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My action lasts longer: Potential link between subjective time and agency during voluntary action

Shu Imaizumi[a,b,c,*], Tomohisa Asai[b]

[a] Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan
[b] NTT Communication Science Laboratories, 3-1 Morinosato-wakamiya, Atsugi, Kanagawa 243-0198, Japan
[c] Japan Society for the Promotion of Science, 5-3-1 Kojimachi, Chiyoda, Tokyo 102-0083, Japan

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ABSTRACT

Time perception distorts across different phases of bodily movement. During motor execution, sensory feedback matching an internal sensorimotor prediction is perceived to last longer. The sensorimotor prediction also underlies sense of agency. We investigated association between subjective time and agency during voluntary action. Participants performed hand action while watching a video feedback of their hand with various delays to manipulate agency. The perceived duration and agency over the video feedback were judged. Minimal delay of the video feedback resulted in longer perceived duration than the actual duration and stronger agency, while substantial feedback delay resulted in shorter perceived duration and weaker agency. These fluctuations of perceived duration and agency were nullified by the feedback of other's hand instead of their own, but not by inverted feedback from a third-person perspective. Subjective time during action might be associated with agency stemming from sensorimotor prediction, and self-other distinction based on bodily appearance.

1. Introduction

1.1. Subjective time modulated by bodily movements

Perceiving time has an important role for humans to behave optimally in the environment. For instance, one has to predict when sensory events will occur and estimate how long these events will last, in order to move their body, interact with others, and act towards an external environment. Such cognitive and perceptual functions regarding subjective time are implemented based on certain cortical and subcortical functions (Buhusi & Meck, 2005; Merchant, Harrington, & Meck, 2013). However, the subjective time is not necessarily consistent with the flow of physical time and is likely to be modulated by other mental and bodily states, for example, emotional valence and arousal (Droit-Volet & Meck, 2007; Lake, LaBar, & Meck, 2016), suggesting that humans adaptively alter subjective time.

Recent studies have shown that motor action modulates time perception including interval and temporal order judgments (Merchant & Yarrow, 2016; Rohde & Ernst, 2016). As the first instance of such motor-induced temporal distortion, Yarrow, Haggard, Heal, Brown, and Rothwell (2001) showed that saccadic eye movements result in an increased perceived duration of visual stimuli near the destination of the saccade. This perceptual illusion, "*chronostasis*", has been thought to play a role in maintaining the spatial consistency of the visual experience, which can be distorted by rapid rewriting of retinal inputs due to the saccadic eye movement. As

* Corresponding author at: Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan.
E-mail address: shuimaizumi@gmail.com (S. Imaizumi).

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for temporal modulation by bodily movements, Yarrow and his colleague have further demonstrated manual chronostasis, in which reaching movement results in the overestimated duration of the consequent vibrotactile event (Yarrow & Rothwell, 2003). Moreover, Park, Schlag-Rey, and Schlag (2003) showed that visual stimuli which emerge as a consequence of the observer's keypress action could be perceived to last longer, similarly to the chronostasis effect. These findings imply that motor system seemingly modulates the subjective time perception in order to optimize sensory processing following the motor action.

Does such a motor-induced time modulation operate throughout the motor processes (i.e., preparation and execution)? A recent study has demonstrated that subjective duration of a visual stimulus dilates during the preparation of a ballistic reaching movement (Hagura, Kanai, Orgs, & Haggard, 2012). Their series of experiments ruled out the mere effect of cognitive preparation and attention and further illustrated increased visual temporal resolution during the motor preparation. They claimed that temporal dilation of subjective time preceding the motor execution might be beneficial for motor planning, in order to optimally respond to sensory events and objects in the changeable environment. For the same reason, it can be expected that subjective time during motor execution can expand for the online motor control and the processing of the accompanying sensory afferences. Recently, Press, Berlot, Bird, Ivry, and Cook (2014) found that during the lifting movement of participants' finger, the vibrotactile stimuli on the same finger was likely to be perceived to last longer than the stimuli introduced to the next finger which did not move. In the other experiment of Press et al. (2014), they replicated the effect using an artificial hand on a monitor, which synchronously moved corresponding to the participant's hand. The movement of the virtual hand's index finger corresponding to the movement of the participant's index finger was perceived to last longer than the movement of the middle finger of the virtual hand induced by the participants' index finger (i.e., spatially incongruent visual feedback). These findings suggest that time dilation may occur in multimodality (i.e., vision, tactile) during motor execution. Press et al. (2014) argued that temporal dilation and compression might stem from congruence and incongruence between motor prediction and the actual sensory feedbacks, respectively.

