Cognition 146 (2016) 100–109

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

How action structures time: About the perceived temporal order of action and predicted outcomes

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ARTICLE INFO

Article history:
Received 27 November 2014
Revised 12 August 2015
Accepted 24 August 2015
Available online 24 September 2015

Keywords:
Action
Prediction
Agency
Causality
Temporal order

ABSTRACT

Few ideas are as inexorable as the arrow of causation: causes must precede their effects. Explicit or implicit knowledge about this causal order permits humans and other animals to predict and control events in order to produce desired outcomes. The sense of agency is deeply linked with representation of causation, since it involves the experience of a self-capable of acting on the world. Since causes must precede effects, the perceived temporal order of our actions and subsequent events should be relevant to the sense of agency. The present study investigated whether the ability to predict the outcome of an action would impose the classical cause-precedes-outcome pattern on temporal order judgements. Participants indicated whether a visual stimulus (dots moving upward or downward) was presented either before or after voluntary actions of the left or right hand. Crucially, the dot motion could be either congruent or incongruent with an operant association between hand and motion direction learned in a previous learning phase. When the visual outcome of voluntary action was congruent with previous learning, the motion onset was more often perceived as occurring *after* the action, compared to when the outcome was incongruent. This suggests that the prediction of specific sensory outcomes restructures our perception of timing of action and sensory events, inducing the experience that congruent effects occur after participants' actions. Interestingly, this bias to perceive events according to the temporal order of cause and outcome disappeared when participants knew that motion directions were automatically generated by the computer. This suggests that the reorganisation of time perception imposed by associative learning depends on participants' causal beliefs.

1. Introduction

The detection of causal relations is essential for our survival. Representing the causal structure of the world permits us to predict events and produce desired outcomes. Furthermore, individuals construct the sense of themselves as a distinct entity in the world through the experience of their own agency (Gallagher, 2000; Haggard & Tsakiris, 2009).

Several studies have shown that the perception of causality in general, and agency in particular, are intimately connected to time perception, and influence one another (Buehner & Humphreys, 2009; Desantis, Roussel, & Waszak, 2011; Eagleman & Holcombe, 2002; Faro, Leclerc, & Hastie, 2005; Shanks, Pearson, & Dickinson, 1989; Young, 1995). For instance, outcomes are perceived to occur earlier in time when people believe that they are self-generated, compared to when they erroneously believe they are generated by another agent (Desantis et al., 2011; Haering & Kiesel, 2012).

In addition, causal relationships are not directly perceived (Hume, 1920; Michotte, 1963) but inferred from the temporal relationships between action and subsequent outcome (Shanks et al., 1989). For instance, temporally contiguous outcomes are more likely to be perceived as generated by our actions (Farrer, Valentin, & Hupé, 2013; Wegner & Wheatley, 1999; Young, 1995). Moreover, the temporal order of our actions and other events is highly relevant to our understanding of agency and causality (Hume, 1920): whether an event is perceived as following or preceding our action can influence perception of agency, because causes must precede outcomes.

Recent studies have shown that the perception of the order of an action and an ensuing outcome is modulated by temporal expectancy. In particular, the brain 'recalibrates' predictable delays. For example, if a sensory event reliably occurs at a predictable delay following an action, but then unexpectedly occurs after a somewhat shorter delay, it may be misperceived as actually

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http://dx.doi.org/10.1016/j.cognition.2015.08.011
0010-0277/

preceding the action that caused it (Stetson, Cui, Montague, & Eagleman, 2006). This important finding suggests that the nervous system forms expectations about the temporal relationship between actions and sensory inputs which, in turn, are used to determine agency and causality.

However, the processing of perceptual outcomes is not only influenced by *when* a perceptual consequence is expected to occur. The nervous system also forms predictions about *which* specific sensory event will occur (Friston, 2005). For instance, it has been shown that predicted sensory outcomes are perceived as less intense compared to unpredicted and externally generated stimuli (Bays, Wolpert, & Flanagan, 2005; Blakemore, Goodbody, & Wolpert, 1998; Cardoso-Leite, Mamassian, Schütz-Bosbach, & Waszak, 2010; Hughes, Desantis, & Waszak, 2013; Tsakiris & Haggard, 2003).

However, the relation between predicting *what* will happen (i.e., outcome prediction), and the experience of *when* it happens remains unclear. Previous studies suggest that predicting the specific outcome of an action does not alter the intentional binding phenomenon (Desantis, Hughes, & Waszak, 2012; Haering & Kiesel, 2014; see also Haggard, Poonian, & Walsh, 2009): the perceptual latency of an event seems independent of whether that specific event could be predicted from the specific action that was made. However, these studies did not investigate whether or not the prediction of a specific outcome restructures the *temporal order* of action and outcome. This issue is of importance, as an effect of this kind would imply a strong link between outcome prediction and agency. Indeed, the ability to predict what will happen as a result of one's action appears to be an important starting point for agency. For example, match or mismatch between predicted and actual sensory events might lead the system to label sensory events as self or externally generated, respectively (e.g., Blakemore, Wolpert, & Frith, 2002; Frith, 2005; Sato & Yasuda, 2005; Wolpert, 1997). Interestingly, recent studies showed that predicted sensory outcomes are represented by the brain during motor preparatory processes (e.g., Desantis, Roussel, & Waszak, 2014; Ziessler & Nattkemper, 2011), thus before action execution. From these two pieces of information we hypothesised that when a specific event is expected to appear as a consequence of a specific action, even though it is presented before that action, it would be experienced as occurring after it, thus creating an illusion of agency for predicted outcomes.

The present study includes three experiments investigating this issue. In all three experiments participants completed a temporal order judgment task. They indicated whether a visual stimulus (downward or upward dot motion) was presented either before or after a voluntary key-press (Desantis et al., 2014). To investigate the influence of the prediction of sensory outcome on time perception we varied the match/mismatch between predicted and actual sensory outcomes (for similar methods see Hughes et al., 2013; Roussel, Hughes, & Waszak, 2013). Notably, visual stimuli could be congruent or incongruent with the action–outcome relation established in a previous operant learning phase.

