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Feedback control of one's own action: Self-other sensory attribution in motor control

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ABSTRACT

The sense of agency, the subjective experience of controlling one's own action, has an important function in motor control. When we move our own body or even external tools, we attribute that movement to ourselves and utilize that sensory information in order to correct "our own" movement in theory. The dynamic relationship between conscious self-other attribution and feedback control, however, is still unclear. Participants were required to make a sinusoidal reaching movement and received its visual feedback (i.e., cursor). When participants received a fake movement that was spatio-temporally close to their actual movement, illusory self-attribution of the fake movement was observed. In this situation, since participants tried to control the cursor but it was impossible to do so, the movement error was increased (Experiment 1). However, when the visual feedback was reduced to make self-other attribution difficult, there was no further increase in the movement error (Experiment 2). These results indicate that conscious self-other sensory attribution might coordinate sensory input and motor output.

1. Introduction

We are always receiving sensory information through our sensory receptive fields. In terms of the origin of the stimulus, these sensations can be categorized into two groups: externally generated sensations and internally generated ones (e.g., Goldman-Rakic, Bates, & Chafee, 1992). The former arise from a stimulus or event that happens outside of our body (external world). This is, in theory, independent of the self, as exemplified by when we see a car moving, hear someone singing, or are touched by someone. In the latter, on the other hand, we ourselves are the origin or the generator of the sensation. The visual input changes when we move. When we sing, we hear it. And, we can touch ourselves. It is important to distinguish the origin of the sensation because there are some utilizations of internally generated sensation (Wolpert & Miall, 1996). For example, self-generated changes in visual input while we walk or run never make us befuddled. The brain can compute and compensate for self-generated movements (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Shergill, Samson, Bays, Frith, & Wolpert, 2005). For that purpose, the brain has to first distinguish between internally and externally generated sensations.

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1.1. Self-other attribution in motor control

How can the brain tell that a sensation is self-generated? The computational theory of motor control has suggested that the coupling between motor commands and sensory feedback are learned (Wolpert, 1997; Wolpert & Miall, 1996; Wolpert, Miall, & Kawato, 1998). In this situation, computationally predicted sensory inputs should be attributed to a motor command from the self (David, Newen, & Vogeley, 2008). On the contrary, if we have a fake sensory input that is congruent to that prediction, that sensation might be attributed to the self as a result of the illusory sense of self-attribution (Daprati et al., 1997). A classic study by Nielsen suggested that is indeed the case (Nielsen, 1963). Participants were instructed to make a reaching movement using a pen to draw a straight line to the goal point. After some repetition of this task, participants naturally attributed the sensory feedback (in this case, movement) to themselves: "I am controlling this movement". The experimenter then suddenly and secretly replaced participants' movement with the experimenter's fake movement. When the experimenter distorted their movement, which participants still attributed to themselves, participants moved their pen in the opposite direction of the experimenter's movement to compensate for the error between the predicted and actual movement. This means that as long as we attribute a movement to ourselves, we try to control it. This is the feedback control of "our own" movement.

1.2. What drives feedback control?

The situation, however, is not that simple because the relationship among conscious detection of error, self-other sensory attribution, and feedback control (compensatory movement) is complicated. The compensatory movement is driven even when participants are unaware of the error between the actual and predicted feedback (Fourneret & Jeannerod, 1998; Knoblich & Kircher, 2004) since the conscious detection needs to exceed certain threshold (Fourneret, Franck, Slachevsky, & Jeannerod, 2001). Even if so, this unconscious compensatory movement must be possible as long as the sensory feedback is attributed to oneself. Too much detected error should entail other-attribution and therefore no compensatory movement: "this is NOT my own action" (small detected error could still be attributed to the self though, Asai & Tanno, 2007, 2013). One study has indicated that is the case in terms of audio-motor regulation. The speech production is one expression of motor control. When we receive delayed auditory feedback of our own speech, speech production is disturbed and stuttering may occur (e.g., Chase, Harvey, Standfast, Rapin, & Sutton, 1959). This is because one tries to utilize this auditory input, attributed to oneself ("this is my own speech"), for feedback control of speech production even implicitly. Accordingly, when the frequency of the auditory feedback is altered and, as a result, one no longer attributes it to oneself, one's speech production is no longer disturbed by delayed auditory feedback ("this is NOT my own speech", Toyomura & Omori, 2005). We don't need and it is impossible to correct others' speech. In addition, people with auditory hallucination experiences do not utilize their auditory feedback in this speech control task (Asai & Tanno, 2013). They do not attribute that auditory feedback to themselves because of the nature of auditory hallucinations in schizophrenia (see also Section 4): the weaker sense of agency is related to schizophrenic traits among patients and even in the general population (Asai & Tanno, 2007, 2008, 2013). These studies have implied that feedback control of action highly depends, not on conscious error detection, but on conscious self-other attribution of sensory inputs.

1.3. The function of agency

Nowadays, this conscious self-other attribution is often referred to as the sense of agency (Gallagher, 2000; Haggard & Chambon, 2012). The sense of agency refers to the subjective experience of controlling one's own action. Since this sense is sometimes regarded as a postdictive illusion of causality (Wegner, 2003), little research has focused on the function of agency. Though previous studies have suggested that feedback control might be realized only when the feedback is attributed to self (Asai & Tanno, 2013; Toyomura & Omori, 2005), which is consistent with the computational theory of motor control (Wolpert & Miall, 1996), no study has yet examined the intrinsic relationship between self-other attribution and feedback control in motor control. The current study manipulated subjective self-other attribution over sensory feedback and examined how this affects participants' motor performance on a time-course basis. Participants were required to make a sinusoidal reaching movement and received its visual feedback (i.e., cursor). On this occasion, when participants receive a fake movement that is spatio-temporally close to their actual movement, illusory self-attribution of the fake movement would be observed. As a result, since participants try to control the cursor but it is impossible, the movement error would be increased. Furthermore, this relationship should, in theory, be dynamically changeable. Even if the illusory self-attribution is made once, when we realize that we can't control that movement anymore, that movement should be attributed to others and we should give up controlling that movement: we don't have a reason to try to control of others' movement.

1.4. The current study

The purpose of the current study was to investigate this dynamic relationship between self-other attribution and feedback control. Experiment 1 simply examined the effect of the prediction error. I hypothesized that illusory self-attribution of a movement needs a fake movement that is spatio-temporally close to participants' own movement. Specifically, when prediction error is small or under a certain threshold for self-attribution, participants would try to control