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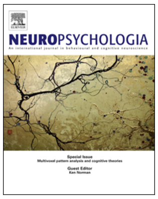

Effects can precede their cause in the sense of agency

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ABSTRACT

The sense of agency, i.e., the feeling that one's action is the cause of an external sensory event, involves causal inference based on the predicted sensory outcome of a motor act. Here, we investigated whether this inference process faithfully implements the physical principle that a cause (motor act) temporally precedes its effect (external sensory feedback). To this end, we presented participants with visual flashes that were temporally offset from voluntary button presses, including scenarios where the flash occurred shortly before the press. Participants then judged their experience of agency. As expected, cause-effect order is an important cue for this task: participants were far more likely to report agency for temporally lagging flashes than for leading flashes, even if very long sensory delays also disrupted the sense of agency (Experiment 1). This suggests that the temporal order between action and sensation is the dominant temporal cue for agency. However, when participants judged whether they had caused a first flash that occurred before the button press or a second flash that occurred afterwards, the temporal threshold for rejecting leading first flashes was relaxed proportionally to the delay of the second flash (Experiment 2). There was competition between different sensorimotor timing cues (temporal order favored the second flash and temporal proximity favored the first flash), and participants' tolerance for cause-effect inversions was modulated by the strength of the later, conflicting cue. We conclude that the perceived order of action and sensation is not used in a winner-take-all fashion in inference of agency. Instead, a probabilistic negotiation of the different timing cues favoring different flash events takes place postdictively, after presentation of the second flash.

1. Introduction

Humans experience a sense of agency (SoA) when sensory events are in agreement with the expected outcome of an action (Haggard and Chambon, 2012). An important cue for this kind of perceptual causal inference is the relative timing of action and sensation (Blakemore et al., 1998). If an action is self-initiated, it has to happen before the sensory consequence (temporal *priority principle*; Wegner and Wheatley, 1999). In addition, the SoA decreases with an increasing sensory delay between action and effect (Dewey and Carr, 2013; Ebert and Wegner, 2010; Farrer et al., 2013; Haggard et al., 2002; Moore et al., 2009; Sato and Yasuda, 2005; Weiss et al., 2014). Generally, to be contingent with a causal interpretation, a sensory event has to occur relatively shortly after the action. This temporal *proximity principle* can be modulated by context (e.g., top-down beliefs about delayed causation; Humphreys and Buehner, 2009) and by changes in the temporal action-sensation statistics (e.g., Ebert and Wegner, 2010; Moore et al., 2009). Yet, it temporally constrains the SoA in most situations.

Most current models of the mechanisms of the SoA assume two stages of processing (e.g., Balslev et al., 2007; Blakemore et al., 1998; Kawabe et al., 2013). A first sensorimotor integration stage compares different incoming streams of sensory information (touch, proprioception, visual or auditory feedback) to a prediction of sensory feedback, based on the history of motor commands (efference copy) and prior knowledge about the task, to assess temporal and spatial coherence. The fact that we cannot tickle ourselves has for instance been explained with such a model. A self-produced tickle sensation is fully expected from motor output and is thus causally assigned to oneself, which makes it non-ticklish (Blakemore et al., 1998). Such low-level comparison includes an assessment of temporal coherence: for instance, if a delay is inserted between a tickling action and the corresponding touch sensation (by robotic manipulation), participants perceive their own tickling as ticklish. The delay leads to a discrepancy between the actual and expected sensory inputs and the brain does not attribute the sensation to the corresponding own tickling action (Blakemore et al., 2000). In such models, the result of the comparison operation is assumed to be fed forward for cognitive

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and conceptual evaluation of the action in the second stage of processing where the agency is assigned (cf., Synofzik et al., 2008).

At least in a naïve interpretation, these models would predict a bottom-up processing of sensorimotor coherence and thus a strict application of the priority principle in the SoA. This prediction is supported by both intuition, as the rule that a cause precedes its effect is one of the most fundamental laws of physics, as well as by existing empirical evidence: Weiss et al. (2014) have shown a strong correspondence between subjective agency judgments and corticospinal activity related to motor preparation that also depended on visuomotor delays. Also, in an audiomotor temporal recalibration study, the threshold for perceiving agency was shown to shift with the threshold for perceiving simultaneity (Timm et al., 2014).

In order to test whether the temporal priority principle is really implemented as a fixed, bottom-up constraint for the SoA, we here investigated how humans negotiate conflicting temporal priority and temporal proximity cues when explicitly judging agency. To determine the relative importance of perceived order and perceived proximity as temporal cues for agency in Experiment 1, we asked participants to perform either agency judgments (AJs) or relative timing judgments (temporal order judgments: TOJ, simultaneity judgments: SJ) after exposure to a visual flash that occurred around the time of a voluntary button press. Contrary to other studies, we measured these judgments for both leading and lagging visual stimuli. This allowed us to characterize the temporal window of perceived agency. We observed a strong asymmetry around the Point of Subjective Simultaneity (PSS) that indicates dominance of the priority principle over the proximity principle. When judging agency, perceptible visual lags are tolerated, but visual stimuli that are perceived to occur before the press are strictly rejected.