In Experiment 1 the temporal order judgement task was couched in a causal judgment framework. Notably, we explicitly instructed participants that either the computer could trigger the visual motion, or their action could do so, depending on the timing of occurrence. In Experiment 2 we eliminated the explicit instructions of agency of Experiment 1. In Experiment 2, participants were simply required to indicate whether the dots moved before or after their action, while no explicit information about precedence or causation was provided.

Regarding Experiments 1 and 2, we hypothesised that learning the relationship between an action and its outcome would impose a reorganised causal structure on these events. In particular, operant learning should lead to the familiar cause-precedes-outcome relation. Thus, learning that a specific action predicts a specific outcome should produce a bias to perceive that specific outcome as occurring *after* an action, rather than before.

Experiment 3 aimed at assessing whether the influence of action–outcome learning on time perception is modulated by the causal context in which participants perform the temporal judgment task. In Experiments 1 and 2, dot motion was indeed contingent upon the participant's action, at least in some trials. However, in the temporal judgment task of Experiment 3, participants were explicitly told that dot motion was always independent of their action. Previous studies showed that causal context and causal belief are strong modulators of the perception of time of action and sensory outcome (Desantis et al., 2011; Moore, Lagnado, Deal, & Haggard, 2009). For instance, outcomes are perceived to occur earlier in time when people believe that they are self-generated, compared to when they erroneously believe they are generated by another agent (Desantis et al., 2011; Haering & Kiesel, 2012). Desantis et al. suggested that people's prior causal belief affects predictive mechanisms, for example, by determining how reliable the cognitive system considers predictive signals to be or whether or not a predictive signal is computed in the first place. Accordingly, we hypothesised that the modulating effects of action–outcome learning on time perception might be reduced or erased when participants knew that they did not generate any dot motion in the test phase.

2. Experiment 1

2.1. Method

2.1.1. Participants

14 Participants (9 females; $M = 23.5$, $SD = 4.13$) participated in the experiment for a payment of £ 7.5/h. All had normal or corrected-to-normal vision and hearing and were naïve as to the hypothesis under investigation. They all gave written informed consent.

2.1.2. Stimuli

The stimuli were presented on a DELL LCD monitor (60 Hz refresh rate) set at about 55 cm from participants' eyes. Stimulus presentation and response recording were controlled in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were Random-Dot-Kinematograms (RDKs): a sequence of random dots that appeared within a 7 deg diameter circular aperture centred around fixation (a blue dot of size 0.169 deg). The black and white dots (size 0.113 deg), were presented on a grey (22 cd/m^2) background with a density of 14.3 dots/deg^2/s. Dots moved randomly in one of all possible directions with a speed of 1 deg/s (0.0167 deg/frame). However, after participants' key-presses (in the learning phases; see below) or on a random basis, before or after participants' key-presses (in the test phases; see below) all dots moved coherently upward or downward. During this coherent motion, on each video frame the dots were shifted 0.0668 deg either upward or downward. This corresponds to a speed of 4 deg/s. Each dot had a life time of 8 frames. Thereafter, it disappeared and immediately reappeared in a new location within the circular aperture.

2.2. Procedure

Participants completed 40 blocks, each consisting of an association phase and a test phase.

2.2.1. Association phase

The aim of the association phase was to make participants learn action–outcome associations. Participants viewed an ongoing RDK. They were required to execute left or right index finger key-presses at a time of their own choosing, but at intervals of at least 330 ms, with random yet approximately equiprobable choice between the two alternatives. Feedback on the proportion of right and left key-presses was provided every 10 trials. Each key-press immediately triggered a 100% coherent dot motion. For half of the participants, left key-presses moved the dots upward and the right downward. For the rest of the participants the reverse mapping was used. Coherent motion was presented for 3 video frames (about 50 ms) beginning with the key-press, and random motion then returned. To ensure that participants were paying attention to the dot motion and that they learned the action–outcome mapping, in 15% of the trials their key-presses triggered an incongruent dot motion, i.e., the motion that was associated with the other hand (Fig. 1). Participants were asked to report detection of the incongruent events by pressing both keys as fast as possible. The association phase consisted of 40 trials in the first block, and 20 trials thereafter.

2.2.2. Test phase

After each association phase, participants completed a short test phase which assessed the influence of action–outcome learning on the perception of temporal order of action and sensory event. Participants were asked to execute left/right actions at about 500 ms after a go signal (a 700 Hz sinusoidal tone, 50 ms of duration, presented at 69 dB). Participants again chose randomly and approximately equiprobably, and were given summary feedback of their choices after every five trials. Only those trials in which participants performed an action within 350 ms and 800 ms after the go signal were considered as "correct" trials. Faster or slower responses were replaced with new trials. Crucially, however, the timing of action and outcome were now randomly varied, so that we could test the perceived temporal order of action and visual motion. Notably, 100% coherent upward or downward motion was delivered at one of ten different latencies −133, −100, −66, −50, −33, 33, 50, 66, 100 or 133 ms relative to the mean action latency on all previous test phases. Negative SOAs indicate that the dot motion was presented before the mean action time and positive SOAs indicate that the dot motion was presented after the mean action time. For the first block, mean action times were calculated in a short training session where participants were simply asked to execute key-presses within a time window of 350–800 ms after a go signal.

Crucially, dot motion direction was random. That is, it randomly did or did not respect the action–outcome congruency participants had learned in the previous acquisition phases. Thus, any outcomes of congruency in the test phase would be results of previous learning during the acquisition phase about the mapping between specific actions and specific motion directions. Coherent dot motion was presented for 50 ms. Thereafter, the dots moved randomly for 433 ms and disappeared. Participants then indicated whether the dots moved coherently "before" or "after" their key-press. In order to ensure that participants understood the relation between causation and temporal order, participants were explicitly told that this task was equivalent to indicating whether the dot motion was triggered by the computer ("before") or by the participant ("after"). They registered their judgement on each trial in a way designed to avoid lateralised responding. Participants were asked to press the space bar to make the two options "before (computer)" and "after (you)" alternate on the screen. Then, participants had to press both left and right keys together to select one of the two options (Fig. 2). This procedure was used to avoid possible bias from a one-handed response being used both to report the decision and to trigger the next trial. Importantly, participants were explicitly told that the direction of the motion was irrelevant for the temporal order task.

