The Role of Causality in Temporal Binding: Evidence for an Intentional Boost

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Abstract

Temporal binding refers to the subjective contraction in time between an action and its consequence. Since it was reported in 2002 the effect has generated much interest, although a consensus regarding the mechanisms behind it remains elusive. While multiple theoretical accounts have been proposed, a key point of contention remains whether the effect is the result of the perception of intentionality or causality. We deployed a new apparatus to compare intentional to mechanical causation. Thirty participants reported the interval between two events in self-causal, mechanical-causal and non-causal conditions. The results of a Bayesian analysis pointed to smaller temporal estimates in the self-causal condition compared with the mechanical-causal condition, in addition to smaller estimates in the mechanical-causal condition compared with the non-causal condition. The evidence presented here suggests that causality alone may be sufficient for temporal binding to occur, but that this effect is boosted by the presence of intentional action.

Introduction

Temporal binding refers to the mutual attraction (in subjective time) between a causal action and its consequence, relative to two unrelated events. In a seminal paper Haggard et al (2002) found evidence for delayed awareness of the time of action and early awareness of the time of its consequence. Subsequent research has replicated this effect with a variety of paradigms, including interval estimation (Humphreys & Buehner, 2009), stimulus anticipation (Buehner & Humphreys, 2009) and the method of constant stimuli (Nolden, Haering & Kiesel, 2012). The use of various interval estimation methods has demonstrated that, in addition to shifts in the perceived time of events, intentional binding also manifests as a shortening of the overall perceived interval between an action and its consequence.

Haggard et al. (2002) originally referred to the effect as *intentional binding* and proposed that it reflects "a general linkage through time between representation of action and effect" (p. 384), and that the subjective shortening of the interval between them may contribute to our sense of agency and motor learning through forward models. While multiple accounts of the mechanisms behind temporal binding have been proposed since then (Buehner, 2015; Moore & Obhi, 2012; Eagleman & Holcombe, 2002), the role of intentionality has been central to much of the work on the subject. More recently, studies have increasingly made use of temporal binding as an implicit measure of sense of agency, for example in studies of mindfulness (Jo, Whittmann, Hinterberger & Schmidt, 2015; Lush, Parkinson & Dienes, 2016) narcissism (Hascalovitz & Obhi, 2015) and Schizophrenia (Voss et al, 2010).

The focus on intentionality in the literature notwithstanding, Buehner and Humphreys (2009) have argued that temporal binding is instead driven by awareness of causality, and should be termed "causal binding": Temporal binding reflects a bi-directional interpretation of David Hume's (1739/1888) assertion that temporally contiguous events are more likely to be perceived as causally related. Specifically, because human time perception is inherently noisy and uncertain, it is subject to top-down modulation. From a Bayesian perspective it thus follows that if contiguous event pairs are likely to be causally related, then event pairings that are known to be causally linked are also likely to have occurred contiguously. Time and causality thus mutually constrain each other in subjective experience.

While there is a general consensus that a causal relationship is *necessary* for temporal binding to occur, there is less agreement on whether causality on its own is also *sufficient* (Moore & Obhi, 2012). However, Buehner (2015) reported mutual attraction in subjective time between voluntary actions and their outcomes (i.e. the typical binding effect) as well as between involuntary, induced, causal actions and their outcomes. Furthermore, Buehner (2012) also demonstrated temporal binding between a non-biological mechanical action (a robot arm pressing a key) and its outcome (an LED flash). While both studies revealed evidence for temporal binding in the presence of causality alone (thus demonstrating its sufficiency to result in binding), they also found a more pronounced effect when the cause was an intentional action. Thus, while causal binding appears to be rooted in causality, it seems to be subject to an intentional boost.

A limiting factor in this earlier research is that it always deployed key-presses as intentional causal actions, meaning that participants had access to precise proprioceptive feedback about the successful completion of the causal action, as well as the precise time of the start of the causal interval (i.e. the moment the key was depressed). In contrast, this type of feedback was not available in control conditions. We set out to maximize the perceptual similarity between experimental conditions. Specifically, we replaced key-presses with a continuous upwards movement made by the participant, and created a mechanical causal as well as a control condition that matched the perceptual experience. In all three conditions, participants were able to rely purely on visual information to determine the onset of a two-event sequence, and we eliminated any tactile or auditory feedback.

