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Intentionality and temporal binding: Do causality beliefs increase the perceived temporal attraction between events?

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ABSTRACT

Intentional motor actions and their effects are bound together in temporal perception, resulting in the so-called intentional binding effect. In the current study, we address an alternative explanatory mechanism for the emergence of temporal binding by excluding the role of motor action. Employing a sensory-based Libet clock paradigm, we examined temporal perception of two different auditory stimuli, and tested the influence of beliefs about the causal relationship between the two auditory stimuli, thus simulating a crucial feature of intentional action. In two experiments, we found a robust temporal repulsion effect, indicating that instead of being attracted to each other, the auditory stimuli were shifted away from each other in temporal perception. Interestingly, repulsion was attenuated by causal beliefs, but this effect was fragile. Furthermore, temporal repulsion was unaffected by the intensity of prior learning. Findings are discussed in the context of intentional action awareness research and multisensory integration.

1. Introduction

The ability to integrate sensory information into a coherent picture of the world is an important human trait. It enables people to build a conscious representation of complex visual scenes and auditory events that are otherwise disconnected in time or space (Serences & Yantis, 2006; Shamma, Elhilali, & Micheyl, 2011). Apart from integrating perceptual input, humans also form coherent representations of their own behavior (Aarts & Custers, 2009; Vallacher & Wegner, 1987). Self-produced actions that predict and result in sensory feedback, such as pressing keys that result in a sound or light, are perceived as coherent events of meaningful behavior (e.g., playing a tone on the piano or illuminating a room), even though action and effect are spatially and temporally separated and do not form a single entity.

This ability to construct a coherent conscious experience of one's own behavior has important implications for the understanding of the self and the sense of agency, i.e. the feeling of causing one's own action and effects in the external world. Specifically, people perceive their intentional actions and resulting outcomes as if they are temporally bound together in conscious awareness; a phenomenon that is referred to as intentional binding (Haggard, Clark, & Kalogeras, 2002b). It is assumed that this temporal binding effect is rooted in internal prediction processes resulting from intentionally selected motor actions, causing the compression of the time interval between action and effect and the formation of a coherent representation of the action-effect event (Frith, Blakemore, & Wolpert, 2000).

Recent research, however, suggests that this temporal binding effect might not be the result of intentionality per se (e.g., Desantis, Hughes, & Waszak, 2012; Dogge, Schaap, Custers, Wegner, & Aarts, 2012; Hughes, Desantis, & Waszak, 2013), but rather a product of

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other factors that are associated with intentional action. In the present study, we examine this subject in more detail and raise the question whether the temporal binding effect is similarly sensitive to events that do not require any form of action. Building on the notion that intentional actions are associated with beliefs in causality that might bias the perceptual relation between two events (Buehner & Humphreys, 2010; Desantis, Roussel, & Waszak, 2011; Eagleman & Holcombe, 2002), we tested whether causality beliefs cause two successive auditory stimuli to be perceptually bound together in the Libet clock paradigm. The emergence of such a binding effect as a function of causality beliefs would undermine the validity of the temporal binding task as a read-out of intentionality and a measure of sense of agency.

One central argument that has been put forward in favor of the central role of intentionality in action concerns the impact of externally induced action on temporal binding. Some studies employed transcranial magnetic stimulation (TMS) to induce an involuntary action followed by a tone (Haggard & Clark, 2003; Haggard et al., 2002b). Subjects judged the time of movement onset and tone onset by using the Libet clock. The time judgments did not reveal a temporal binding effect but a clear and strong repulsion effect instead, indicating that subjects perceived the motor movement and subsequent tone as two separate events.

While these TMS experiments suggest that the temporal binding task can distinguish involuntary from voluntary action in producing a coherent representation of one's own action, it is important to note that the magnetic stimulation of motor areas results in an abrupt, reflexive and oddly felt movement of a limb (here a finger). Clearly, human agents have the capacity to evoke actions by direct brain stimulation, but such action onset does not fit with everyday externally induced motor movement where intentionality is ruled out, for example when someone else pushes or pulls one's hand into a specific direction. Building on this notion, recent studies show that temporal binding might be reduced but does not vanish for actions that are not self-chosen or driven by internal motivation (Antusch, Aarts, & Custers, 2019; Caspar, Christensen, Cleeremans, & Haggard, 2016) or passively induced in the agent by another experimenter or a mechanical lever press (Borhani, Beck, & Haggard, 2017; Dogge et al., 2012; Engbert & Wohlschläger, 2007; Moore, Wegner, & Haggard, 2009). These findings suggest that it is not intentionality per se that drives the temporal binding effect, as externally induced movement does not cancel out temporal binding in settings that include clear causal relations between action and outcome.

One explanation for the observed binding between externally induced actions and a tone might be that participants were able to predict the outcome and believed to have a causal role in producing it. Causal beliefs impact cognitive processes at several stages, e.g., learning, judgment and decision-making (Harris, Fiedler, Marien, & Custers, 2019; Lucas & Griffiths, 2010). Moreover, higher-order causal beliefs have been shown to affect low-level processes of perception (Buehner & Humphreys, 2009, 2010; Cravo, Claessens, & Baldo, 2009). A study by Buehner and Humphreys (2009), for example, suggests that mentally linking one's key press to a subsequent tone following a presumed causal association enhances the anticipation of the tone. However, not only effects stemming from motor actions are subject to temporal binding, also external (visual) events can be spatially bound together when they share a common causal association (Buehner & Humphreys, 2010). Accordingly, holding a higher-order belief about the causal relationship between two events increases binding between them, even when action is not actively involved.

In a further exploration of the role of causality beliefs in temporal binding of involuntary movement and effect, Dogge et al. (2012) subjected their participants to a temporal binding task with the Libet clock. Participants either executed a voluntary key press or an involuntary key press that was induced by a lever pulling down their index finger. In the involuntary conditions, some participants were asked to consider themselves as the agent, construing the resulting effect (tone) as being caused by their key press. The magnitude of the binding effect increased between the simple involuntary and involuntary self-causation condition, with mean judgment errors (indicating a stronger binding effect) being larger in the involuntary self-causation condition (Dogge et al., 2012). Similarly, it has been shown that explicit beliefs of being the causal agent resulted in stronger intentional binding in participants in a joint action task (Desantis et al., 2011). Whereas informative, these studies do not entirely rule out the role of motor prediction and intentionality in temporal binding between action and effect. It is for example conceivable that participants started up their motor system once they noticed a slight movement of the mechanical lever, causing them to experience a motor prediction signal and/or intentionality over the key press. Because of the tight link between perception and action (e.g., Decety & Grèzes, 2006; James, 1890; Prinz, 1997), a similar reasoning might account for findings that show binding effects as a result of observing others' action (e.g., Desantis et al., 2012; Kirsch, Kunde, & Herbort, 2018).

