occurred in isolation. In the unpredictable session, the critical events occurred without temporal cue. In the predictable session, the critical events were cued by a color change of the clock hand. See the online article for the color version of this figure.

tone (E, F) and the tone was not preceded by a key press (G). Each block included 36 Trials.

The two sessions differed slightly with respect to the trial structure. The main difference was related to the predictability of the critical events. In the unpredictable session, the trial structure was largely based on the usual procedure of previous studies. That is, in blocks with involuntary key presses (C, D, F) and with single tones (G), these critical events were not predictable. In particular, after an interval that randomly varied between 2000 and 4000 ms in respect to the start of clock hand rotation the key was pulled down or the tone was presented. In case of voluntary key presses, participants were instructed to respond at a time of their choice within four seconds after the clock hand started moving, not to respond during the first rotation, and not to press at a preplanned clock position.

Table 1
Critical and Judged Events in Each Block of Each Experimental Session

Block type	Critical event(s)	Judgment type
Operant blocks		
A	Voluntary key press, tone	Tone
B	Voluntary key press, tone	Key press
C	Involuntary key press, tone	Tone
D	Involuntary key press, tone	Key press
Baseline blocks		
E	Voluntary key press, no tone	Key press
F	Involuntary key press, no tone	Key press
G	No key press, tone	Tone

In the predictable session, all critical events were predictable. This was achieved by a color change of the clock hand that served as a temporal cue indicating a forthcoming event. In particular, following a randomly chosen interval of 2000, 3000, or 4000 ms after the clock hand started rotation it turned from black to red. In response to this signal, participants either had to press the key in the voluntary blocks or they experienced the key being pulled down in the involuntary blocks. The time of the involuntary key press was approximately adjusted to the expected RTs in the voluntary blocks (i.e., it was set to 350 ms in respect to the color change). The tone was presented either 250 ms following the key press (operant blocks) or 600 ms (i.e., 250 ms + 350 ms) following the color change in the tone baseline block (G).

Participants received error feedback and the trial was immediately repeated when (a) the initial start position of the clock hand was not changed by the participant during the judgment procedure, (b) no key press was registered within 100 ms after the finger was pulled by the motor (i.e., when participants did not keep their finger relaxed), (c) the key was not voluntarily pressed within 4 seconds after the clock started moving (unpredictable session) or within 500 ms after the imperative signal (predictable session), or (d) the key was pressed before the imperative signal occurred (predictable session).

Each session started with seven practice blocks which were identical to the experimental blocks except that only five trials per block were presented. The data from these blocks were not analyzed.

Data Analysis

A temporal estimation error was computed for each trial by subtracting the angle of the clock hand at which the critical event occurred from the angle adjusted by the participant. Then, median estimation errors were computed for each participant and each block and converted into time values (in ms). Finally, baseline corrected errors were computed by subtracting the values of the baseline blocks from the values of the corresponding operant blocks. Positive errors reflect overestimation, negative errors indicate underestimation. The raw data have been made publicly available (https://osf.io/8y6h3/).

Visual inspection of the data indicated that three participants obviously did not follow the task instructions. Two of them seemed to consistently adjust the clock hand to a certain angle in at least one session. Another participant did not change the initial start position of the clock hand substantially across the most of the blocks in one session. The data of these participants were not included in the analyses.

Results

Baseline Corrected Estimation Errors

Figure 2 shows baseline corrected estimation errors as a function of the type of key press (voluntary, involuntary) and of predictability manipulation (i.e., of session type). Intentional binding was observed by and large regardless of key press type and predictability: Tone was estimated to occur earlier when presented after the key press as compared with when it was presented alone, $t(36) = 2.5$, $p = .017$ (voluntary, unpredictable session), $t(36) = 2.7$, $p = .010$ (involuntary, unpredictable session), $t(36) = 4.8$, $p < .001$ (voluntary, predictable session), $t(36) = 2.7$, $p = .011$ (involuntary, predictable session). Also, the key press was judged to be later in time when paired with the tone as when it occurred alone, $t(36) = 2.8$, $p = .009$ (voluntary, unpredictable session), $t(36) = 2.5$, $p = .019$ (involuntary, unpredictable session), $t(36) = 1.5$, $p = .135$ (voluntary, predictable session), $t(36) = 3.0$, $p = .004$ (involuntary, predictable session).