Participants took part in three conditions: self-causal, mechanical-causal and non-causal control. On each trial, participants had to reproduce the interval between two sequential events (which were causally linked in the two causal conditions). Both the self-causal and mechanical-causal conditions made use of a laser pointed at a light sensor. Upon detecting the laser beam (event 1) the light sensor responded by switching on a red LED after a randomized delay (event 2). In the self-causal condition participants allowed the laser to reach the light sensor manually by moving a wooden paddle out of its way, whereas in the mechanical-causal condition this was done mechanically, without input from the participant. In the non-causal control condition the laser was replaced with a small red LED which was positioned where the laser beam could be seen in the other two conditions. In this condition, the two event sequence consisted of deactivating of the small LED (simulating the perceptual experience of the laser hitting the light sensor), followed by the switching on of the red LED as in the other two conditions. This sequence was controlled by a computer.

According to the intentional binding account, temporal estimates for the two –event sequences should be smaller in the self-causal condition than in the other two (self-causal < mechanical-causal = non-causal control); according to the causal binding account, temporal estimates should be larger in the non-causal control condition than in the self-causal and mechanical-causal conditions (self-causal = mechanical-causal < non-causal control). Finally, if temporal binding is rooted in causality, but subject to an intentional boost temporal estimates should be lowest in the self-causal condition, followed by the mechanical-causal condition, with both being shorter than the non-causal control condition (self-causal < mechanical-causal < non-causal control).

Methods

Participants

Thirty Cardiff University students and staff (2 male, age range 18-33) participated in exchange for a payment of £3 or course credits. Participants were recruited through Cardiff University's electronic Experiment Management System and electronic noticeboard. Participants were asked to report (in writing) whether they felt they knew the purpose of the experiment prior to debriefing. Of the thirty, only three responded 'yes', and none correctly understood the purpose of the experiment.

Apparatus

A schematic diagram of the apparatus can be seen in Figure 1. The apparatus was situated on top of a desk and placed on a platform at a height of 9.8cm, with a gap 18.8cm in length. The light sensor was positioned opposite the laser module, both at a height of 14.5cm. Between the laser and light sensor a wheel (21.5cm diameter) was placed with a round 1cm diameter hole positioned in the location through which the laser beam passed. The wheel was attached to a motor which allowed it to spin clockwise at a speed of approximately one revolution per four seconds.

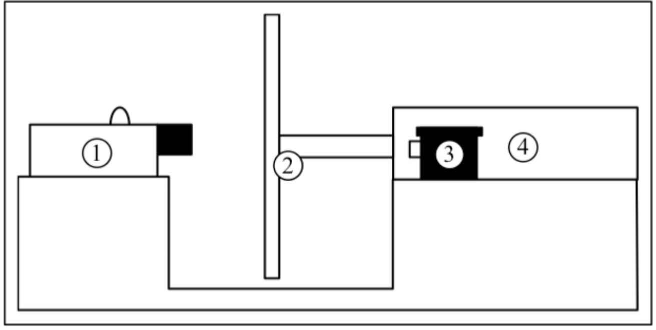

Figure 1: a schematic diagram of the apparatus. 1 = light sensor (containing a Raspberry Pi computer) connected to a red LED bulb; 2 = wheel with 1cm diameter perforation; 3 = laser module; 4 = a box housing a geared motor able to spin the wheel clockwise.

The light sensor module consisted of a 7x7x10cm box housing a raspberry pi computer, with a 10mm LED bulb mounted at its top and the light sensor on its front (facing the laser module). A separate, portable, 5mm red LED bulb was also connected to the computer, but only visible to participants during the non-causal condition (see design and procedure). For the self-causal condition (see design and procedure), a rectangular wooden paddle (6cm in width and 14cm in height, with handle at its centre) with a 1cm diameter hole was used in place of the wheel.