A more stringent test of the role of causality beliefs in temporal binding is provided by sensory paradigms that do not employ motor action. In one such study by Haggard and colleagues (2002a), participants judged the temporal onset of two identical successive auditory stimuli that were separated by a 250 ms time interval. Results revealed that especially the second stimulus was temporally repulsed from the first stimulus (Haggard, Aschersleben, Gehrke, & Prinz, 2002a). Similar results were obtained by Desantis et al. (2012) who compared the temporal perception of two non-motor stimuli separated by a 400 ms time interval against an operant action condition in a Libet clock paradigm. The findings were such that both, congruent and incongruent (with precedingly learned associations), tone pairs resulted in temporal repulsion instead of temporal binding, suggesting that temporal contiguity and identity prediction were not sufficient for binding to emerge (Desantis et al., 2012). The first tone was perceived as occurring earlier than in actuality, and the second stimuli was perceived as occurring later than in actuality, leading to a repulsion instead of a binding effect. Thus, instead of integrating the two stimuli such as in intentional binding, participants seemed to detach the two from each other by experiencing them as two separate entities and shifting them away from each other in temporal perception.

It is important to note that these studies did not investigate the role of causal beliefs and might have suffered from flaws that reduced the probability of observing a temporal binding effect. For example, Haggard et al. (2002a) used successive tones of the same frequency and length. Hence, there might have been little inclination for participants to integrate the tones into a coherent event and to perceive them as causally related. Thus, participants perceptually shifted the tones away from each other. Using tones of different frequencies, Desantis et al. (2012) paired the tones in congruent and incongruent within-subject blocks and employed an unconventional 400 ms time interval. Because the tones were sometimes congruent and sometimes incongruent, a stable predictive link could not be formed. Furthermore, it is unclear how the extended time interval affected the results. Finally, while suggesting temporal repulsion, comparisons with the baseline tone condition in the Haggard et al. (2002a) study only suggest temporal repulsion of the second tone, while the first tone seems to even be bound to the subsequent tone. Desantis et al. (2012) only tested the temporal perception of the second tone while a comparison baseline condition was lacking completely. Hence, the interpretation of the findings as demonstrating temporal repulsion was neither statistically tested nor can it be claimed in the absence of a comparison baseline condition. Thus, it remains subject to empirical scrutiny whether external stimuli in successive contexts are repulsed or bound to each other in temporal perception.

The present study therefore aimed to replicate the temporal binding (repulsion) effect with two different auditory stimuli by employing a unimodal sensory paradigm based on the Libet-clock. In our task, participants acquired the associations between two auditory stimuli pairs, such that the first stimulus predicted the onset of the second one. Each pair consisted of a noise sound (such as a scratch sound) followed by a sinusoidal tone 250 ms later. The pairings remained constant for each participant, allowing for participants to perceive the stimuli as being linked and represented as one event. Furthermore, as an important addition to earlier work, we examined the role of causality belief in the perceived temporal attraction between the two auditory stimuli. To that end, we manipulated explicit beliefs about the causal relationship between the two successively presented auditory stimuli to more stringently test their influence on temporal binding of the stimuli. The first experiment addresses the basic role of perceived causality in modulating the temporal binding between two different auditory stimuli. Experiment 2 was designed to further explore the role of perceived causality in a context where the association between the first and second auditory stimulus was strengthened by practice.

2. Methods

2.1. Participants and design

In total, 64[1] individuals (49 females), with a mean age of 23 years ($M = 23.02$, $SD = 6.15$) participated in the experiment in exchange for course credit or monetary reimbursement. Participants were randomly assigned to one of two between-subject conditions, resulting in 33 participants in the control condition and 31 participants in the causal belief condition. The study was carried out in line with the guidelines of the Declaration of Helsinki and was approved by the Ethics committee of the Faculty of Social and Behavioral Sciences at Utrecht University as part of a project line (ethics approval code: FETC17-124). All participants gave written informed consent.

A 2 (target: noise vs. tone) × 2 (type of trial: baseline vs. succession trials) × 2 (condition, between: control vs. causal belief) mixed design was employed.

2.2. Procedure

The experiment consisted of an altered Libet clock paradigm as used by Haggard et al. (2002) and was programmed using Eprime Software version 2.0. Four different auditory stimuli of 100 ms length were used: two noise sounds and two sinusoidal tones. The noise sounds resembled scratch sounds while the sinusoidal tones were of either 300 Hz or 1000 Hz frequency.[2] All stimuli were played via a Sennheiser headphone.

2.2.1. Acquisition phase

The experiment began with an acquisition phase in which participants were familiarized with the auditory stimuli and their combinations. At the start, participants were told that four different auditory stimuli would be used in the experiment and that they would begin with experiencing each stimulus once. While participants experienced a stimulus, an on-screen message stated which stimulus they were experiencing. By pressing F1, they could advance to hearing the next stimulus. Subsequently, to facilitate the distinguishability of the stimuli, participants experienced each stimulus four additional times. These trials advanced automatically and like in the preceding trials, it was stated on screen which stimulus participants were experiencing.

After participants were familiarized with the different auditory stimuli, they learned that each noise sound would be paired with one of the sinusoidal tones during the experiment. In the control condition, participants were told that the computer would determine the combinations of the noise and tone, and that they would therefore be independent of each other. Put differently, the pairs of auditory stimuli would not be causally related. They then heard the independent noise – tone combinations. In the causal belief

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[1] As to the best of our knowledge, no data for a comparable effect in a stimulus-based paradigm was available at the point of data collection. For a-priori sample size calculation in G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007), we first used the following parameters: $f = 0.25$, $\alpha = 0.05$, power = 0.80, nonsphericity correction $\varepsilon = 1$ and $r = 0.5$ to determine the sample size in an ANOVA: Repeated measures within–between interaction. This yielded an estimated sample size of 24 participants. Given a moderate effect size and a lower power than the default of 0.90 in G*Power 3.1, we wanted to avoid power issues for testing effects in the within-between subject design. Thus, we aimed at a sample size of at least $n = 60$ (we could run a few more within the time frame of our lab availability).

[2] Both random noise sounds were generated using the following website: https://www.wavtones.com/functiongenerator.php. An amplitude alteration was applied to make the noises distinguishable from each other. The noise sounds are also added to the Supplementary Materials.

condition, participants learned that the computer would choose the noise that would cause the second tone to occur. The second tone would thus be dependent on the selection of the noise. Put differently, the pairs of auditory stimuli would be causally related. They then heard the dependent noise – tone combinations. The noise – tone combinations were counterbalanced across participants but remained constant for a given participant.

In both conditions, the noise – tone combinations were presented five times each (i.e., ten trials in total). Participants were asked to pay close attention. They then completed eight trials in which they heard noise – tone combinations that were either congruent or incongruent with the previously learned pairs. In the control condition, they were asked to indicate which combinations of tones were presented before, whereas in the causal belief condition, they were asked to indicate which combinations of tones were causally related. This was done to further emphasize and boost the independent (control condition) and the dependent nature (causal belief condition) of the stimuli pairs in the respective conditions before the start of the actual experiment.