1.2. Subjective time and self-representation during voluntary action

The internal forward model of the human sensorimotor system, including motor prediction and its predicted sensory feedback, enables not only motor learning but also phenomenal experiences of the bodily self (Frith, Blakemore, & Wolpert, 2000; Haggard, 2005; Wolpert, Ghahramani, & Jordan, 1995); in particular, the sense of agency that refers to the feeling that "I am causing this action and controlling my body" (Gallagher, 2000). This "comparator" model is based on an efference copy, which is generated as a copy of motor commands from self-initiated actions (von Holst & Mittelstaedt, 1950) and predicted sensory afferent feedback corresponding to the motor commands before actual sensory feedback. These predictions are matched against the actual feedback. If the prediction matches the actual feedback, the sense of agency will be generated. Because congruency between the predicted and actual sensory feedback is necessary to generate the sense of agency, spatially and/or temporally mismatched sensory feedback may disturb the self-attribution of sensory feedback, e.g., cursor and hand video of the participants' action with spatial bias and/or temporal lag can decrease the perceived sense of agency (Asai, 2016a; Asai & Tanno, 2007; Farrer, Bouchereau, Jeannerod, & Franck, 2008; Franck et al., 2001; Imaizumi, Asai, Kanayama, Kawamura, & Koyama, 2014; Longo & Haggard, 2009; Tsakiris, Longo, & Haggard, 2010). Although the sense of agency can be prospectively facilitated, such as by fluency of action selection before action execution itself (Chambon & Haggard, 2012), the current study focuses on the sense of agency based on an online action-feedback matching in terms of the comparator account.

If, as Press et al. (2014) have claimed, subjective time dilation during finger movements can be caused by a match between action and its visual feedbacks, the sense of agency over the action and/or self-attribution of the visual feedback, rather than mere consistency between action and feedbacks, might be associated with the subjective time dilation. A previous study reported that self-initiated moving dots towards an orientation corresponding to the prediction was perceived to move slower than the moving dots initiated by a computer (Dewey & Carr, 2013), essentially suggesting that self-initiated stimuli can be perceived to last longer. Although these findings suggest a linkage between subjective time and agency, the Dewey and Carr's task, which required participants to press a key and judge the speed of subsequent moving dots, failed to examine time dilation during motor action entailing a concurrent sense of agency. Besides, as the appearance of visual feedback used in the above studies were moving artificial hand (Press et al., 2014) and dots (Dewey & Carr, 2013), the effect of the difference in visual feedback of one's own hand or other's hand on perceived time and concurrent sense of agency has yet to be examined. If the action-induced time dilation is associated with the sense of agency, presentation of other's hand as a visual feedback should affect not only the sense of agency or self-attribution of the feedback (Daprati et al., 1997; Sirigu, Daprati, Pradat-Diehl, Franck, & Jeannerod, 1999; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005; van den Bos & Jeannerod, 2002) but also the possible time dilation during the hand movements.

On the other hand, from the psychiatric perspective, people with schizophrenia (Daprati et al., 1997; Franck et al., 2001) and those with high schizotypal personality (Asai, 2016b; Asai & Tanno, 2007) are likely to report a *weaker* sense of agency as their positive symptoms, presumably due to their deteriorated motor prediction in the forward model (Synofzik, Thier, Leube, Schlotterbeck, & Lindner, 2010). In contrast, others have suggested that schizophrenia leads to *exaggerated* agency using an implicit measure (Haggard, Martin, Taylor-Clarke, Jeannerod, & Franck, 2003; Moore et al., 2011). Recent meta-analyses confirmed this contradiction by arguing that sense of agency in schizophrenia can be weaker due to deteriorated self-recognition (Waters, Woodward, Allen, Aleman, & Sommer, 2012) and stronger due to over-attribution to the self (Hur, Kwon, Lee, & Park, 2014). A more recent study has suggested that in fact this is not contradiction (Asai, 2016b); a reduced self-other discriminability in schizophrenia can lead to the attribution of self-initiated feedback to others (i.e., weaker agency) and attribution of other-initiated feedback to self (i.e., exaggerated agency). Moreover, the patients can display altered duration perception in sub- and supra-second intervals with decreased sensitivity compared to normal controls (Allman & Meck, 2012; Carroll, O'Donnell, Shekhar, & Hetrick, 2009; Densen,