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Re-construction of action awareness depends on an internal model of action-outcome timing

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ABSTRACT

The subjective time of an instrumental action is shifted towards its outcome. This temporal binding effect is partially retrospective, i.e., occurs upon outcome perception. Retrospective binding is thought to reflect post-hoc inference on agency based on sensory evidence of the action – outcome association. However, many previous binding paradigms cannot exclude the possibility that retrospective binding results from bottom-up interference of sensory outcome processing with action awareness and is functionally unrelated to the processing of the action – outcome association. Here, we keep bottom-up interference constant and use a contextual manipulation instead. We demonstrate a shift of subjective action time by its outcome in a context of variable outcome timing. Crucially, this shift is absent when there is no such variability. Thus, retrospective action binding reflects a context-dependent, model-based phenomenon. Such top-down re-construction of action awareness seems to bias agency attribution when outcome predictability is low.

1. Introduction

When a motor action is followed by a sensory event within a few hundred milliseconds, the subjective time of the action can be shifted towards that sensory event (Haggard, Clark, & Kalogeras, 2002; for a review, see Moore & Obhi, 2012). This binding of subjective action time by a subsequent stimulus depends on learning the underlying contingency (Moore, Lagnado, Deal, & Haggard, 2009; Walsh & Haggard, 2013). It is considered to reflect intentional (Haggard et al., 2002) and/or causative (Buehner & Humphreys, 2009) aspects of the learnt action – outcome association that contribute to a pre-reflective sense of agency (Moore & Obhi, 2012).

Temporal action binding is partially retrospective, in so far as it occurs at the time of outcome perception (Moore & Haggard, 2008). This retrospective component of temporal binding has frequently been regarded as evidence in favour of a post-hoc implicit inference on agency based on sensory evidence, as opposed to a prospective implicit agency ascription during action preparation and/or execution (Moore & Haggard, 2008). This distinction relates to the broader question (Baldwin et al., 2003) of how awareness of prior expectations of an action-outcome (e.g. during unsuccessful trying) on

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the one hand, and the observation of physical action consequences on the other, are weighted and integrated in the process of sensing intention and causation (Wegner & Wheatley, 1999; Wolpert & Flanagan, 2001).

These interpretations of retrospective action binding assume an underlying inferential, top-down process. In principal, however, a retrospective change of action awareness could be driven by two physiologically distinct mechanisms. A top-down process could re-construct action awareness by integrating prior knowledge and sensory evidence of the action – outcome association. A similar model-based process has been proposed, for example, for an integration of motor predictions and sensory re-afference in comparator models of motor control (Wolpert & Flanagan, 2001). Alternatively, retrospective action binding could reflect bottom-up interference of sensory outcome processing with on-going cognitive processes involved in action awareness, or, at a lower level, with the integration of visual information in the Libet clock paradigm typically deployed in these experiments (Libet, Gleason, Wright, & Pearl, 1983). In this case, the retrospective shift of subjective action time would be solely stimulus-driven, similar to the effects of backward masking on conscious perception, for example (Werner, 1935), and would be independent of an internal model of the action – outcome association.

Previous evidence of retrospective temporal binding comes predominantly from studies that compare subjective action time in the presence and absence of a subsequent stimulus, i.e., two conditions that differ substantially in bottom-up drive (Moore & Haggard, 2008). In these studies, a shift of subjective action time due to outcome presentation reflects retrospective action awareness. Therefore, these studies cannot distinguish between model-based re-construction of action awareness and bottom-up interference with action awareness. Evidence for the idea that a top-down re-constructive process is involved in retrospective binding comes from a study that manipulated the contingency of an outcome on an action, specifically the probability of an outcome given no preceding action (Moore et al., 2009). This study held bottom-up drive constant across trials of interest and used a contextual manipulation instead to demonstrate that retrospective binding depends on an internal representation of *how necessary an action is* for a sensory event.

Similarly, we here used a contextual manipulation while keeping bottom-up influences constant to address the question whether action awareness depends on an internal model of outcome *timing*. Previous studies have shown that binding of an outcome to an action depends on temporal outcome predictability (Haggard et al., 2002). We asked whether retrospective and prospective components of action awareness also reflect temporal outcome predictability.

Moore and Haggard (2008) have previously shown that outcome presentation shifts subjective action time under conditions of low outcome predictability, as achieved by lowering the probability of outcome *occurrence* (the "whether" of the outcome). Here, we tested whether a contextual manipulation of *temporal* outcome predictability leads to a similar shift of subjective action time. In brief, we compared retrospective binding in two conditions that differ in temporal variability of the outcome with respect to the action (the "when" of the outcome) while keeping the structure and timing of trials of interest constant, i.e., bottom-up drive. Any difference in retrospective binding between conditions of variable and fixed outcome timing would reflect an influence of context, rather than any bottom-up interference with action awareness. In addition, Moore and Haggard (2008) demonstrated a shift of action awareness towards an expected outcome even when the outcome was omitted. The authors interpreted this shift as a prospective component of action awareness. To examine effects of temporal outcome predictability on this prospective component, our study introduced an expectation of outcome occurrence by presenting outcomes on 75% of trials in both "variable" and "fixed" outcome timing blocks.

2. Methods

2.1. Participants

We recruited 16 healthy volunteers (age 23.5 ± 2.78 years (mean ± SD), 10 females; all right-handed) via an online database. All participants gave written informed consent prior to participation with the right to exit the study at any time. The study was approved by the local ethics committee (University College London, UK). Participants received £10 per hour as reimbursement.

2.2. Task

Presentation® software (Neurobehavioral Systems, www.neurobs.com) was used to generate all stimuli and to program the paradigm. The task was presented on an LCD screen (vertical refresh rate 60 Hz) on a white background. The experiment was run in a dark and sound-proof room. Participants were seated 75 cm in front of the screen and kept their chin on a chin rest. Sound was presented binaurally at 74 dB SPL via Sennheiser HD 380 pro headphones.

The task (Fig. 1) was a variation of the temporal binding paradigms used by Haggard et al. (2002) and Moore and Haggard (2008). On each trial, participants pressed a button with their right index finger once, at a time of their choice, and verbally reported the time of this button press with respect to the rotating clock hand of a Libet clock (Libet et al., 1983) (period of 2.55 s) at the end of the trial.

The experiment was based on a 2 × 2 factorial design, with one factor ("trial type", two levels: "action + tone" vs. "action only") varied on a trial-by-trial basis and the other ("outcome timing variability": "variable outcome timing" vs. "fixed outcome timing") varied block-wise. There was an additional, blocked condition that served as baseline for subjective time judgements ("baseline" blocks).