



Sensation of agency and perception of temporal order



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ABSTRACT

After adaptation to a fixed temporal delay between actions and their sensory consequences, stimuli delivered during the delay are perceived to occur prior to actions. Temporal judgments are also influenced by the sensation of agency (experience of causing our own actions and their sensory consequences). Sensory consequences of voluntary actions are perceived to occur earlier in time than those of involuntary actions. However, it is unclear whether temporal order illusions influence the sensation of agency. Thus, we tested how the illusory reversal of motor actions and sound events affect the sensation of agency. We observed an absence of the sensation of agency in the auditory modality in a condition in which sounds were falsely perceived as preceding motor acts relative to the perceived temporal order in the control condition. This finding suggests a strong association between the sensation of agency and the temporal order perception of actions and their consequences.

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1. Introduction

Precise temporal judgments of actions and their corresponding sensory consequences are an important component of human time perception. Several studies showed that temporal order judgments are constructions of the brain, which are easily manipulated in the laboratory (Eagleman, 2008; Haggard, 1999; Haggard & Clark, 2003; Haggard, Clark, & Kalogeras, 2002; Tsakiris & Haggard, 2003). Particularly, it has been shown that when a fixed temporal delay is consistently introduced between a motor act and its sensory consequences, participants' perception adapts to this delay. If, subsequently, the delay between the action and its effect is shortened, participants may perceive that the sensory consequence preceded the motor act (i.e., they perceive an illusion of reversed temporal order between actions and sensory consequences). This illusion was first described for visual stimuli generated via button presses (Stetson, Cui, Montague, & Eagleman, 2006). Specifically, participants were asked to press a button, which was followed by a flash. A fixed temporal delay between button presses and flashes was introduced. After participants had adapted to this delay, they perceived unexpected flashes presented at shorter delays as occurring before the button press. The illusion has subsequently been replicated in the tactile and the auditory modality (Heron, Hanson, & Whitaker, 2009; Sugano, Keetels, & Vroomen, 2010) and with more complex stimuli (Keetels & Vroomen, 2012; Yamamoto & Kawabata, 2011). The illusion has been explained as a recalibration of motor-sensory timing, resulting from the participants' prior expectation that there should be little or no delay between actions and their sensory consequences (Stetson et al., 2006). Recalibrating the temporal interpretation of motor acts and sensory consequences may also be crucial to the perception of causality, because causality requires a judgment of whether the motor act precedes or follows the sensory input. It has been proposed that this can only be achieved by a multisensory integration mechanism that

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calibrates the relative timing of sensory events from different modalities, so that 'before' and 'after' can be accurately determined (Eagleman, 2008). As the illusion has been replicated in different sensory modalities, it has been suggested that the recalibration mechanism is supramodal (Heron et al., 2009).