In Experiment 2, we then studied how priority and proximity cues are negotiated in the case of a conflict, and whether a later second flash can postdictively alter the temporal processing of a leading first flash. Participants had to discriminate, which of two flashes (one before and one after their button press) they had caused. By varying the delay between the two flashes and their timing with respect to the action, we modulated the conflict between the priority cue (is the order of first flash and the press contingent with agency?) and the proximity cue (how close in time is the second flash to the press?). We observed that the size of the conflict influences how strictly the priority principle is applied when judging agency for the first flash. That is, if the second flash occurred late, participants sometimes reported agency for a flash that occurred noticeably before their press. This shows that the priority principle is negotiated probabilistically in the inference of agency and can be relaxed postdictively, so as to accommodate the later conflicting cue.

2. Experiment 1: the temporal window of perceived agency

In the experimental group (agency group), participants were asked to discriminate whether a flashed disk stimulus that was timed randomly around a button press was feedback to their own button press or feedback to a recorded press of a previous participant. From the literature (e.g., Farrer et al., 2013; Timm et al., 2014) we expected to find an asymmetrical window of perceived agency that contains lagging, but not leading visual stimuli relative to the PSS. In the control group (simultaneity group), participants had to rate whether the flash occurred at the same time as the press or not. We expected this window of perceived simultaneity to be narrower on the side of lagging visual stimuli than the window of perceived agency, but the same size for leading visual stimuli.

2.1. *Method*

2.1.1. *Participants*

20 participants (age range 18–42, 15 females, all right-handed by self-report) took part and received a small monetary compensation (6 €/h). Another four measurements had to be discarded due to technical device failure or participants disobeying the experimenter's instructions (two in the agency group, and two in the simultaneity group). Participants gave written consent and were naïve with respect to the experimental hypothesis. The experiment was conducted in agreement with the ethics standards laid out in the 1964 Declaration of Helsinki and was approved by the ethics committee of the Department of Medicine of the University of Tübingen (Germany).

2.1.2. *Materials and apparatus*

We used the same set-up as in previous research (Rohde and Ernst, 2013; Rohde et al., 2014). A PHANToM™ force-feedback device (SensAble Technologies Inc.) was used to render a virtual haptic button consisting of a simulated mass ($m=0.1$ kg) on a 4 mm spring (spring constant $k=500$ kg/s^2). Below the spring, there was an additional dead-band of 4 mm. When entering the dead-band, a button press event was registered and there was a sudden noticeable decrease in force-feedback (haptic click; see Fig. 1A and Methods section in Rohde and Ernst, 2013). The participants reached out from a defined start position and pressed this

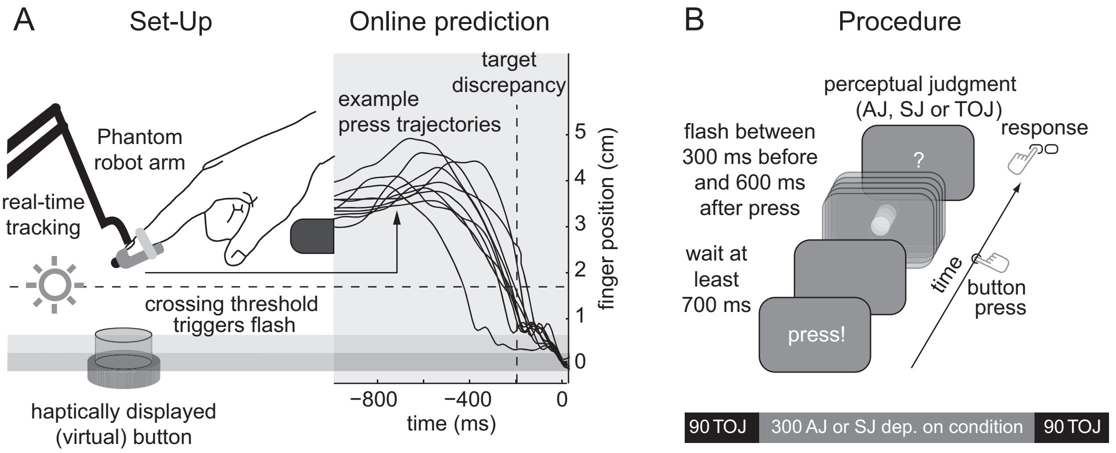

Fig. 1. Setup and procedure. A: the set-up. Starting at the home position, participants reached out to press a button that was haptically rendered using a PHANToM™ force-feedback device. The height of the finger was analyzed online to estimate the timing of the upcoming button press, which allowed us to display visual stimuli also before the press. B: procedure. Flashes were displayed around the time of the voluntary button press. Perceptual judgments asked were: agency judgments ("did you or another participant cause the flash?"), simultaneity judgments ("did the button press and the visual flash occur at the same time?"), and temporal order judgments ("which occurred earlier: button press or visual flash?"). The order of conditions is displayed as timeline at the bottom.