2.2.2. Experimental trials (altered Libet clock task)

Next, participants commenced with the experimental trials. In both conditions, participants completed four blocks in randomized order. The blocks consisted of two baseline blocks (baseline noise, baseline tone) and two succession blocks (succession noise, succession tone). Each block comprised 24 trials, including four practice trials and 20 experimental trials. The practice trials preceding the experimental trials of each block were identical to and indistinguishable from the experimental trials but were not analyzed.

Each trial began with the presentation of a dotted clock face consisting of forty grey dots arranged in a circle around the center of the screen, with a diameter of six centimeters. A black dot served as a clock hand and was moving alongside the grey dots with a speed of 2560 ms per rotation. The starting position of the clock hand varied between trials and was random. Participants were asked to attend to the clock face and the rotating clock hand. Depending on the trial, they then either perceived a single auditory stimulus or a stimuli pair in succession. The onset of the stimuli was programmed to always occur during the second rotation of the clock hand.

In baseline blocks, participants either perceived one of the two noise sounds (baseline noise) or either of the two sinusoidal tones (baseline tone). In the succession blocks, participants always perceived an initial noise sound followed by the paired sinusoidal tone at 250 ms. After the presentation of the last stimulus, the clock hand continued moving for a duration of 1000 ms before it disappeared. Subsequently, the mouse cursor as well as a prompt to make a time judgment appeared in the center of the clock face. Participants were required to judge either the temporal onset of the noise sound (succession noise trials) or the temporal onset of the sinusoidal tone (succession tone trials) by clicking on one of the dots to indicate the position of the clock hand at the time of the event. In baseline trials, participants always judged the onset of the single presented stimulus (noise in baseline noise and sinusoidal tone in baseline tone trials).

While blocks and trials were identical in both between-subject conditions, instructions differed. In the causal belief condition, instructions for the individual blocks emphasized the causal and dependent relationship of the two stimuli on each other. For example, participants in the causal belief condition read that they would hear two stimuli in succession, meaning that the tones were dependent on each other and that the first noise would cause the following sinusoidal tone. In the control condition, in contrast, the independence of the stimuli was emphasized.

At the end of the experimental trials, participants filled in their age and gender. Moreover, participants also answered a question concerning their belief in the causal dependence of the second stimulus on the first stimulus (as indicated on a 9-point Likert scale ranging from 1 - *absolutely not* to 9 - *very much*). This question served as a manipulation check. Finally, participants were debriefed and thanked for their participation as well as reimbursed.

3. Data analysis plan

Prior to the main statistical analyses, extreme temporal judgments were excluded on a trial basis. Following Aarts et al. (2012), temporal judgments, which were more than ± 640 ms away from the actual temporal onset, were excluded as it can be assumed that participants either rated the onset of the wrong stimulus or were inattentive in general on those trials. Overall, the number of judgments excluded based on this criterion was very small (0.14% of all judgments).

Based on earlier research suggesting a temporal repulsion effect between auditory stimuli (Desantis et al., 2012; Haggard et al., 2002a), we first aimed to test whether there was a significant overall temporal repulsion effect independent of condition. First, for each trial a judgment error (in milliseconds) was calculated as the difference between the judged time of an event and its actual time of occurrence. A positive judgment error corresponds to delayed awareness of the event, and a negative judgment error corresponds to anticipatory awareness. Next, for each participant separate shifts for the first (noise) and second (sinusoidal tone) stimulus were computed by subtracting the mean baseline judgment errors from the mean judgment errors in succession trials (noise shift = mean judgment error in succession noise trials – mean judgment error in baseline noise trials; tone shift = mean judgment error in succession tone trials – mean judgment error in baseline tone trials). Finally, overall binding scores were computed by subtracting the shift of the second stimulus from the shift of the first stimulus (i.e., overall score = noise shift – tone shift). Positive overall binding scores thus indicated temporal compression of the interval between the stimuli (temporal binding) while negative scores were indicative of temporal repulsion. See Fig. 1 for the distribution of the raw data in the full sample.

First, we examined the direction of the overall temporal shift. To that end, we conducted a one-sample *t*-test of the overall binding score against zero. As we had no hypothesis pertaining to either a temporal binding or a temporal repulsion effect, we conducted a two-tailed test. Next, we aimed to test whether temporal perception of the stimuli in the two conditions was statistically different. Specifically, we assumed that stimuli in the causal belief condition would be bound more strongly than in the control condition. In

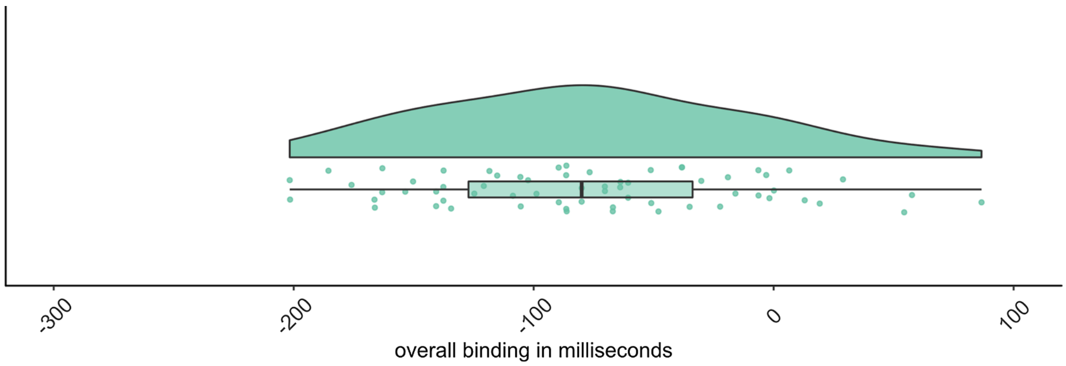

Fig. 1. Distribution of the binding scores in ms in Experiment 1 for the whole sample. Boxplot summaries are based on the median.

line with that, we conducted a one-tailed independent samples *t*-test on the overall binding scores in both conditions. Finally, we tested the direction and significance of the temporal shift in the two conditions. That is, we tested whether the perceptual shift was equally present in both conditions. For that purpose, two one-tailed one-sample t-tests of the overall binding scores in each condition against zero were conducted.

Additionally, to illustrate the strength of the evidence and confirm the Frequentist analyses, equivalent Bayesian analyses were performed. For the convenience of the reader, complete Bayesian analyses are reported.

4. Results

4.1. Manipulation check

Prior to the main analysis, we conducted an independent samples *t*-test, testing the belief in causality rating between control and causal belief condition. Confirming our manipulations, the results revealed that participants in the causal belief condition ($M = 6.68$, $SD = 2.15$) believed more strongly in the causal dependency of the second stimulus on the first stimulus than participants in the control belief condition ($M = 5.24$, $SD = 2.48$), $t(62) = -2.4688$, $p = .016$, two-tailed, $d = 0.61$, 95% CI [-1.12, -0.11].

4.2. Main analyses

Next, we proceeded with the main analysis as outlined in the data analysis plan.