There is some evidence that voluntary action is required for the perceptual recalibration of motor-sensory timing to take place. Specifically, Stetson et al. (2006) found that illusory reversals occurred only when participants moved their finger actively, but not when the button was moved with a motor to tap the finger of the participants. The finding that voluntary movements strongly influence the temporal order perception of actions and sensory effects is also reflected in the intentional binding phenomenon, where participants perceive a sensory event earlier in time when it is the consequence of a voluntary action than when it is not (Engbert, Wohlschläger, & Haggard, 2008; Haggard & Clark, 2003; Haggard et al., 2002; Moore & Haggard, 2008; Moore & Obhi, 2012; Tsakiris & Haggard, 2003; Voss et al., 2010). Voluntary movements involve a strong sensation of agency, that is, an experience of causing an action and its sensory consequences (Haggard, 2005). It has been suggested that the sensation of agency is strongly related to the concept of causality (Hume, 1888, 1900; Wegner, 2003, 2004). Those models assume that causation is inferred from the temporal relation between cause and sensory effect. That is, causality can only be established when an action precedes its sensory consequences. The sensation of agency, in turn, reflects the experience of being a causal agent (Wegner, 2004). Thus, temporal order judgments should be directly linked to sensation-of-agency judgments. This assumption is supported by previous findings showing that temporal order judgments are influenced by the belief of causing an effect (Desantis, Roussel, & Waszak, 2011; Haering & Kiesel, 2012). Desantis et al. (2011) revealed a stronger intentional binding effect, which is an implicit measure of the sensation of agency, when participants believed that they triggered a sound, compared to when they believed that another person triggered the sound. This coupling between temporal order judgments and sensation of agency seems intuitive: if we perceive an effect occurring simultaneously with or shortly after an action, then we have likely caused it. Conversely, if we are certain we caused an effect, then it could not have happened before the action. Nevertheless, the relationship between temporal order judgments and sensation-of-agency judgments is not that trivial. People are in general readily able to experience perceptions that are rationally contradictory, indicated in the large variety of perceptual illusions (Eagleman, 2008). Furthermore, motor-to-sensory links can be highly automatic, especially in the auditory modality. Thus, motor acts could affect sensory processing independently of the subject's sensation of agency over the stimuli. For example, self-initiated sounds elicit attenuated auditory brain responses compared to externally initiated sounds, an effect commonly related to the subject being the agent of the stimuli (Aliu, Houde, & Nagarajan, 2009; Baess, Horváth, Jacobsen, & Schröger, 2011; Bäss, Jacobsen, & Schröger, 2008; Ford, Gray, Faustman, Roach, & Mathalon, 2007; Horváth, Maess, Baess, & Tóth, 2012; Knolle, Schröger, Baess, & Kotz, 2012; Knolle, Schröger, & Kotz, 2012; Martikainen, Kaneko, & Hari, 2005; McCarthy & Donchin, 1976; SanMiguel, Todd, & Schröger, 2013; Schafer & Marcus, 1973; Timm, SanMiguel, Saupe, & Schröger, 2013). However, several studies have shown that a contingent relationship between the motor act and the sound is not necessary for this effect to occur, as sensory processing of sounds seems to be also attenuated when the sound is merely coincidentally concurrent with the motor act (Horváth et al., 2012; Makeig, Müller, & Rockstroh, 1996). Given these examples, it is conceivable that sensation-of-agency judgments may be independent from temporal order perceptual illusions, particularly in the auditory modality. We tested whether subjective temporal order judgments are directly related to the sensation of agency, using the experimental design of Stetson et al. (2006). We asked participants to report their sensation of agency over the production of a sound in conditions in which they either perceived an illusory reversal of the temporal order of events or not. Assuming a direct relationship, we hypothesized that in conditions, in which the recalibration of the timing between actions and sensory consequences causes an illusory perception of temporal order (i.e. the stimulus is perceived as occurring before the motor action), it should also cause a lack of a sensation of agency, that is, participants should not have the feeling that their action caused the sensory event.

We also addressed three additional unresolved issues in this study. The first relates to the counterintuitive finding that, under normal circumstances, participants perceive motor actions and sensory consequences as simultaneous when the sensory event precedes the motor action by up to 100 ms (McCloskey, Colebatch, Potter, & Burke, 1983). Several studies investigating perceptual effects of voluntary movements have reported this finding without directly discussing it (Haggard, 1999; Haggard & Clark, 2003; Haggard, Clark, et al., 2002; Tsakiris & Haggard, 2003). Stetson et al. (2006) circumvented this issue in their experiment by first training participants so that their perception of the relative timing between actions and effects closely matched the real timing. It is unclear how this training might have influenced the illusion results. Thus, we further tested whether the visual temporal order illusion reported by Stetson et al. (2006) can be replicated with untrained participants, first in the visual, and subsequently in the auditory modality. Previous studies have shown that temporal recalibration can also take place when the motor acts result in auditory instead of visual stimuli (Heron et al., 2009; Sugano et al., 2010; Yamamoto & Kawabata, 2011), hence we expected to observe the illusion in the auditory modality as well. However, as temporal resolution (Recanzone, 2003, 2009; Wada, Kitagawa, & Noguchi, 2003) and duration discrimination (Grondin, 1993) are much better in the auditory than in the visual system, it is possible that the auditory system is less prone to temporal order illusions. Moreover, to the best of our knowledge, replications of the original illusion effect described by Stetson et al. (2006) in other sensory modalities have never presented the participants with real temporal order reversals. This is particularly relevant with untrained participants, given that the point of subjective simultaneity (PSS) seems to lie in the negative latency range (stimulus comes before motor act) under these circumstances. Thus, we aimed to establish the real PSS, and corroborate that it can be recalibrated by adapting to a constant motor-sensory delay, leading to the temporal order reversal illusion when shorter delays are presented in both the visual and the auditory modality.

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