Note that for all except for the two longer positive SOAs (i.e., +100 and +133) the dot motion was automatically triggered by the computer. The dot motion scheduled at 100 ms and 133 ms after participants' mean action time was presented only if participants actually executed a key-press before the scheduled dot onset time. That is, if in a trial n the dot motion was scheduled to be presented 633 ms after the go signal (i.e., 500 ms [mean action time] + 133 ms [SOA]), dot motion was presented only if the participant executed a key press at time $t < 633$ ms. If this delay passed without any key-press, the trial stopped and no dot motion was presented. This was meant to maintain the participants' belief that in some trials key-presses were causally related to the presentation of the stimulus.

To make sure that participants encoded the direction of the dots in 15% of the trials, in addition to the TOJ task, participants were required to indicate the direction of the coherent motion. To indicate their response participants pressed either the left (letter A) or the right key (letter L). To be more precise, according to the action–outcome mapping for half of the participants the left key indicated upward motion and the right key downward motion. For the other half the reversed mapping was used. For instance, if in the association phase a left key-press (letter A) triggered an upward motion, in the test phase the same key-press indicated the upward motion response in the catch trials. We thought that this would be an easy way to indicate the motion direction participants perceived, and it would also reinforce action–outcome mappings. In addition, at the end of the experiment participants were asked whether they had the impression of generating "more", "less" or "roughly an equal"

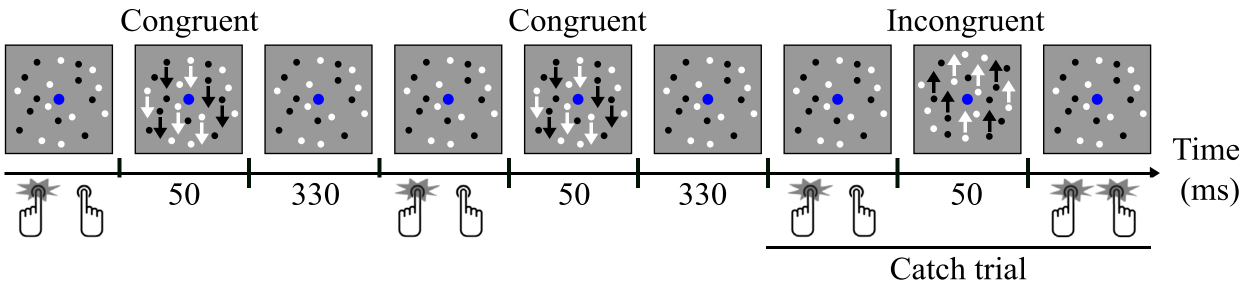

Fig. 1. Illustration of the acquisition phase. Participants executed randomly and about equally often left or right index finger key-presses, at intervals of at least 330 ms. Each key-press triggered a 100% coherent dot motion. Coherent motion was presented for 50 ms immediately after the key-press. Thereafter the dots moved randomly until the next key-press was executed. Occasional 'catch' trials produced an incongruent motion direction. Participants were required to respond to this event with a rapid bimanual key press.

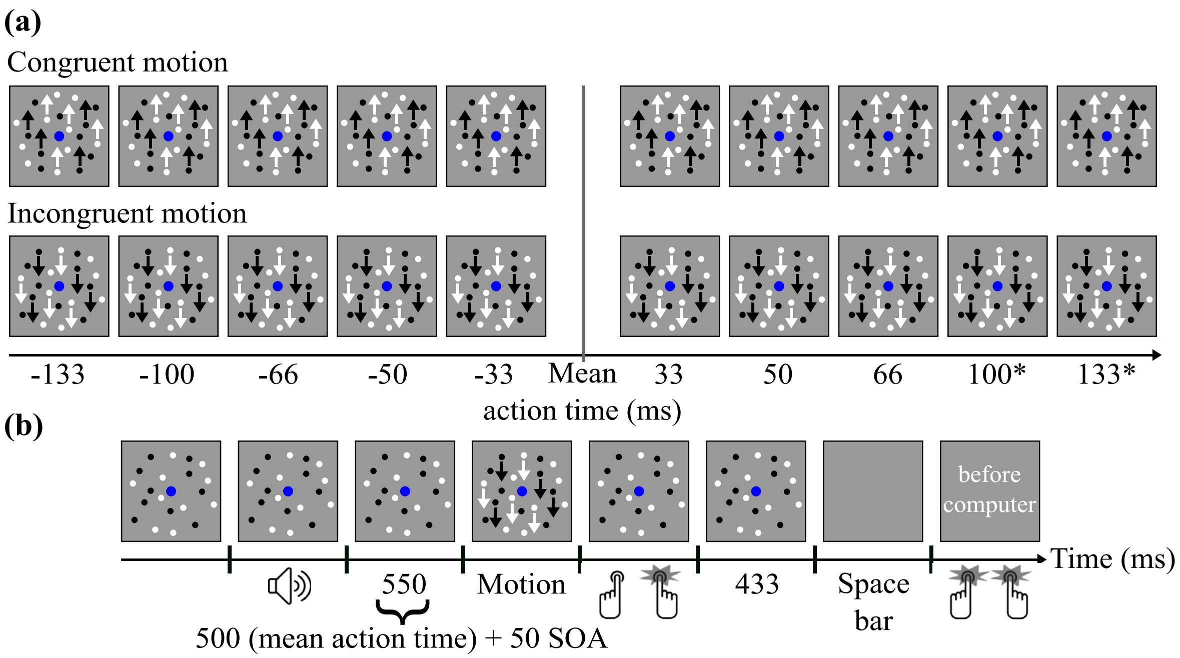

Fig. 2. (a) Illustration of the factorial design. Participants executed a left/right key-press in a time window of 350–800 ms after a pure tone. They were randomly presented with congruent or incongruent trials in which the action–outcome association they learnt in the association phase was respected or violated, respectively. Congruent/incongruent motion was delivered at one of ten different latencies −133, −100, −66, −50, −33, 33, 50, 66, 100 or 133 ms relative to the mean action latency on all previous test phases. (b) Illustration of a test phase trial. Participants executed a left/right action after the presentation of a sound. The onset of the dot motion was determined by adding/subtracting one of the SOA (i.e., +50 ms SOA) to/from the mean action latency calculated on all previous test phases (i.e., 500 ms [mean action time] + 50 ms (SOA) = 550 ms dot motion onset). Participants were required to indicate whether the coherent dot motion was presented before or after their key-press.

amount of coherent dots motion compared to those generated by the computer.