Participants were placed at a chin rest behind the laser module. Participant responses were recorded using a computer mouse on a separate computer. Finally, a debrief questionnaire was used to measure perceived causality using a 9-point Likert Scale (see appendix 1). For each condition, participants were presented with the question "in the condition where [condition description] did it seem like [first event] was causing [second event] (1 = definitely yes, 5 = not sure, 9 = definitely no)?" These scores were inverted for analysis.

Design and Procedure

After completing a consent form, participants were given safety instructions and were allowed to adjust the height of their seat. Instructions were presented verbally at the beginning of the experiment and before each trial. Throughout the experiment participants kept their head in the chin rest, ensuring that the light sensor, wheel and laser beam were visible. Participants were instructed to fixate their gaze on the laser point during the self-causal and mechanical-causal conditions, and on the 5mm diameter LED bulb during the non-causal control condition.

Participants worked through the three conditions, with order of conditions counterbalanced between participants. Each condition consisted of 40 trials, during which participants observed a critical two-event sequence lasting for an interval between 200 – 400ms (randomized, described below) and were asked to reproduce this interval by holding down the left mouse key for their perceived duration. Prior to each experimental block, participants worked through as many practice trials as they needed (minimum: three, regardless of performance) to understand the task. Task comprehension was assessed by the experimenter by observing the participants performing the task to ensure that participants were performing the correct movement (if any) and reporting time intervals after each trial. Probing questions were used to ensure that participants were reporting the correct time intervals and that they did not have any further questions.

The conditions were as follows (see Figure 2 for a photographs of each experimental condition):

Self-causal: Participants performed an intentional action that generated a causal consequence after a short delay. The wheel was placed with the hole aligned to the laser beam and light sensor and remained stationary throughout (i.e. the laser beam could pass through to the light sensor, when allowed through by the participant. The light sensor responded to the laser beam by switching on the 10mm red LED at the top of the housing after a randomised delay of 200-400ms, and switching off after a randomised interval of 200-400ms, if the beam was no longer received. All randomised delays used in the experiment were drawn from a uniform distribution. Participants were told that the sensor responds to the beam after a delay, and this was demonstrated by the experimenter prior to the practice trials by using hand movements to either block the laser or allow it through. Participants were not told any additional information about these delays. Participants were instructed to place the paddle at the bottom of the apparatus, with the hole beneath the laser beam, such that the paddle blocked the beam. Participants were instructed to keep the paddle positioned adjacent to the wheel and move it upwards in front of the laser beam in each trial, such that the laser would pass through the hole. This was done to keep this condition as perceptually similar as possible to the mechanical-causal condition (see below). Participants were instructed to reproduce the time interval between the laser beam reaching the light sensor and the LED lighting up before placing the paddle back for the next trial.

Mechanical-causal: The wheel rotated continuously at a speed of approximately 4 seconds per revolution and blocked the laser beam from reaching the sensor, except when the hole came in line with it (once every 4 seconds). The light sensor was switched on and functioned in the same way as in the self-causal condition. This was demonstrated prior to the practice trials; the experimenter demonstrated that when the laser beam was blocked the light sensor did not respond at all, regardless of the position of the wheel, and that the light sensor always responded after the laser passed through the hole in the wheel. Participants were instructed to reproduce the interval between the laser reaching the sensor and the LED lighting up as in the self-causal condition. Note that in both the self-causal and mechanical-causal conditions, the critical causal event 1 (the laser reaching the light sensor) coincided with the perceptual experience of the laser spot (temporarily) being no longer visible against the paddle or wheel.

Non-causal control: Participants reproduced the interval between two sequential LED flashes. The wheel was positioned in the same way as in the self-causal condition. The laser module was switched off, and the 5mm LED was placed in the hole in the wheel. At the beginning of each trial, the 5mm LED switched on for one second before switching off, followed by the 10mm LED at the top of the housing switching on for 200-400ms. Following this, participants were asked to reproduce the time interval between the 5mm LED switching off and the 10mm LED switching on. Participants were not told any information about the causal relationship between the two lights, but only that they turned on and off in a regular sequence. In order that the switching off of the first light would be equally predictable as the laser passing through the wheel in the mechanical-causal condition participants were informed that the first light will switch off after exactly one second on each trial. This sequence repeated automatically for the duration of the condition, with an overall trial length matching the duration of a single wheel revolution. Participants were instructed to fixate their gaze on the 5mm LED bulb throughout.