4.2.1. Overall temporal repulsion

To examine the direction of the perceptual shift and its statistical significance, a one-sample *t*-test of the overall binding scores against zero was conducted. Results revealed a highly significant repulsion effect equaling 77 ms ($M = -77.20$, $SD = 65.94$), $t(63) = -9.366, p < .001$, two-tailed, $d = -1.17$, 95% CI [-1.49, -0.85]. This temporal repulsion effect occurred bi-directionally. That is, noises were significantly more anticipated on succession trials ($M = 13.12$, $SD = 46.97$) as compared to baseline trials ($M = 50.97$, $SD = 47.94$), $t(63) = 5.949$, $p < 001$, two-tailed, $dz = 0.74$, 95% CI [0.36, 0.80]. Similarly, tones were perceived significantly later on succession trials ($M = 90.17$, $SD = 49.34$) than on baseline trials ($M = 40.83$, $SD = 50.82$), $t(63) = -6.932$, $p < .001$, two-tailed, $dz = -0.87$, 95% CI [-1.31, -0.66].

4.2.2. Difference in temporal repulsion between conditions

In addition, to test whether temporal perception differed for participants in the control and the causal belief condition, overall binding scores were subjected to an independent samples *t*-test based on condition. The results revealed that participants in the causal belief condition (M = -52.50, $SD = 67.24$, $N = 31$) perceived the stimuli as significantly closer to each other in time than participants in the non-causal control condition ($M = -100.40$, $SD = 56.35$, $N = 33$), $t(62) = -3.096$, $p = .0015$, one-tailed. The difference of -47.9 ms was of moderate effect size, $d = -0.77$, 95% CI [-1.28, -0.26].[3] See Fig. 2 for a visualization of the overall shifts for the separate between-subject conditions.

4.2.3. Temporal repulsion per condition

Following, two one-sample t-tests were conducted to test whether the judgments were significantly different from zero. In the control condition ($M = -100.40$, $SD = 56.35$), judgments showed a statistically significant temporal repulsion effect, $t(32) = -10.24$, $p < .001$, one-tailed, $d = -1.78$, 95% CI [-2.33, -1.22]. Similarly, also in the causal belief condition

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[3] Note that this effect equals the three-way within-between interaction effect between target, type of trial and condition in a repeated measures ANOVA, $F(1,62) = 9.58$, $p < .003$, $\eta_p^2 = 0.134$, f = 0.39.

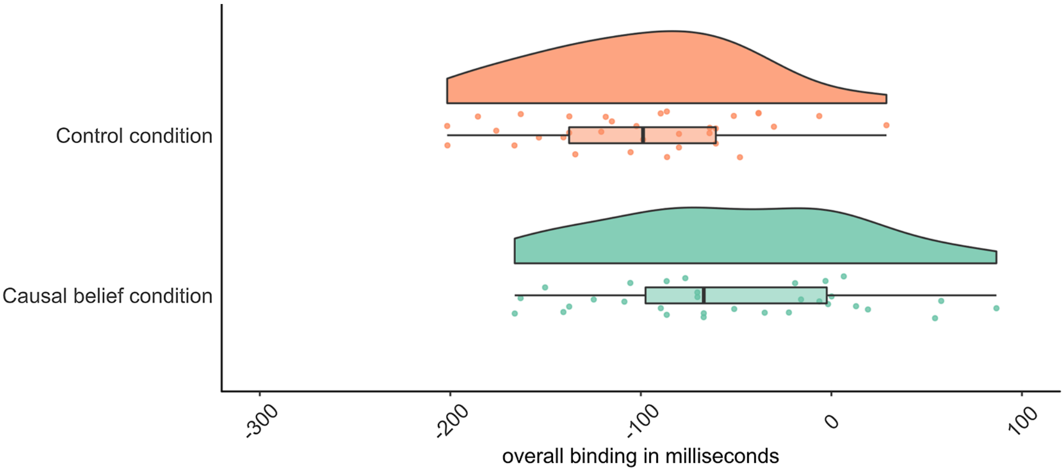

Fig. 2. Distribution of the binding scores in ms in Experiment 1 in the between-subject conditions. Boxplot summaries are based on the median.

($M = -52.50$, $SD = 67.24$), individuals showed a significant temporal repulsion effect, $t(30) = -4.35$, $p < .001$, one-tailed, $d = -0.78$, 95% CI $[-1.18, -0.37]$. The separate shifts for the noise and the tone in the between-subject conditions are visualized in Fig. 3.

4.3. Bayesian analyses

To assess the strength of the evidence, we performed Bayesian analyses in JASP (JASP Team, 2018, Version 0.9). In the absence of sufficient information regarding a reasonable effect size and given the novelty of the paradigm, the default Cauchy prior of 0.707 instead of an informed prior was used for the Bayesian t-tests (Bartlett, 2018; Quintana & Williams, 2018). To assure the robustness of Bayes Factors, robustness checks were conducted. The results indicated that the chosen prior did not inflate the Bayes Factors. Hence, the results of all tests can be assumed to be robust. The results of all robustness checks are reported in the Supplementary Materials.

4.3.1. Bayesian t-test on overall repulsion

To test the strength of the temporal repulsion effect, we conducted a Bayesian two-tailed one-sample *t*-test on the overall temporal repulsion score. The alternative hypothesis stated that the temporal repulsion effect differed from zero (zero meaning no perceptual shift). The results revealed a $BF_{10} = 5.199e + 10$ (=51,990,000,000), 95% CrI $[-1.46, -0.84]$, indicating extreme evidence for the

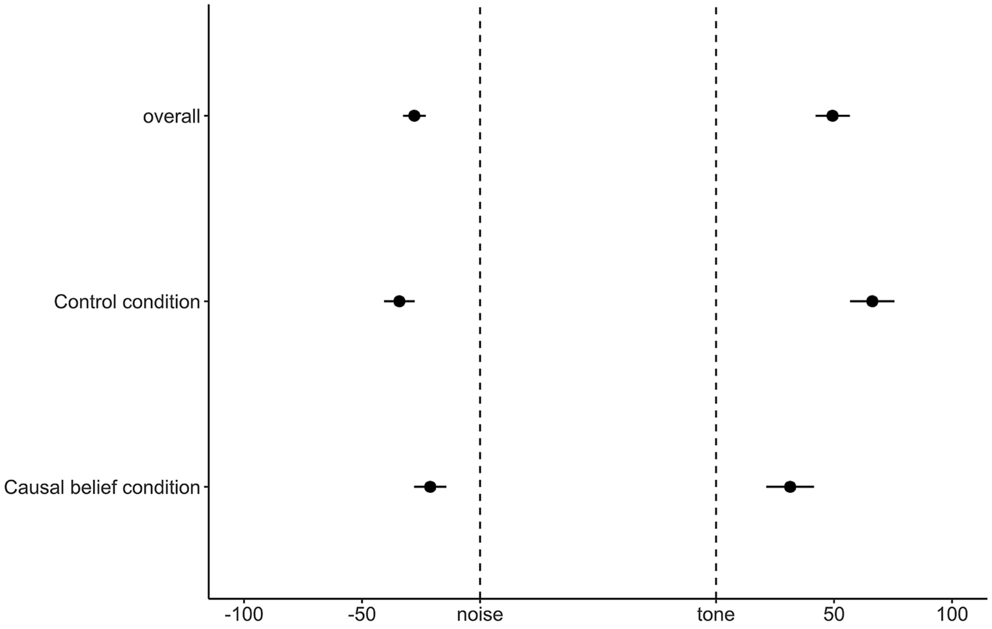

Fig. 3. Separate temporal shifts from baseline in ms for Experiment 1. Dots denote the mean, bars represent standard errors.

alternative hypothesis.