Each test phase consisted of 10 trials (400 test trials in total). Each SOA was presented 20 times (200 trials in total) multiplied by 2 congruency conditions.

2.3. Data analyses

Because stimuli were delivered on the basis of *estimated* action time, we calculated the actual action–motion interval for each trial. Then, we divided the stimulus-before-action trials into 5 time intervals of equal number of trials for both congruent and incongruent trials (see Table 1 for mean and standard deviation of number of trials for each bin). We applied the same procedure to the stimulus-after-action trials (see Table 2 for mean and standard deviation of time intervals for each bin).

The proportion of “dot motion after” responses was then calculated separately for each participant, each congruency condition and each time interval. Psychometric Functions (cumulative Gaussians) were fitted using the Palamedes Toolbox for Matlab which implements the maximum-likelihood method described by Prins and Kingdom (2009; www.palamedestoolbox.org). Based on each individual function, we calculated the Point of Subjective Simultaneity (PSS) and the Just Noticeable Difference (JND). The PSS reflects the time interval before/after action execution at which the dot motion had to be presented to be perceived as occurring simultaneously with the action. The JND, defined as half the inter-quartile range, is a measure of the slope of the psychometric function, and reflects participants’ sensitivity to time discrimination. The level of significance of our analysis was set at $p < .05$ for all statistical tests.

2.4. Results

The results of the test phase are shown in Fig. 3. Participants reported congruent motion to occur *after* their action, relative to incongruent motion. The PSS values (congruent $M = -103$ ms, $SD = 54$ ms; incongruent $M = -82$ ms, $SD = 52$ ms) were significantly different $t(13) = -6.29$, $p < .000$, $d = 0.396$ (Fig. 3a). Moreover, single t-tests showed that both congruent ($t(13) = 7.155$,

Table 1
Mean (*SD*) number of trials for each of the ten resampled bins in Experiments 1, 2 and 3.

Conditions	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Experiment 1										
Congruent	21.1(2.9)	21.1(2.9)	21.1(2.9)	21.1(2.9)	21.2(2.8)	19(3.3)	19(3.3)	19(3.3)	19(3.3)	19.1(3.7)
Incongruent	21.6(3.3)	21.6(3.3)	21.6(3.3)	21.6(3.3)	21.3(3.3)	18.3(2.7)	18.3(2.7)	18.3(2.7)	18.3(2.7)	18.3(2.7)
Experiment 2										
Congruent	21.3(4)	21.3(4)	21.3(4)	21.3(4)	20.8(4.5)	19(3.9)	19(3.9)	19(3.9)	19(3.9)	18.6(4.5)
Incongruent	21.7(2.8)	21.7(2.8)	21.7(2.8)	21.7(2.8)	22.2(3)	17.9(3.2)	17.9(3.2)	17.9(3.2)	17.9(3.2)	17.9(3.2)
Experiment 3										
Congruent	21.3(5.3)	21.3(5.3)	21.3(5.3)	21.3(5.3)	21.3(6.2)	19(5.4)	19(5.4)	19(5.4)	19(5.4)	19.1(6.6)
Incongruent	20.3(5.5)	20.3(5.5)	20.3(5.5)	20.3(5.5)	20.1(5.6)	19.4(5.3)	19.4(5.3)	19.4(5.3)	19.4(5.3)	19(3.3)

Table 2
Mean (*SD*) of time intervals in milliseconds for action–motion interval for each of the ten resampled bins in Experiments 1, 2 and 3. Because stimuli were delivered on the basis of *estimated* action time, we calculated the actual action–motion interval for each trial.

Conditions	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9	Bin 10
Experiment 1										
Congruent	−213(33)	−128(20)	−85(17)	−48(13)	−11(5)	27(5)	57(11)	92(12)	133(15)	198(21)
Incongruent	−220(30)	−134(23)	−87(18)	−49(15)	−12(6)	26(5)	56(10)	90(12)	133(17)	199(21)
Experiment 2										
Congruent	−225(35)	−135(27)	−87(20)	−45(13)	−10(4)	26(4)	53(9)	85(11)	126(12)	188(13)
Incongruent	−219(39)	−133(27)	−87(23)	−51(17)	−12(5)	25(3)	57(8)	89(12)	130(14)	192(14)
Experiment 3										
Congruent	−218(44)	−131(32)	−84(23)	−45(16)	−10(5)	25(5)	57(15)	93(19)	137(26)	199(33)
Incongruent	−216(39)	−131(34)	−82(22)	−42(14)	−9(6)	27(6)	62(15)	95(22)	137(31)	198(43)