An analysis of variance (ANOVA) including the type of key press and the session type as within-participants factors and tone judgments as a dependent measure did not reveal any significant results, $F(1, 36) = 0.62$, $p = .438$, $\eta_p^2 = .017$ (for the main effect of type of key press), $F(1, 36) = 2.79$, $p = .104$, $\eta_p^2 = .072$ (for the main effect of session type), $F(1, 36) = 2.84$, $p = .101$, $\eta_p^2 = .073$ (for the interaction). An analogous ANOVA including judgments of key presses revealed similar results, $F(1, 36) = 0.18$, $p = .676$,

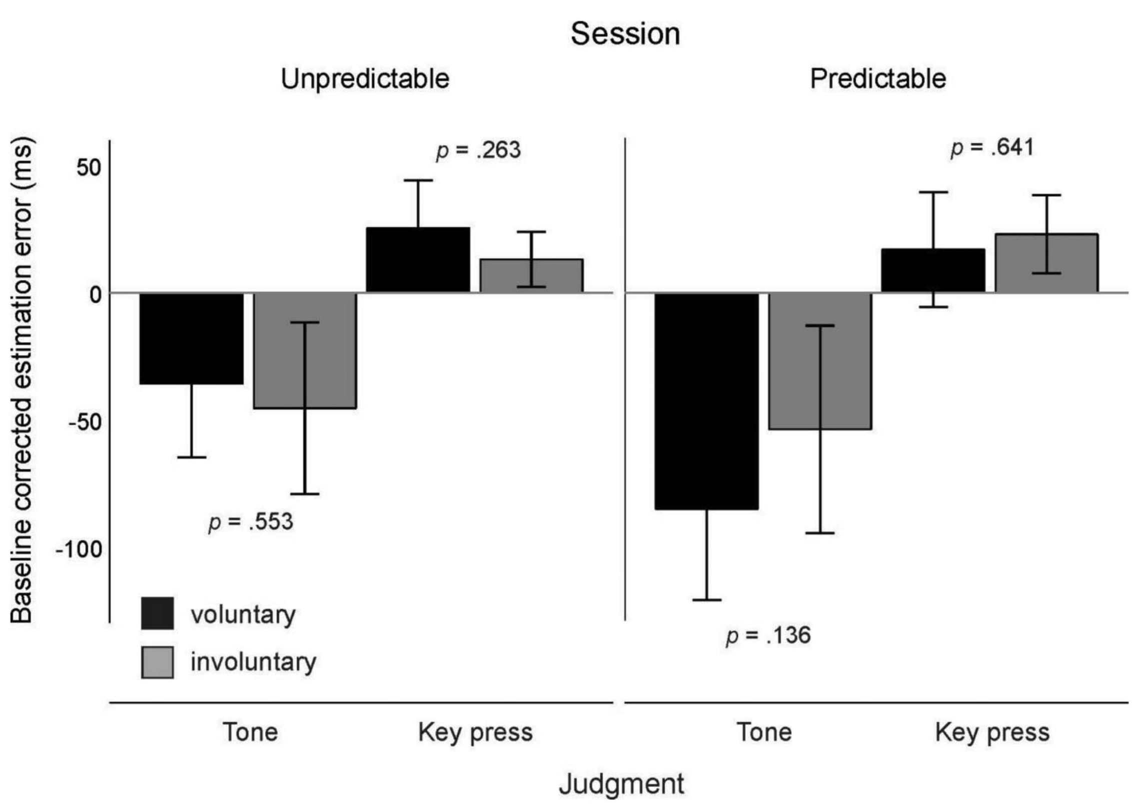

Figure 2. Baseline corrected estimation errors of tone and key press judgments for voluntary and involuntary movements and for each session type. Error bars indicate 95% confidence intervals of the mean.

η_p^2 = .005 (for the main effect of type of key press), $F(1, 36)$ = 0.01, p = .934, η_p^2 < .001 (for the main effect of session type), $F(1, 36)$ = 0.99, p = .326, η_p^2 = .027 (for the interaction). Thus, the type of key press did not substantially affect the magnitude of intentional binding regardless of whether all events were predictable or not. To substantiate this conclusion we also directly compared voluntary and involuntary conditions for each session and each type of judgment using paired t tests. The results are imbedded in Figure 2. As shown, there were no indications for systematic effects of type of action.