4.3.2. Bayesian t-test on temporal repulsion between conditions

Next, to test the strength of the difference between the two conditions, a one-tailed Bayesian independent-samples *t*-test was conducted. The alternative hypothesis assumed that the temporal judgments in the causal belief condition would be smaller than in the control condition, indicating less repulsion. The BF_{+0} was 25.01, 95% CrI [0.19, 1.19], suggesting that the data was 25 times more likely to occur under the alternative than under the null hypothesis. Thus, there was strong evidence for the idea that temporal repulsion was smaller in the causal belief condition than in the control condition.

4.3.3. Bayesian t-tests on temporal repulsion in the separate conditions

Consecutively, two Bayesian one-sample t-tests were conducted. Both overall binding scores were tested against a population mean of zero. For the causal belief condition, a $BF_{10} = 183.4$, 95% CrI [−1.13, −0.34], was found, indicating very strong evidence for the alternative hypothesis. For the control condition, a $BF_{10} = 7.136e + 8$ (=713,600,000), 95% CrI [−2.36, −1.13], was found, indicating even extreme evidence for the alternative hypothesis.

5. Discussion

In this first experiment, we aimed to replicate the temporal repulsion effect between two auditory stimuli suggested by existing literature (Desantis et al., 2012; Haggard et al., 2002a). Employing a sensory based Libet clock paradigm, strictly excluding the possibility for motor action, for the first time, we empirically tested and statistically demonstrated this temporal repulsion effect (i.e., corroborated by Frequentist and Bayesian analyses).

Additionally, we found that participants who held an explicit belief about the causal dependency of the stimuli on each other, perceived the stimuli as being less strongly repulsed than participants who did not hold such belief. This finding suggests an increased perceived coherence between the stimuli in the causal belief condition. However, temporal binding was still absent, indicating that the temporal integration of the two auditory stimuli was weak and thus did not produce a full coherence experience.

6. Experiment 2

To test the reliability of the temporal repulsion effect in the perception of successive auditory stimuli and the attenuation thereof in the causal belief condition, a second experiment was set up. It is conceivable that temporal repulsion persisted in the light of causal belief because of the arbitrary nature of the stimuli and their associations. For example, recent research using a different paradigm suggests that stimuli that have a naturalistic link (such as the picture of a hand and a clapping sound) are more easily bound in temporal perception (Thanopoulos, Psarou, & Vatakis, 2018). Research suggests that these associative links between stimuli are acquired through learning and repeated exposure (Turk-Browne, Scholl, & Chun, 2008). Especially in the absence of motor action such learning might be pivotal for forming a stable predictive link. Hence, in an attempt to strengthen these associations, we increased the amount of learning trials from ten to sixty trials in the additional learning conditions.

6.1. Methods

6.1.1. Participants and design

The sample of the second experiment consisted of 100[4] (66 females) volunteers with a mean age of 22 years ($M = 22.22$, $SD = 2.03$) who participated in the experiment in exchange for course credit or a monetary reimbursement. The study was carried out in line with the guidelines of the Declaration of Helsinki and was approved by the Ethics committee of the Faculty of Social and Behavioral Sciences at Utrecht University (ethics approval code: FETC17-124). All participants gave written informed consent.

The design of the second experiment resembled the design of the first experiment with the addition of another between-subject factor. The complete design was a 2 (target: first vs. second tone) × 2 (type of trial: baseline vs. succession) × 2 (condition, between: control vs. causal belief) × 2 (additional learning, between: no vs. yes) mixed design. The addition of the learning factor resulted in two additional between-subject conditions. That is, participants could be randomly assigned to either one of the following conditions: control condition or causal belief condition (replication of the conditions of Experiment 1), control learning condition or causal belief learning condition (resulting from the addition of the learning factor to the design).

6.1.2. Procedure

The general procedure of the experiment resembled that of the first experiment. Also the stimuli used were identical to the stimuli in the first experiment. The experiment was programmed using Eprime 2.0. The procedural differences between the first and the

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[4] Like in Experiment 1, we started with the following parameters in G*Power 3.1 (Faul et al., 2007): $f = 0.25$, $\alpha = 0.05$, power = 0.80, nonsphericity correction $\varepsilon = 1$ and $r = 0.5$ to determine the sample size in an ANOVA: Repeated measures within–between interaction, including the moderator test of the learning factor as well. This yielded an estimated sample size of 36 participants. As this was again a rather liberal estimation, we decided to increase the power to detect the moderating influence of the learning factor. Hence, we increased the sample size to $n = 100$.

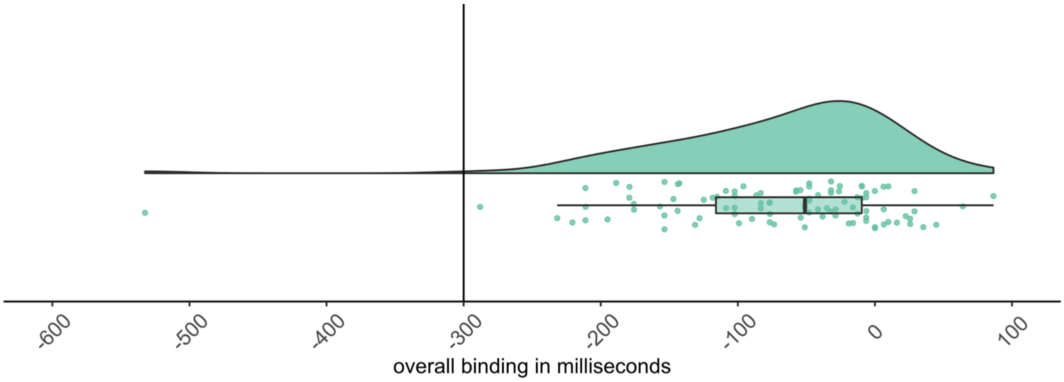

Fig. 4. Distribution of the overall binding scores in ms in Experiment 2 for the whole sample. Boxplot summaries are based on the median.

second experiment are outlined below.

6.1.2.1. Acquisition phase. The experiment began with an acquisition phase. In the control and causal belief condition, the same acquisition phases as in the first experiment were employed (for details see Experiment 1).