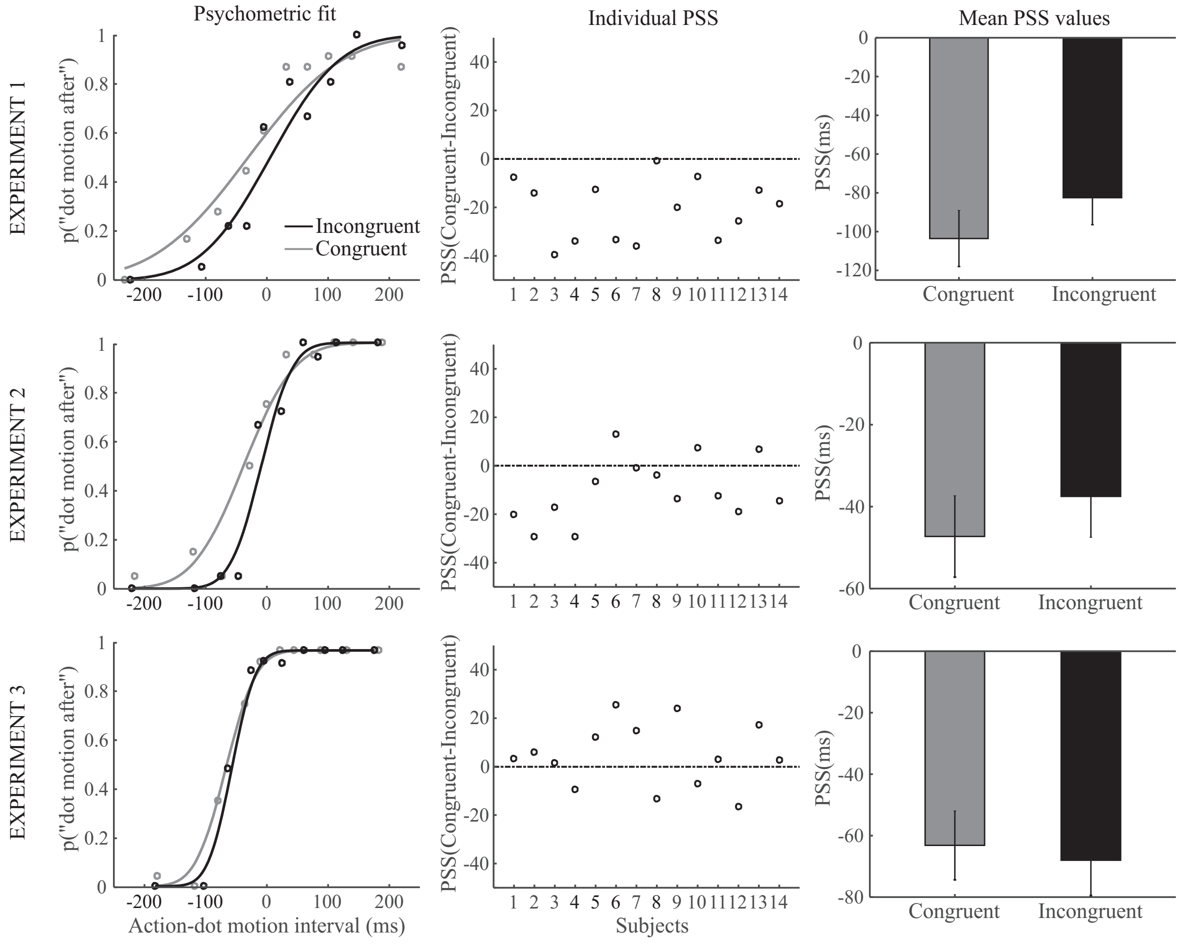

Fig. 3. Left panel: The psychometric function for one participant in Experiments 1, 2 and 3. The figures depict the proportion of "dot motion after" responses for congruent (grey line) and incongruent stimuli (black line) as a function of the ten time intervals. Central panel: The figures depict the difference PSS (congruent) – PSS (incongruent) for each participants in Experiments 1, 2 and 3. A negative difference indicates that congruent dot motion was perceived more often as occurring after the action compared to incongruent dot motion. Right panel: Mean PSS value and standard errors for both congruent and incongruent trials in Experiments 1, 2 and 3.

$p < .000$, $d = 1.907$) and incongruent coherent dot motions ($t(13) = 5.909$, $p < .000$, $d = 1.577$) where perceived more often after the physical onset time of actions (i.e., 0 ms, physical temporal simultaneity between action and coherent dot motion).

We did not observe any differences between congruent and incongruent JND values $t(13) = 1.14$, $p = .27$. Mean r^2 – as a measure of the goodness-of-fit – for the two conditions were as follows: congruent $M = 0.874$, $SD = 0.076$; incongruent $M = 0.888$, $SD = 0.077$.

Three control analyses investigated whether the differences between congruent and incongruent judgements could reflect factors other than the match/mismatch between predicted and actual sensory outcome. Participants were asked to press the left and the right key equally often. Since presentation of coherent dot motion was in some trials triggered before action execution, participants could have been biased towards executing more congruent than incongruent key-presses. In order to rule out this possibility we compared the number of congruent and incongruent key-presses for the stimulus-before-action trials. A paired two-tailed *t*-test showed no significant difference between number of congruent ($M = 105.5$; $SD = 14.31$) vs. incongruent ($M = 107.93$; $SD = 16.08$) trials, $t(13) = -0.65$, $p = 0.53$. Thus, participants were not biased in executing the congruent action after perceiving the dot motion.

Furthermore, we assessed whether the difference between congruent and incongruent trials was driven by a difference in action time. To do so, we compared action time for congruent ($M = 525$ ms, $SD = 45$ ms) vs. incongruent ($M = 530$ ms, $SD = 48$ ms) trials. A paired two-tailed *t*-test did not show any difference between action times $t(13) = -1.54$, $p = 0.15$ confirming that action time did not modulate the congruency effect.

To assess whether participants were attending more congruent compared to incongruent stimuli we compared the proportion of correct stimulus identification in the catch trials for congruent ($M = 0.91$, $SD = 0.09$) and incongruent motion ($M = 0.87$, $SD = 0.10$) and no significant difference was found $t(13) = 1.58$, $p = 0.14$.

Finally, participants had the impression of generating "roughly an equal" amount of coherent dot motion in the TOJ task compared to the computer.

2.5. Preliminary discussion

Experiment 1 shows that congruent sensory events were perceived more often as occurring after action execution. This suggests that the match or mismatch between predicted and actual outcome can restructure the perceived time of occurrence of action and outcome. The causal association between specific actions and specific sensory events established in the acquisition phase subsequently shapes participants' perception of temporal order of action and sensory events. That is, the perception of time was constrained by learning specific action–outcome relations.

However, the temporal order judgement task was couched in a causal judgment framework, because we explicitly instructed participants that either the computer could trigger the visual motion, or their action could do so, depending on the timing of occurrence. Thus, participants had causal information about action–outcome relations from two distinct sources. First, they implicitly acquired causal information about the relation between particular action identities and particular motion directions during the acquisition phase. Second, they were explicitly given causal information about temporal precedence between action and visual motion during the instructions, but this information made no reference to congruence of identity relations. Our modulation of PSS by congruence suggested that the acquired causal relation between action and motion identities influenced time perception. However, we cannot exclude the possibility that participants might link action–outcome congruence to time perception because our instructions explicitly drew attention to the temporal precedence aspects of causation. To investigate this issue, we ran a second experiment in which participants were simply required to indicate whether the dots moved before or after their action, while no explicit information about precedence or causation was provided.