Baseline Uncorrected Estimation Errors

As mentioned in the Introduction, several previous studies did not include single event baseline conditions and reported differences between voluntary and involuntary movements regarding the magnitude of intentional binding (Caspar et al., 2015; Engbert et al., 2007, 2008; Moore et al., 2009; Nolden et al., 2012). We, in contrast, could not identify any differences between the voluntary and the involuntary conditions in the present study using baseline corrected measures (see above). This suggested that the effects reported previously could be attributable to variables unrelated to the supposed temporal attraction between an action and its effect and are artifacts of lacking baseline conditions. The goal of the following analyses of baseline uncorrected estimation errors was to test this hypothesis. An ANOVA including the type of key press and the session type as within-participants factors and the judgments of key presses as a dependent measure revealed a significant main effect for session, $F(1, 36)$ = 7.40, p = .010, η_p^2 = .171, and a significant interaction, $F(1, 36)$ = 10.86, p = .002, η_p^2 = .232. For the unpredictable session, voluntary key presses were judged to occur significantly later in time as compared with involuntary key presses, $t(36)$ = 3.66, p = .001 (see "B" and "D" in Figure 3 for means). For the predictable session, there were no significant differences, $t(36)$ = 1.19, p = .244. These results show that when voluntary and involuntary movements are directly compared with each other without the control for temporal prediction as was often done previously (see above and Introduction), less binding is in fact observed for involuntary than for voluntary conditions (here in respect to the perceived action). However, this effect vanishes when all events are made predictable, suggesting that it roots in temporal prediction rather than in intentionality. This also indicates that the same effect should be evident in the baseline blocks of the unpredictable session. This was in fact the case, $t(36)$ = 3.32, p = .002 (see "E" and "F" in Figure 3). Analogous analyses including tone judgments as a dependent measure did not reveal any significant results, all p > .058.[2]

Discussion

The present study examined the role of actor's intention in subjective temporal attraction between an action and its sensory effect known as intentional binding. Participants judged the time point of occurrence of a key press and of a tone, either when both were presented in isolation or when the key press preceded the tone. The critical experimental variation was related to the way the key was pressed. In one condition, the key was pressed voluntarily by the participant. In another condition, a machine pressed the key leading to a finger movement comparable to the one experienced during voluntary actions. The crucial difference between both was thus the presence of voluntary motor command in the former and its absence in the later condition.

Previous research has indicated a decrease in intentional binding for involuntary as compared with voluntary actions (see Introduction). In line with these reports we observed that voluntary actions are perceived as occurring later than involuntary actions. However, this effect was only present in baseline uncorrected measures, and only when both types of action differed with respect to event predictability. Moreover, the same effect was evident in a baseline condition where actions were not followed by the external effect. In contrast, when the data were corrected by the subtraction of baseline conditions, which eliminated any effects unrelated to a common occurrence of the key press and the tone, no differences between voluntary and involuntary actions were observed. This outcome indicates that the results of previous studies in which the predictability of the onset of action differed between voluntary and involuntary conditions reflect, at least to some extent, differences in temporal perception of predictable versus unpredictable events rather than an impact of intentionality on temporal binding (Borhani et al., 2017; Caspar et al., 2015; Engbert et al., 2008; Haggard et al., 2002; Moore et al., 2009; Tsakiris & Haggard, 2003; Wohlschläger et al., 2003). It should also be noted that event predictability did not affect the baseline corrected measures substantially. Thus, whereas the temporal prediction had an impact on the perception of involuntary versus voluntary actions it does not seem to affect the temporal attraction between these actions and their external effects.

The overall results of the present study suggest that intentional binding is unrelated to action intention, which is in line with prior observations. Buehner (2012), for example, did not observe differences in intentional binding between actions caused by human participants and those caused by a machine (cf. also the results for a short action-effect interval in Nolden et al., 2012). This finding has been used as argument for the assumption that causation rather than intentionality is the root of intentional binding. According to this view, the present results indicate that the participants inferred from the experimental setup that their involuntary key presses caused the tones similarly to the voluntary key presses. An attempt to handle noisy sensory signals in the context of knowledge of this causal relation could then give rise to the temporal attraction of a similar magnitude between both types of action and their subsequent effects (cf. Buehner, 2012, 2015).

Another approach in which causality plays a crucial role can also account for the observed outcome. In the context of a cue integration framework the present results suggest that the temporal attraction between an action and its effect is an instance of cross-modal integration of redundant signals which are supposed to have a common source. The problem of assessing whether two signals belong together and thus should be combined is called *causal inference problem* or *correspondence problem* (e.g., Deroy, Spence, & Noppeney, 2016; Ernst, 2006). Several factors such as spatial or temporal correspondence or causal belief about these events can inform whether the signals relate to a common source.

[2] This marginally significant effect indicated that in the unpredictable session the tone was judged to occur slightly later than in the predictable session (cf. Figure 3).

