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

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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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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.