3. Experiment 2

3.1. Methods

3.1.1. Participants

14 Participants (7 females; $M = 22.14$, $SD = 2.60$) participated in the experiment and received payment of £ 7.5/h. All had normal or corrected-to-normal vision and hearing and were naïve as to the hypothesis under investigation. They all gave written informed consent.

3.1.2. Association phase

Same as in Experiment 1.

3.1.3. Test phase

The test phase was identical to Experiment 1, except that in Experiment 2 no instruction was given linking the judgment "before" and "after" and the causal attribution "computer" and "self" was provided. Participants were simply asked to indicate whether the dots moved before or after their key-press. They were instructed that dot motion direction was irrelevant to the task.

3.2. Results

The results are shown in Fig. 3. Participants reported congruent motion to occur *after* their action, relative to incongruent motion. PSS values comparing congruent ($M = -47$ ms, $SD = 37$ ms) and incongruent ($M = -37$ ms, $SD = 37$ ms) trials showed a significant difference $t(13) = -2.81$, $p = .015$, $d = 0.27$. Single *t*-tests showed that both congruent ($t(13) = 4.79$, $p < .000$, $d = 1.27$) and incongruent coherent dot motions ($t(13) = 3.75$, $p = .002$, $d = 1$) where perceived more often after the physical onset time of actions.

We did not observe any differences between congruent and incongruent JND values $t(13) = 1.39$, $p = 0.19$. Mean r^2 – as a measure of the goodness-of-fit – for the two conditions were as follows: congruent $M = 0.861$, $SD = 0.088$; incongruent $M = 0.893$, $SD = 0.089$.

We performed the same three control analyses as in Experiment 1, to investigate whether the differences between congruent and incongruent judgements could reflect factors other than the match/mismatch between predicted and actual sensory outcome. In order to rule out the possibility that in the stimulus-before-action trials dot motion biased participants in executing congruent key-presses we compared the number of congruent vs. incongruent stimulus-before-action trials. Two-tailed *t*-test showed no significant difference between number of congruent ($M = 106.21$, $SD = 20.58$) vs. incongruent ($M = 109.07$, $SD = 14.04$) trials, $t(13) = -0.85$, $p = 0.41$. Thus, participants did not execute more often congruent actions.

To assess whether the difference between congruent and incongruent trials was not driven by a difference in action time, we compared action time for congruent ($M = 494$ ms, $SD = 30$ ms) vs. incongruent ($M = 492$ ms, $SD = 30$ ms) trials. A paired two tailed *t*-test showed no difference between reaction times, $t(13) = 1.06$, $p = 0.30$.

To assess whether participants were attending more congruent compared to incongruent stimuli we compared performances to catch trials for congruent ($M = 0.92$, $SD = 0.08$) and incongruent ($M = 0.92$, $SD = 0.05$) motion, $t(13) = -1.33$, $p = 0.89$. Finally, participants had the impression of generating "roughly an equal" amount of dot motion in the test phase.

3.3. Preliminary discussion

Experiment 2 appeared to participants as a 'pure' TOJ task, without the causal judgement framework given in Experiment 1. We nevertheless replicated the findings we observed in Experiment 1. Explicit instructions regarding temporal precedence in Experiment 1 did contribute significantly to congruence effects on time perception. However, and crucially, the acquired causal link between action and outcome identity significantly affected time perception even when the experimental framework made no reference to the temporal precedence aspects of causation.

Taken together these results suggest that causal relation between action and outcome during the association phase creates a perceptual bias in the test phase, so that visual stimuli congruent with the acquired operant agency relation are perceived as occurring later than comparable stimuli that do not share the agency relation. The modulating effect of action–outcome learning on time perception can best be understood in terms of predictive processes.

Notably, the match or mismatch between predicted and actual sensory events led participants to perceive dot motion after/before action execution respectively (see Section 5).

Experiment 3 aimed at investigating whether the congruence effect depends on participants' causal beliefs about the relation between actions and sensory events. Previous studies have shown that the belief of being or not the cause of a sensory event modulates the intentional binding phenomenon. Desantis et al. (2011), for example, showed that the shift in the perceived time of the sensory outcome was abolished when participants were led to believe erroneously that the outcome was not caused by them but by another agent. Moreover, Moore et al. (2009) asked participants to make key-press actions to cause a tone. In an experimental block, the same tone frequently occurred anyway, even in the absence of actions, while in a control block it did not. Thus, the contingency of the tone on the action, which is widely taken as a cue for causation and agency (Dickinson & Balleine, 2000) was lower in the experimental block. The lower contingency in the experimental block lead to a reduction in action binding (a perceived shift in time of the action towards the consequent tone; Haggard, Clark, & Kalogeras, 2002). Taken together these studies suggest that the causal context is a strong modulators of the perception of time of action and sensory outcome. People presumably learn whether their actions cause particular sensory events, leading to changes in temporal experience.

In the temporal order judgment task of experiments 1 and 2 participants' experienced that in some trials they were generating the dot motion presentation. In Experiment 1 this experience partly depended on our instructions. However, in Experiment 2, in which no explicit information about causation was provided, this impression of causality must have been inferred from the temporal precedence of action with respect to the dot motion; an inference that was corroborated by the small number of trials in which the action actually triggered the onset of directional visual motion (i.e., the +100 and +133 ms see Section 2.2.2 of Experiment 1). Indeed, if participants failed to respond within the designated time window, no visual motion was presented (those trials represented 2.7% of the total number of trials). This sensory evidence presumably lead them to correctly believe that their actions do cause the visual motion stimulus in some trials.

In Experiment 3 we investigated the importance of the causal context in the congruence effect we observed, by making two key changes to the experimental design. First, participants were now explicitly told that dot motion was automatically generated by the computer. Second, we removed all trials in which stimulus presentation was contingent to action execution, replacing them with trials at similar latency with respect to the action, but triggered by the computer based on an estimate of the participant's action time. If our effects on time perception are due to participants' understanding of the causal structure of temporal order judgment task then these changes should abolish/significantly reduce congruence effects on TOJ.

4. Experiment 3

4.1. Method

4.1.1. Participants

14 Participants (9 females; $M = 24.07$, $SD = 4.18$) participated in the experiment for a payment of £ 7.5/h. All had normal or corrected-to-normal vision and hearing and were naïve as to the hypothesis under investigation. They all gave written informed consent.