At the end of the experiment participants were asked to fill in the debrief questionnaire, where they were asked to report whether they believed the first event in the interval they were judging caused the second event to occur, per condition. These causal ratings were taken as a manipulation check, to ensure participants correctly perceived the causal structure of the self-causal and mechanical-causal conditions (the laser beam causing the light sensor to respond) and the non-causal control condition (both lights shared a common cause). Following this participants were debriefed as to the purpose of this experiment.

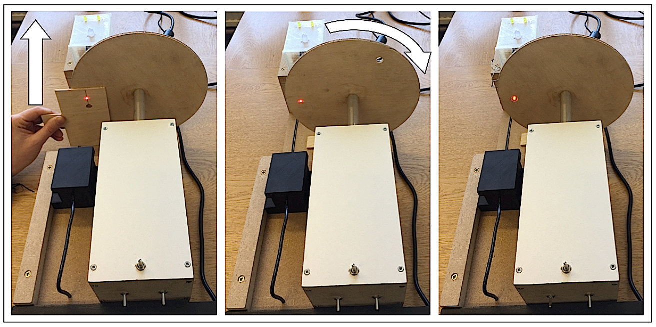

Figure 2: Photographs of all experimental conditions from the participants' perspective. Self-causal condition (left): the paddle is set with the hole below the laser beam at the beginning of a trial. Mechanical-causal condition (centre): the wheel is rotating clockwise and the laser beam is obstructed. Non-causal control (right): the laser beam is

replaced with a red LED bulb positioned where the laser point can be seen in the other two conditions.

Results

Exclusions

Three participants were excluded for failing to follow instructions (consistently making multiple estimates per trial, or making estimates during, rather than between, trials). One further participant was excluded due to a technical error. For all other participants, individual trials for which there were two estimates and estimates which overlapped with the time of the event being judged were removed from analysis (8 participants with excluded trials, mean average 4.88 exclusions out of 120 trials).

Causal estimates

A Friedman's ANOVA was used due to the ordinal nature of the causal scores. We found a significant main effect of condition on causal scores ($X^2(2) = 15.58$, $p < .001$). Post-hoc testing using a Bonferroni correction found significantly lower scores for the non-causal control condition (median = 6) compared with the self-causal condition (median = 8, $p < .05$) and the mechanical-causal condition (median = 8, $p < .05$). No significant difference was found between the self-causal and mechanical-causal conditions ($p > .05$).

Temporal estimates

Transformation A preliminary analysis of the data found significant variability in the range of reproductions between participants (see Table 1 for pre-transformation data). Additionally, a Shapiro-Wilk test found significant deviations from the normal distribution in two of the three conditions ($p < .05$). In order to reduce the influence of individual differences and reduce the positive skew of the data, temporal reproductions were converted to z-scores. To do this, each participant's grand mean was subtracted from each of their interval estimates. The difference from the mean of each score was divided by the standard deviation of all estimates (per participant). The mean z-score per condition for each participant was used for the temporal estimates analysis. Following transformation, the assumption of normality was met for all conditions ($p > .05$). The mean z-scores can be seen in Figure 3.

Table 1: Descriptive Statistics for raw Temporal Reproductions

Condition	Mean	Standard deviation
Self-causal	380.26	197.49
Mechanical-causal	406.8	134.81
Non-causal Control	501.14	315.39