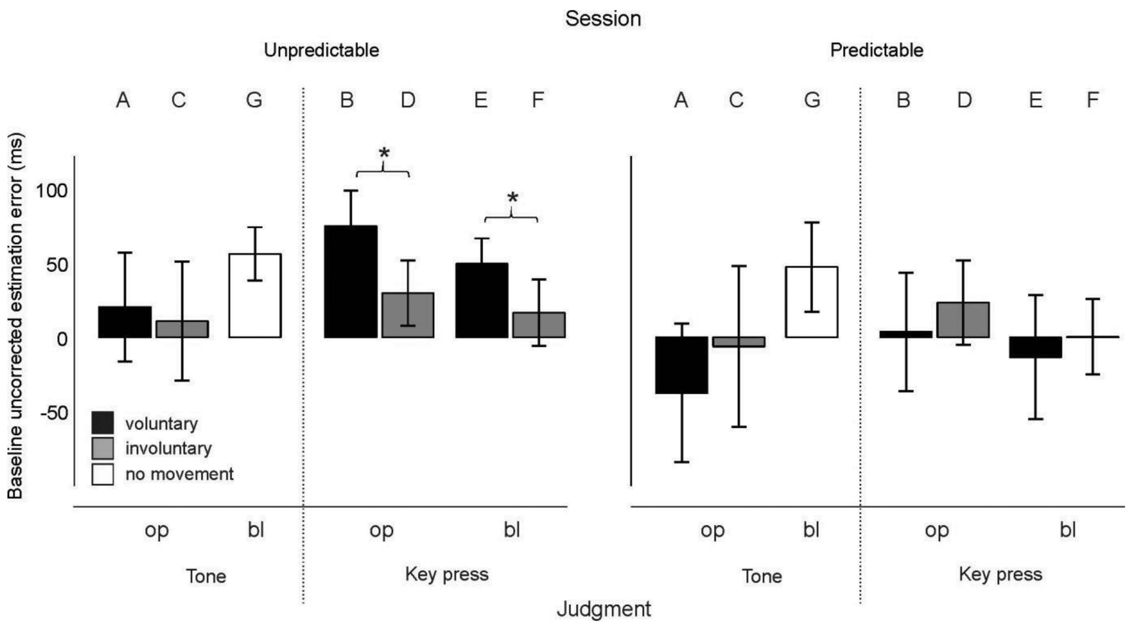

Figure 3. Mean estimation error for each experimental block and each experimental session. Here, the values of operant blocks (denoted as “op”) are not corrected by the data of baseline blocks (denoted as “bl”). Error bars indicate 95% confidence intervals of the mean. Asterisks denote statistical significance ($p < 0.05$).

Against this background, findings indicating the role of outcome predictability (Moore & Haggard, 2008), reliability of outcome timing (Haggard et al., 2002), or of causal beliefs (Buehner, 2012; Buehner & Humphreys, 2009; Desantis, Roussel, & Waszak, 2011) in intentional binding are all well in line with this approach. Thus, the cue integration approach seems to provide a powerful framework that can, in principle, account for a wide range of experimental observations reported previously (cf. also Moore & Fletcher, 2012).

A special note should be assigned to studies which used transcranial magnetic stimulation (TMS) to induce involuntary movements and which reported reversed binding effect (Haggard et al., 2002; Tsakiris & Haggard, 2003). From the perspective of the cue integration approach, such a contrast or repulsion effect indicates that the participants considered their body movement and the following sensory effect as separate events which should not be integrated. The reason for this could be related to a scarce experience with combination of TMS and auditory and somatic events, at least as compared with voluntary actions which usually produce sensory effects in everyday life. The setup of the present study, which paired voluntary and involuntary key-presses with an auditory event, in contrast, could have strengthened the participants' belief that the key press, be it involuntary or voluntary, and the subsequent tone represent a single event. The causal approach provides a similar explanation. Participants do not perceive the muscle twitch induced by the TMS as a cause of the tone, but they do so if they voluntarily press a key. As a consequence, the computer is considered as a common cause of both involuntary muscle twitch and the tone in the TMS condition (Buehner, 2015). This leads to a temporal repulsion of both events.

Diverse methods, such as interval and event time point estimations, have been applied in previous studies to measure intentional binding. We followed this rationale and considered the results of these studies as indicators of the same phenomenon regardless of the specific method used (see, e.g., the results of baseline uncorrected estimation errors; and e.g., Caspar et al., 2015; Engbert et al., 2007; Moore et al., 2009, Nolden et al., 2012 for the same approach). This reasoning, however, might be disputed. For example, binding decreases with an increase in interval size when event time points are measured (e.g., Haggard et al., 2002), but it increases when interval estimates are used (Humphreys & Buehner, 2009). Thus, binding measured with different methods could be subserved by different mechanisms. To the extent that this argument holds, our findings might be limited to binding processes tapped by the clock method used here.

To sum up, the results of the present study suggest, unlike several previous reports, that the subjective temporal attraction between an action and its sensory effect previously termed as intentional binding is not related to the intentionality of the actor. The results highlight the role of temporal prediction, stress the importance of appropriate baseline conditions for the study of intentional and unintentional actions, and suggest that the origin of the subjective temporal attraction between an action and a subsequent sensory event is closely related to the integration of multimodal signals and to the causal inference about their relation.

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