4.1.2. Acquisition phase

See Experiments 1 and 2.

4.1.3. Test phase

In Experiment 3, participants were told that coherent dot motion was automatically generated by the computer. Thus, participants' key-presses never generated coherent dot motion. Whereas +100 and +133 ms trials in Experiments 1 and 2 were directly triggered from the participants' key-press, the equivalent trials in Experiment 3 were, like all the other trials, generated based on the expected mean action latency, with no reference to current action.

4.2. Data analyses

See above.

4.3. Results

A paired two tailed *t*-test on PSS values comparing congruent ($M = -63$ ms; $SD = 42$ ms) and incongruent trials ($M = -68$ ms; $SD = 43$ ms) did not show any significant effect $t(13) = 1.33$, $p = .21$. However, single *t*-tests showed that both congruent ($t(13) = 5.63$, $p < .000$, $d = 1.5$) and incongruent coherent dot motions ($t(13) = 5.91$, $p < .000$, $d = 1.58$) where perceived more often after the physical onset time of action execution (i.e., 0 ms, physical temporal simultaneity between action and coherent dot motion).

We did not observe any differences between congruent and incongruent JND values $t(13) = 0.55$, $p = .59$. Mean r^2 – as a measure of the goodness-of-fit – for the two conditions were as follows: congruent $M = 0.816$, $SD = 0.118$; incongruent $M = 0.815$, $SD = 0.124$.

We performed the same three control analyses as before, for consistency with the previous experiments. In order to rule out the possibility that in the stimulus-before-action trials dot motion biased participants in executing congruent key-presses we compared the number of congruent vs. incongruent stimulus-before-action trials. Two-tailed *t*-test showed no significant difference between number of congruent ($M = 105.5$, $SD = 14.31$) vs. incongruent trials ($M = 107.93$, $SD = 16.08$), $t(13) = 1.40$, $p = 0.18$. Thus, participants did not execute more often congruent than incongruent actions.

We compared action time for congruent ($M = 508$ ms, $SD = 41$ ms) vs. incongruent trials ($M = 506$ ms, $SD = 41$ ms), a paired two tailed *t*-test showed no difference between reaction times $t(13) = 1.57$, $p = 0.14$.

To make sure that participants encoded equally congruent and incongruent dot motion in the test phase, we compared performances to catch trials in the test phase for congruent ($M = 0.88$, $SD = 0.11$) and incongruent motion ($M = 0.89$, $SD = 0.11$). No difference was observed $t(13) = 0.40$, $p = 0.70$.

In addition, we conducted a between-experiment mixed ANOVA on PSS with Experiment (Experiments 1, 2, and 3) as a between-subjects factor and Congruency (congruent, incongruent) as a within-subjects factor. There was a significant interaction between Experiment and Congruency $F(2,39) = 13.863$, $p < .000$, $\eta_p^2 = 0.415$. The interaction effect was driven by a significant difference in the congruence effect observed in the three experiments i.e., the presence of a congruency effect in Experiments 1 and 2 and the absence of one in Experiment 3 (see also results of experiments 1 and 2). The analyses reported also a main effect of Experiment $F(2,39) = 4.574$, $p = .016$, $\eta_p^2 = 0.19$. Independent samples *t*-tests showed that visual motion stimuli were more often perceived after action execution in Experiment 1 compared to Experiment 2 ($p = .007$, $d = 1.113$), no difference was observed between Experiments 1 and 3 ($p = .140$), and between Experiments 2 and 3

($p = .132$). We observed also a main effect of Congruency and $F(1,39) = 18.520$, $p < .000$, $\eta_p^2 = 0.322$, with congruent dot motion being perceived more often after participants action than incongruent dot motion.

The same ANOVA was conducted on JND values. The analyses showed no significant interaction $F(2,39) = .050$, $p = .951$, $\eta_p^2 = 0.002$. No main effect of congruency was observed $F(1,39) = 2.634$, $p = .113$, $\eta_p^2 = 0.063$. We observed a main effect of Experiment $F(2,39) = 4.061$, $p = .025$, $\eta_p^2 = 0.172$. Higher JND values were observed in Experiment 3 compared to experiment 2 ($p = .048$, $d = 0.782$), and to experiment 1 ($p = .031$, $d = 1.08$). This suggests that temporal discrimination was reduced in Experiment 3 compared to the other experiments. This might indicate that the temporal order judgment task was harder for the participants of Experiment 3.

There is the possibility that the congruence effect on PSS values we observed in Experiments 1 and 2 compared to Experiment 3 is driven by the fact that participants did not learn action–outcome associations in Experiment 3. In order to assess this issue we conducted a one-way ANOVA on the proportion of correct detection of incongruent dot motion in the learning phase with Experiment (one, two, and three) as factor. The ANOVA showed no difference of detection performances between Experiments $F(2,39) = .666$, $p = .519$, $\eta_p^2 = 0.033$, indicating that action–outcome associations were learnt with the same strength in the 3 experiments: proportion of correct detection performances in the learning phases were as follow: Experiment 1: $M = 0.72$, $SD = 0.13$; Experiment 2: $M = 0.78$, $SD = 0.10$; Experiment 3: $M = 0.74$, $SD = 0.20$.

5. General discussion

The present study investigated the relations between the prediction of sensory outcome, causal beliefs and the perceived temporal order of action and their outcomes. Participants were required to indicate whether dots moved upward or downward before or after their key-presses. Coherent dot motion was either congruent or incongruent with respect to the action that participants executed in a given trial. In congruent trials participants' key-press was preceded (or followed) by the dot motion direction that was associated with that same key-press in the learning phase. In incongruent trials their action was preceded (or followed) by the dot motion direction associated with the other hand.

The results of our study could be summarised as follows. Firstly, we observed that congruent sensory events were perceived more often as occurring after participants' actions. Secondly, the congruency effect was observed only when participants believed that they caused the outcome. In particular, the presence of some trials in which actions contingently triggered the dot motion appeared to be important in sustaining this belief. Finally, in all three experiments, both congruent and incongruent dot motions were perceived more often after the physical onset time of participants' actions.