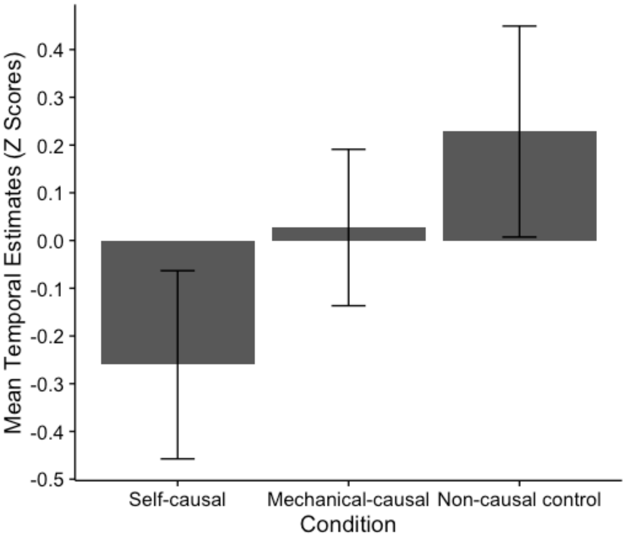

Figure 3: Mean z scores of Temporal Reproductions by condition. Error bars represent the 95% confidence interval.

Analysis A one-way ANOVA found a significant main effect of condition on the z score-transformed estimates, $F(2,50) = 4.46$, $p < .05$, $\eta^2 = .15$, $MSE = 1.57$. Planned simple contrasts were used to investigate the differences between the mechanical-causal condition and both other conditions. A significant difference was found between the mechanical-causal and self-causal conditions ($p = .048$), but not between the mechanical-causal and non-causal control ($p = .23$). The frequentist analysis, therefore, appears to favour the intentional binding account.

A Bayesian analysis was carried out using the BayesFactor package for R statistics (Morey, Rouder, Jamil & Morey, 2015). A Bayesian repeated-measures ANOVA (see Rouder, Morey, Speckman & Province, 2012 for details) found a Bayes factor of 17.23 for the unconstrained model (self-causal ≠ mechanical-causal ≠ non-causal control), indicating that the data observed is over 17 times more likely under the unconstrained model compared with the null model (intercept only). We also analysed three further models, as predicted by the intentional binding account (self-causal < mechanical-causal = non-causal control), the causal binding account (self-causal = mechanical-causal < non-causal control) and the 'intentional boost' account (self-causal < mechanical-causal < non-causal control). The highest Bayes factor was found for the model predicted by the intentional boost account ($BF_{10} = 91.82$), and as such it is the preferred model compared with the models predicted by the intentional binding account ($BF_{10} = 44.57$) and causal binding account ($BF_{10} = 16.22$; denominator = intercept only model for all Bayes factors).

Discussion

We set out to investigate whether the perception of causality is sufficient for temporal binding to occur. We compared temporal estimates across three conditions: self-causal, mechanical-causal and non-causal control. In contrast to the previous work on this topic, the first and second events in each sequence were equally predictable and perceived in the same modality (visual), thus eliminating possible confounding variables.

The results of the Bayesian analysis suggest that the most plausible model underlying our data is one of causal binding with an 'intentional boost'. It is noteworthy, however, that evidence of causal binding is only present in the Bayesian analysis, and cannot be seen in the frequentist planned contrasts. This apparent discrepancy may be the result of effect size; in this case there may have been a causal binding effect which was too small to be detectable under frequentist statistics, but still contributed the intentional boost model being the preferred model in the Bayesian analysis.

Our manipulation check (causal ratings) revealed higher-than-expected perceived causality between the two lights in the non-causal control condition. Although participants reported significantly weaker causal impressions in the non-causal control condition, the median score was 6 (on a 1-9 scale), indicating that 13 of the 26 participants included in the analysis perceived some causal relationship between the two lights. The causal binding view therefore would predict a reduced binding effect in those participants, due to reduced distinctiveness of the causal compared to the control conditions. .Therefore, while the manipulation has been successful in that the majority of participants reported weaker causal links between the two lights than the laser and light sensor, this may not have been sufficiently consistent across the entire sample to result in an effect size detectable by a frequentist analysis.

Although two previous studies have reported an intentional boost to causal binding (Buehner, 2015; 2012), it is still unclear how causal and intentional binding relate to each other. The causal ratings obtained here appear to rule out the possibility that participants perceived stronger causal relationships between the two events when the cause was self-initiated, so the intentional boost cannot be attributed to enhanced causal impressions following self-initiated vs mechanical causal actions. Instead, our findings suggest three possibilities. The first is that there may be two, separate causal and intentional binding effects, of differing strengths and with different roots, acting independently. This appears unlikely, however, in light of previous research suggesting that temporal binding does not occur in the absence of causality (Moore, Langado, Deal & Haggard, 2009; Buehner & Humphreys, 2009). Such findings indicate that the temporal binding effect is inextricably linked to perceived causality; specifically, that causality is necessary for the binding to occur.