In the additional learning condition, after having acquired the stimuli, participants completed extensive learning phases of the stimuli pairs. In total, participants completed 60 learning trials (2 × 30 trials, separated by a 30 s break). The repeated exposure to the stimuli pairs thus would strengthen the association between the stimuli. Like in the first experiment, in the causal belief condition, the causal relationship between the two stimuli of a pair was emphasized whereas in the control condition their independence was emphasized.

6.1.2.2. Experimental trials (altered Libet clock trials). The control and causal belief condition were identical to the first experiment. The instructions for experimental blocks in the learning conditions were borrowed from the respective control conditions.

6.1.2.2.1. Data analysis plan. As in Experiment 1, we excluded temporal judgments that were more than ± 640 ms away from the actual temporal onset of the stimulus on a trial basis (Aarts et al., 2012). Overall, the amount of excluded trials was very small (0.15% of the total amount of judgments). Furthermore, we calculated separate shift scores as well as overall binding scores per participant using the same formula as in Experiment 1. Upon inspection of the overall binding scores, one participant seemed to be an extreme outlier with an average mean judgment score of −532.38 ms. As this score was more than six standard deviations away from the average overall binding score of the remaining participants ($M = -67.28$, $SD = 74.34$), we decided to remove this person from further analysis. A visualization of the raw data including the outlier is provided in Fig. 4.

We proceeded with testing the significance of the overall temporal perceptual shift. Since we had no directional hypothesis regarding the perceptual shift in the overall sample (either temporal binding or temporal repulsion), we conducted a two-tailed one-sample *t*-test on the overall temporal binding scores. After establishing the significance of the temporal repulsion effect in the sample, we subjected the overall binding scores to an ANOVA with causal belief and learning as between-subject factors to assess their influence on temporal perception. Following, four separate one-tailed one-sample t-tests were conducted to test the significance of the temporal repulsion shift in the separate between-subject conditions.

Finally, equivalent Bayesian analyses are reported to give an impression of the strength of the evidence.

7. Results and discussion

7.1. Manipulation check

To check that the belief in the causal relationship between paired stimuli was indeed stronger in the causal conditions than in the control conditions, we conducted an ANOVA with causal belief condition and learning as between-subject factors on causal belief. The results revealed that, on average, participants in the causal belief conditions ($M = 5.6$, $SD = 2.24$, assessed on a 9-point Likert scale) believed more strongly in the causal dependency of the second stimulus on the first stimulus than participants in the control belief conditions ($M = 3.67$, $SD = 2.17$), $F(1, 95) = 19.615$, $p < .001$, $\eta^2 = 0.17$, 95% CI [0.05, 0.30]. Learning was not found to have an influence on the causal dependency belief, $F(1, 95) = 0.101$, $p = .751$, $\eta^2 = 0.00$, 95% CI [0.00, 0.04]. Similarly, also the interaction between the causal belief manipulation and learning was not significant, $F(1,95) = 1.631$, $p = .205$, $\eta^2 = 0.01$, 95% CI [0.00, 0.10].

7.2. Main analyses

7.2.1. Overall temporal repulsion

A one-sample *t*-test on the overall binding score across conditions was conducted to assess the direction of the perceptual shift and

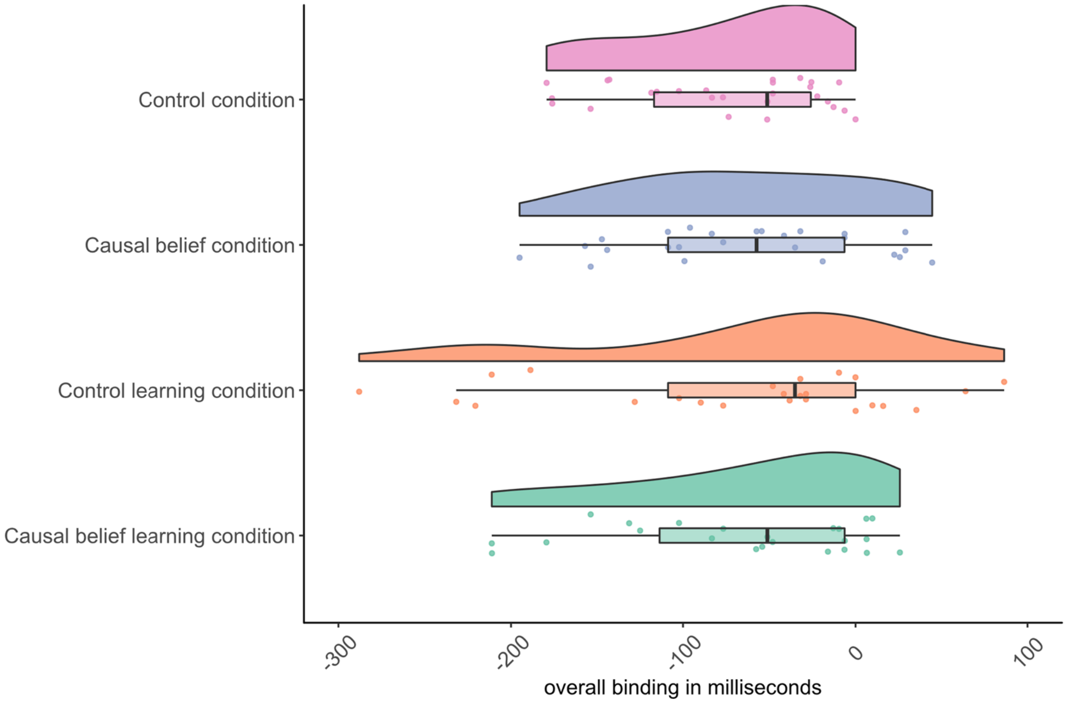

Fig. 5. Distribution of the binding scores in ms in the between-subject conditions of Experiment 2. Boxplot summaries are based on the median.

to test its statistical significance. The results revealed a significant repulsion effect of around 67 ms ($M = -67.28$, $SD = 74.34$), $t(98) = -9.005$, $p < .001$, two-tailed, $d = -0.91$, 95% CI [−1.14, −0.67]. Simple main effects confirmed that temporal repulsion occurred on both sides – the noise and the tone side, meaning that they were both perceptually repulsed from each other. While noises were perceived as occurring earlier on succession trials ($M = 3.49$, $SD = 39.06$) than on baseline trials ($M = 35.44$, $SD = 41.05$), $t(98) = 7.805$, $p < .001$, two-tailed, $dz = 0.78$, 95% CI [0.31, 0.73], tones were perceived significantly later on succession trials ($M = 64.58$, $SD = 60.34$) than on baseline trials ($M = 29.25$, $SD = 44.54$), $t(98) = -6.018$, $p < .001$, two-tailed, $dz = -0.60$, 95% CI [-0.90, -0.43].