Recent studies suggest that predicted sensory outcomes are represented by the brain during motor preparatory processes (e.g., Desantis et al., 2014; Ziessler & Nattkemper, 2011). Accordingly, we think that the congruence effect we observed in Experiments 1 and 2 can be partly understood in terms of predictive processes. Notably, the prediction of the outcome generated by an action would be available before participants execute their key-press. A match between the predicted and actual sensory event (i.e., congruent dot motions) led participants to perceive dot motion more often after action execution compared to incongruent dot motions, respectively.

Several explanations could be relevant to understand this effect. Salient stimuli strongly attract our attention (Kerzel & Schönhammer, 2013). Thus, unexpected events might be perceived to occur earlier than expected events, perhaps because of their high attentional salience. However, this explanation is controversial since two recent studies investigating the influence of outcome prediction on the intentional binding failed to find the difference between perceived onset time of congruent and incongruent outcomes (Desantis, Hughes, et al., 2012; Haering & Kiesel, 2014).

An alternative explanation of our findings would be in terms of motor preparatory processes. Studies show that participants' awareness of movement initiation consistently anticipates the actual starting time of the movement (Libet, Gleason, Wright, & Pearl, 1983; McCloskey, Colebatch, Potter, & Burke, 1983). Moreover, these judgments are linked to lateralised readiness potentials (LRP; see Blakemore et al., 2002; Haggard & Eimer, 1999), which are thought to reflect lateralised action-specific activation in M1 (Coles, 1989; Leuthold & Jentzsch, 2002). Accordingly, awareness of initiating an action relates to preparing a specific movement (Haggard & Eimer, 1999).

Interestingly, recent studies have shown that predicted outcomes presented before movement execution modulates motor preparatory activity and in particular LRP (Nikolaev, Ziessler, Dimova, & van Leeuwen, 2008). For instance, in an EEG study, Nikolaev et al. (2008) showed that unpredicted (incongruent) outcomes result in extended motor processing compared to predicted outcomes. This suggests that congruency modulates the motor preparatory processes on which participant's awareness of initiating an action is based. Accordingly, in our study, participants would report their action as occurring earlier in congruent trials compared to incongruent trials. However, only the concurrent assessment of motor preparatory processes and temporal discrimination of action and outcome can settle this issue conclusively.

Importantly, note that the congruence effect was observed only when participants' had clear evidence that their actions were indeed causally linked to the occurrence of the dot motion, at least on some of the trials (Experiments 1 and 2). In fact, the effect was abolished when participants knew that dot motion in the TOJ task was always triggered by the computer (Experiment 3). This suggests that the influence of the prediction of sensory outcome on the temporal order of action and outcome is conditional to participants' understanding of their causal effectiveness. Notably, prediction influenced performances only when action–outcome contingency was preserved. Causal context might determine how reliable the sensorimotor system considers internal predictions to be. Specifically, depending on whether or not the agent believes to be the cause of an upcoming event, predictive signals might get high or low weights and accordingly have a larger/smaller influence on the processes underlying time perception. Notably, when participants believed that they themselves generated the dot motions, the weight attributed to the predicted outcomes would be higher compared to when they believed that stimuli were triggered by the computer. This might result in stronger expectation for congruent events in the agency vs. the non-agency experiments. Consequently, a mismatch between predicted and actual outcome would have led to higher conflict in the case in which participants believed of generating the dot motion (for similar account see Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012; Desantis et al., 2011; Moore & Fletcher, 2012; Synofzik, Vosgerau, & Newen, 2008). Thus, the effect of outcome prediction is strongly conditional to people's understanding of the causal context in which their actions are performed. Indeed, participants' beliefs of causality can strongly magnify (Experiment 1) or abolished entirely (Experiment 3) the congruence effect.

These results provide further evidence relative to the relationship between time perception and agency (cf. Farrer et al., 2013;

Wegner & Wheatley, 1999). Learning the relation between a specific action and a specific sensory outcome leads to a change in time perception, by imposing the usual temporal order of causes preceding outcomes. Crucially, these effects significantly depend both on experience of action–outcome contingency, and on beliefs or instructions about the causal arrangement of the task. This suggests a hierarchical organisation, in which contingency/causality provides the key information for time perception. The ability to predict a specific sensory event based on a learned action–outcome mapping has a further effect, but only if contingency is present.

Finally, across all experiments participants perceived both congruent and incongruent stimuli more often after their actions even though they were physically presented before action execution (i.e., on average a coherent dot motion presented 67 ms before the action was perceived as occurring simultaneously with the action). This might be explained by the fact participants estimate the time of actions partly from efferent signals linked to motor preparation (Haggard & Eimer, 1999; Obhi, Planetta, & Scantlebury, 2009; Strother & Obhi, 2009) rather than from sensory feedbacks arising from the movement itself. In our study this led participants perceive dot motions more often after action execution even though they were presented physically before participants' movement. In agency and voluntary action, this observation seems to be particularly important as perceiving plausible sensory events as occurring after a movement even though they are presented before action execution might erroneously lead to a self-attribution of these events. Thus, disturbance in efferent signals might sensibly alter the perceived temporal order between actions and plausible sensory events, ultimately leading to over/under-attribution of agency, in a manner reminiscent of delusions of control.

To conclude, there is accumulating evidence showing that action strongly influences perception (Blakemore et al., 1998; Roussel et al., 2013; Zwickel, Grosjean, & Prinz, 2007). These studies suggest that motor processes mediate the transformation of physical stimulation into perceptual experience (Wilson & Knoblich, 2005). Here, we show that a learned association between specific actions and specific outcomes can modify the temporal structure of time of action and outcome: predicted outcomes are perceived more often as occurring after participants' actions. However, this is observed only when contextual factors such as the causal context, instructions, and belief frameworks are provided (Buehner & Humphreys, 2009; Desantis et al., 2011; Moore et al., 2009). Thus, participants acquire causal knowledge both implicitly from sensory events, and more contextually or more explicitly, through other means. Temporal perception could emerge from the weighted combination of these different kinds of information. The end result would be a coherent representation of the causal structure of the world, in which the directionalities of time and of causation are mentally linked.

Acknowledgements

This research was supported by ERC Advanced Grant HUMVOL, awarded to PH. PH was additionally supported by an ESRC Professorial Fellowship. We are grateful to Mr. Nick Hartston for his participation in the data collection.

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