An alternative explanation may be that causal binding and the intentional boost are a product of the same Bayesian processes, specifically, Bayesian cue integration. Humans appear to integrate information from multiple sensory cues in a manner that is statistically optimal: Ernst & Banks (2002) found that when judging the height of a stimulus based on visual and haptic information, participants attached more weight to the cue that has lower variance. Moore, Wegner & Haggard (2009) suggested that Bayesian cue integration may also govern our sense of agency. Just as multiple sensory cues contribute to our judgment of physical properties such as size or shape, the perception of intentionality results from multiple cues, both internal (e.g. forward model predictions) and external (sensory cues). Applying this rationale to temporal binding, one could argue that the size of the effect depends on the noisiness of perceptual cues – specifically, the (perceived) times of the action and its consequence. One would expect that if prior expectation of the time of an effect is determined to some extent by the time of its cause, increased certainty in the time of the cause would lead to an increased weight being attached to it. Specifically, the shift in the perceived time of the effect (towards the cause) would be greater, the more certain one was about the time of the cause. While both the manual and mechanical actions were equally predictable in this experiment, participants had additional internal cues to the onset of their own action than to an observed mechanical event. It would be expected that the combination of these cues and visual feedback would lead to a more reliable and less variable percept of the time of the self-cause relative to the time of the machine-cause. As the expected time of the second event must be determined by the time of the first event (the cause is predictive of the effect), a more reliable percept of the time of the cause would lead to a more reliable prior for the time of the second event, which would be weighted more heavily against new cues to the time of the second event. This in turn would result in a greater backwards shift of the perceived time of the effect in the self-causal compared to the mechanical-causal condition. In line with this idea, Zhao et al. (2016) found greater temporal binding when participants had tactile cues to the time of the cause (key-press), compared with an action without tactile feedback (key release).

However, greater certainty in the time of the first action would also mean that it is less liable to be biased by the time of the second event. Altogether, Bayesian cue integration would thus be expected to lead to a lesser forward shift in the perceived time of the self- compared to the mechanical-cause, but a greater shift in the perceived time of the consequence towards a self- compared to a mechanical-cause. Thus, Bayesian cue integration based purely on the noisiness of the temporal cues leads to two distinct shifts in event perception working in opposite directions. We would argue that in addition to perceptual cues, the Bayesian integration process also takes into account expectations of cause-effect contiguity, in line with Hume's (1888) principles of causal inference. Crucially, that causes are predictive of their effect forms a key part of how we perceive causality; we perceive one event as causing another when it comes before it, when the second event occurs close in time to the first event and when the second event is contingent upon the first. The cause is thus more predictive of the effect than vice versa. These assumptions, however, do not necessarily accompany the perception of events which are not causally related (e.g. a non-causal sequence of events). Furthermore, previous research (e.g. Haggard et al., 2002) has shown that outcome binding (i.e. shifts in the awareness of an outcome towards its cause) is typically greater than action binding (shifts in the awareness of a causal action towards its consequence). Therefore, the combined influence of the nature of causal relationships and the perceptual differences between self-action and mechanical actions may explain the presence of both causal binding and an intentional boost in our findings, within a single model.

More research is needed to determine what underlies the intentional boost to causal binding. The majority of research investigating the effect of agency on temporal binding to date has failed to take account of the potential role of causality: This is evidenced by failure to include adequate non-causal control conditions (e.g. Caspar, Christensen, Cleeremans & Haggard, 2015; Zhao et al, 2016), or to obtain causal ratings as manipulation checks (e.g. Haggard et al, 2002). The present findings demonstrate the importance of control conditions in temporal binding, without which a reduced magnitude of temporal binding is indistinguishable from the absence of temporal binding. In particular, if there is indeed an intentional boost to causal binding, this calls for a reinterpretation of research suggesting there is no temporal binding effect in the absence of intentional action.

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