7.2.2. Influence of causal belief and learning on temporal repulsion

The overall binding scores were then subjected to an ANOVA with condition and learning as between-subject factors. Neither the main effect for condition, $F(1, 95) = 0.203$, $p = .653$, $\eta^2 = 0.00$, 95% CI [0.00, 0.05], nor the main effect for learning, $F(1, 95) = .061$ $p = .806$, $\eta^2 = 0.00$, 95% CI [0.00, 0.03], was significant. Moreover, also the interaction between condition and learning was not significant, $F(1, 95) = 0.117$, $p = .733$, $\eta^2 = 0.00$, 95% CI [0.00, 0.05]. Also the planned comparison between the control and the causal belief condition did not yield a significant effect, $F(1, 95) = 0.331$, $p = .566$, $\eta^2 = 0.00$, 95% CI [0.00, 0.06]. The causal belief effect that we found in the first experiment was thus not replicated. See Fig. 5 for a visualization of the overall binding scores in the four between-subject conditions.

7.2.3. Temporal repulsion per condition

The scores of all four between-subject conditions were negative, indicating temporal repulsion of the two stimuli from each other: control condition ($M = -74.94$, $SD = 57.46$, $N = 27$), causal condition ($M = -62.90$, $SD = 68.02$, $N = 25$), control learning condition ($M = -66.01$, $SD = 98.73$, $N = 24$) and causal learning condition ($M = -64.37$, $SD = 73.30$, $N = 23$). Separate one-sample t-tests were conducted to test if temporal repulsion in the conditions was significantly different from zero. The results were as follows: $t(26) = -6.777$, $p < .001$, one-tailed, $d = -1.30$, 95% CI [−1.81, −0.78] (control), $t(24) = -4.624$, $p < .001$, one-tailed, $d = -0.92$, 95% CI [−1.39, −0.45] (causal), $t(23) = -3.275$, $p = .0015$, one-tailed, $d = -0.67$, 95% CI [−1.11, −0.22] (control, learning), $t(22) = -4.211$, $p < .001$, one-tailed, $d = -0.88$, 95% CI [−1.35, −0.39] (causal, learning). Fig. 6 provides an overview of the separate temporal shifts for the perception of the noise and the tone as compared to baseline.

7.3. Bayesian analyses

Furthermore, Bayesian analyses were conducted using JASP software (JASP Team, 2018, Version 0.9). Like in Experiment 1, the default Cauchy prior of 0.707 was used for the Bayesian t-tests as a lack of existing information regarding a realistic effect size did not allow for the determination of an informed prior (Bartlett, 2018; Quintana & Williams, 2018). To assure the robustness of the Bayes Factors, robustness checks were conducted. The results indicated that the chosen prior did not inflate the Bayes Factors and that all

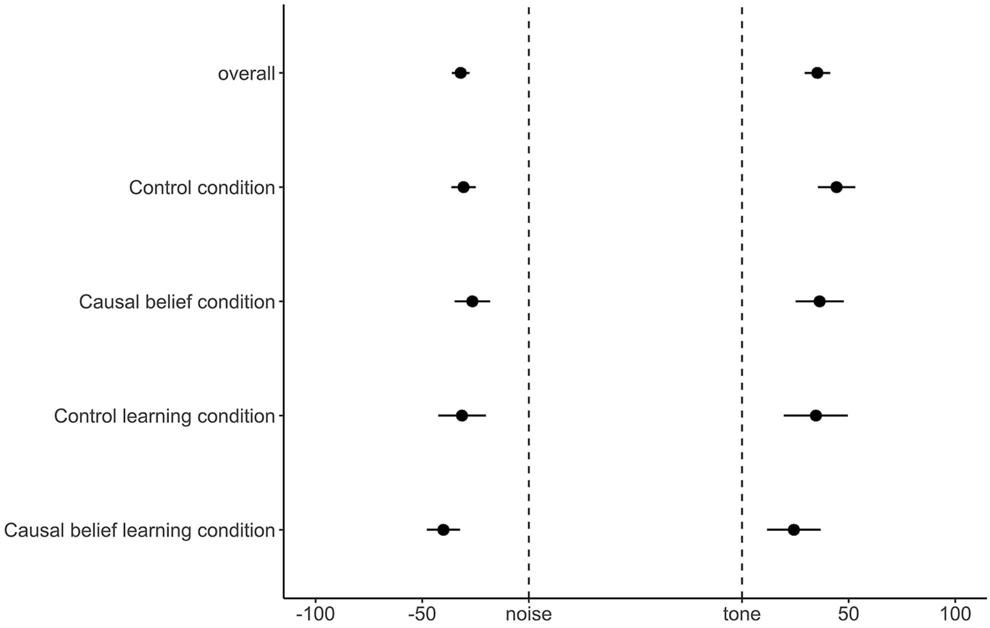

Fig. 6. Separate perceptual shifts from baseline in ms for the first and second auditory stimulus in the overall sample and per condition for Experiment 2. Dots denote the mean per condition, bars represent standard errors.

test can be assumed to be robust. The results of all robustness checks are reported in the Supplementary Materials.

7.3.1. Bayesian t-test on overall repulsion score

Like in the first experiment, to test the strength of the temporal repulsion effect, we conducted a Bayesian two-tailed one-sample *t*-test on the overall temporal repulsion score. The alternative hypothesis stated that the temporal repulsion effect differed from a population mean equal to zero. The $BF_{10} = 3.979e + 11(=397{,}900{,}000{,}000)$, 95% CrI $[-1.46, -0.84]$ indicated extreme evidence for the alternative hypothesis.

7.3.2. Bayesian ANOVA

Subsequently, we conducted a Bayesian ANOVA on the overall binding scores with causal belief and learning as between-subject factors. The results showed that, given the data, there was no evidence that the separate effects of causal belief ($BF_{10} = 0.234$) and learning ($BF_{10} = 0.219$) were a good addition to the null model explaining the extent of temporal binding or repulsion. Similarly, neither a model including both factors ($BF_{10} = 0.051$) nor a model including both factors and the interaction term ($BF_{10} = 0.015$) was favorable given the data.

7.3.3. Bayesian t-test on the difference between the control and causal belief condition

Next, to test the likelihood of decreased temporal repulsion in the normal causal belief condition as compared to in the normal control condition (replication of Experiment 1) given the data, a one-tailed Bayesian independent-samples *t*-test was carried out. The null hypothesis that there was no difference between the two conditions was tested against the alternative hypothesis that the temporal repulsion in the causal condition was smaller than in the control condition. The $BF_{+0} = 0.497$, 95% CrI [0.01, 0.7], suggested no evidence for the alternative hypothesis.

7.3.4. Bayesian t-tests on temporal repulsion per condition

Finally, we conducted separate Bayesian one-sample t-tests to test each group judgment against zero. The results were as follows: control condition $BF_{10} = 47998.34$, 95% CrI $[-1.75, -0.75]$, causal condition $BF_{10} = 250.6$, 95% CrI $[-1.34, -0.39]$, control learning condition $BF_{10} = 12.36$, 95% CrI $[-1.05, -0.19]$, and causal learning condition $BF_{10} = 87.08$, 95% CrI $[-1.23, -0.30]$. That is, while there was extreme evidence in favor of the alternative hypothesis in the control and causal condition, the evidence for the alternative hypothesis was (very) strong in the two learning conditions. This suggests that the evidence for temporal repulsion was strong in all conditions but slightly less strong in the learning conditions.

In short, we replicated the temporal repulsion effect of the first experiment, but we could not replicate the moderating influence of causal belief, even when participants received more extensive practice in causally linking the two auditory stimuli.

8. General discussion

Research on action awareness consistently finds voluntary actions and their effects to be attracted to each other in temporal perception. This temporal binding effect is said to be rooted in factors inherent to intentional action – hence the name, intentional binding. Here we explored a potential confound of intentional action in producing temporal binding. Specifically, we explored the role of beliefs of causality, and cancelled out any role of action by examining temporal perception of auditory stimuli. Employing an adapted sensory-based version of the Libet clock paradigm, in two experiments we found a temporal repulsion effect for the perception of auditory stimuli in the absence of motor action. This finding supports past research that observed a similar effect (Desantis et al., 2012; Haggard et al., 2002a). However, we were able to statistically test it with a sufficiently large sample, and unambiguously demonstrated the existence and robustness of such an effect. That is, both - the noise and the sinusoidal tone - were significantly shifted away in comparison to baseline.

We also found evidence for a moderating effect of causal belief on temporal binding of auditory stimuli. Specifically, in Experiment 1 we showed that making participants believe that the first auditory stimulus is causally related to the second auditory stimulus reduced the repulsion effect, suggesting an increased form of temporal integration and perceived coherence. The repulsion effect was not fully reduced, and we could not replicate the moderating influence of causal belief in a second experiment, even though we exposed participants to more training in applying causal beliefs to the auditory stimulus combinations. Hence, while we demonstrated a robust and clear temporal repulsion effect for sensory stimuli in the absence of motor action, the influence of higher order beliefs was less robust and not sufficient to cause actual temporal binding, as would be the case in intentional action.

One possible explanation for the absence of a causal belief effect on temporal binding of auditory stimuli might lie in the naturalistic character of the stimuli combinations. Recent research on voluntary action, for example, suggests that naturalistic as compared to non-naturalistic links between action-events carry an implicit (learned) causality experience which makes them likely to bind to an effect (Dogge et al., 2012; Dogge, Hofman, Custers, & Aarts, 2019; Thanopoulos et al., 2018). Following this line of reasoning, the absence of temporal binding may be due to the lack of a natural association between the two auditory stimuli. Although previous research showed that spatial binding of visual stimuli could emerge rather rapidly (Buehner & Humphreys, 2010), auditory sequences might require practice for temporal binding and perception of coherence to occur (Hsu, Le Bars, Hämäläinen, & Waszak, 2015; Lange, 2009; Turk-Browne et al., 2008). We found that the number of trials that we used was not enough and that it is unclear how much prior experience is necessary to induce temporal binding between non-naturalistic stimuli links. While there is research suggesting that a few trials might suffice (Shimi & Logie, 2018), other research suggests that more elaborate prior learning is necessary (Ernst, 2007). The failure to replicate the causal belief effect on temporal binding thus indicates the fragility of building a coherent representation of a non-naturalistic combination of sounds (Grotheer & Kovács, 2014; Jacobsen & Schröger, 2001), which seems less problematic for intentional action where one produces sounds by key-presses that might be more naturalistic and more easily to acquire.

All in all, the present finding might give reason to assume that intentionality has a special status in binding action and effect. As far as the evidence in the current literature can tell, temporal binding mainly occurs when people perform, observe and simulate actions (such as key-presses) to produce effects. Despite potential flaws in experimental designs and testing (Hughes et al., 2013), these overall findings strongly suggest that sensorimotor processes are vital to conscious experiences of action coherence and agency. It is unclear, though, whether the predictions involved in this sensorimotor mechanism stem from intentional action, actual body movement or action simulation, or whether temporal binding arises from multisensory causal integration that links physical sensations to predicted sensory effects (Ehrsson, Spence, & Passingham, 2004; Prikken et al., 2019). Future research might therefore design temporal binding studies that more indirectly operate on the motor-sensory system, possibly ruling out action simulation and using conditions that resemble sensory experiences (e.g., tactile stimulation of the finger) that often accompany intentional motor action during interaction with the world.

Finally, the present experiments employed the Libet clock paradigm to examine how two successive auditory stimuli are temporally bound together in conscious awareness. A key feature of the Libet clock in a full temporal binding within-subject design is that one can specifically examine whether repulsion (or attraction) is caused by a shift away from the first stimulus or from the second stimuli, or both. Our data suggest that the temporal repulsion effect occurred bi-directionally, such that subjects perceived the first stimulus earlier and the second stimulus later in time than actually was the case. Repulsion in the temporal binding task thus represents an instance in which two successive stimuli are disconnected and separated in conscious experience.

It is important to note that recent research uses alternatives for the Libet clock, in particular time interval estimations. Whereas these time estimations seem to yield findings that correspond with a temporal binding effect, the measure does not offer a clear inspection of the effect: time interval estimations are compared with the actual time intervals, leading to under- or overestimations of time intervals. Notably, in some studies underestimations are considered to represent temporal binding, whereas in other studies overestimations are treated as temporal binding when comparing conditions that are hypothesized to modulate binding effects (Damen, Van Baaren, Brass, Aarts, & Dijksterhuis, 2015; Kühn, Brass, & Haggard, 2013; Wen, Yamashita, & Asama, 2015). Thus, although the time interval estimation measure is practical and easy to administer, it is ambiguous in showing whether attraction or repulsion effects are at stake (for studies on time interval estimations with respect to auditory and visual stimuli links, see e.g., Humphreys & Buehner, 2009; Imaizumi & Tanno, 2019). Therefore, whereas the Libet clock paradigm has downsides on its own (Pockett & Miller, 2007), it allows for reliable assessments of the relative temporal shifts compared to baseline time perception, which may be preferred over time interval estimation to examine whether, how and when a positive temporal binding (attraction) binding or negative temporal binding (repulsion) effect will occur.

To conclude, the present research clearly shows that two auditory stimuli occurring in the absence of motor actions are not subject to temporal binding but temporal repulsion, even when people believe that the stimuli are causally related. Understanding the role of causal beliefs in binding action and effect has received some attention lately, but most studies still involve motor movement, and hence, it remains unclear whether and how intentional action shapes coherent representations and a sense of agency of our own behavior. We believe that ruling out any role of motor movement (albeit overtly or covertly) might be crucial in examining alternative mechanisms for temporal binding between action and effect, such as multisensory causal binding that integrates associated information from different sensory modalities. The current research might serve as a first step in this enterprise.

Author contributions

S. A., R. C. and H. A. conceived the idea and planned the experiment. S. A. programmed the experiment, supervised data collection and analyzed the data. S. A. and H. M. interpreted the data. S. A., H. A. and R. C. wrote the manuscript. H. M. provided useful comments.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

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