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Multisensory integration induces body ownership of a handtool, but not any handtool

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A B S T R A C T

Bodily boundaries are computed by integrating multisensory bodily signals and can be experimentally manipulated using bodily illusions. Research on tool use demonstrates that tools alter body representations motorically to account for changes in a user's action repertoire. The present experiment sought to unify perceptual and motoric accounts of tool embodiment using a modified Rubber Hand Illusion (RHI) that also addressed the skill and practice aspects of the tool use literature. In Experiment 1, synchronous multisensory stimulation induced perceptual embodiment of a tool, chopsticks. The embodiment of chopsticks was stronger for more skilled participants, and if the illusion was preceded by tool use. In Experiment 2, the illusion was not elicited with a different type of tool, a teacup, showing that not all objects can be incorporated. This experiment helps to clarify the role of perceptual and motoric embodiment and suggests future avenues for research into tools embodiment using this method.

1. Introduction

The representation of the body is remarkably flexible. The brain continuously integrates a complex stream of sensory inputs and uses this information to dynamically scale the representation of the body according to its current state (e.g. Botvinick & Cohen, 1998; Ehrsson, 2012, chap. 43; Tsakiris, 2008, 2010). This flexibility makes it possible to efficiently interact with the environment and is strikingly important during tool use.

Successful tool use expands the physical limits of the wielder's body and facilitates a dramatic increase in action capacity (Shumaker, Walkup, & Beck, 2011; Vaesen, 2012). Experimental research indicates that the flexibility of the body representation contributes to the human tool proficiency. Psychophysical studies demonstrate that the physical expansion afforded by a tool is accompanied by an incorporation of the tool in the body representation, such that the tool is treated as an extension of the limb wielding it (e.g. Cardinali et al., 2009; Maravita, Spence, Kennett, & Driver, 2002).

If tools are treated as an extension of the wielder's body, then might the extended body representation also demonstrate the same ability to plastically adapt to multisensory stimuli? The present work set out to shed light on this issue. In particular, we asked whether the manipulation of multisensory stimuli could induce a recalibration of the extended body representation encompassing both the tool and the effector wielding it. Furthermore, we aimed to examine whether skill and previous experience with a particular

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tool modulate the representational plasticity of the body.

Recent advances in our knowledge of how the brain represents the body have been pioneered through the experimental use of perceptual illusions. One of the most used and best known paradigms is the Rubber Hand Illusion (RHI) (Botvinick & Cohen, 1998). In its classic form, synchronous visuo-tactile stimulation of a rubber hand and the participant's hidden hand induces a recalibration of the proprioceptive felt position of the participants' hand and a feeling ownership of the rubber hand (Botvinick & Cohen, 1998; Costantini, 2014; Tsakiris, 2017; Tsakiris & Haggard, 2005). This has been classically interpreted in the literature as evidence that the manipulation of multisensory inputs (i.e. visual and tactile stimulation), can induce the embodiment of an external, dummy hand into one's own body representation (Blanke, 2012; Ehrsson, 2012, chap. 43), for a different view (David, Fiori, & Aglioti, 2014). Similar experiences of illusory ownership have been obtained, for example, for faces (Tsakiris, 2008), whole bodies (Petkova & Ehrsson, 2008), and even for virtual avatars (Banakou, Groten, & Slater, 2013; Hägni et al., 2008; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008) and small dolls (van der Hoort, Guterstam, & Ehrsson, 2011). Together, these findings show that the multisensory representation of our body is not fixed and immutable, but rather extremely flexible and continuously updated through the integration of multisensory information (for a review, see Costantini, 2014). This scalability of the body representation is also thought to contribute to human tool use proficiency (e.g., Cardinali et al., 2012). When we use tools to manipulate the environment, the brain receives somatosensory signals evoked at the hand wielding the tool. Yet, we often have the subjective feeling that the touch is occurring on the tip of the tool itself. This feeling seems to be a by-product of how the body representation is rescaled to incorporate the tool.

For instance, seminal work with both humans and primates demonstrated that the use of a tool for a prolonged period of time extends the multisensory neural representations of the space surrounding the hand (Bonifazi, Farnè, Rinaldesi, & Làdavas, 2007; Iriki, Tanaka, & Iwamura, 1996). Similarly, Cardinali et al. showed that tool use can induce a morphological update of the body representation (Cardinali et al., 2009, 2011), and of body kinematics (Cardinali, Brozzoli, Finos, Roy, & Farnè, 2016; Cardinali et al., 2011, 2012). This modification of the body representation is likely to reflect an incorporation of the tool into the body representation. For instance, a series of studies showed that the tactile signals felt in the hand that occur when a held tool comes into contact with an object are referred directly to the tip of the tool (Maravita et al., 2002; Yamamoto & Kitazawa, 2001; Yamamoto, Moizumi, & Kitazawa, 2005). Moreover, the self-produced touch attenuation phenomena occurs when the participant touches his or her own limb using a tool: self-produced touches are lighter than identical touches applied by another because these touches have already been anticipated by a forward sensory model that takes handheld tools into account (Kilteni & Ehrsson, 2017). In other words, even though the somatosensory signal is originating from the receptors located on the hand, the brain treats this information as if it originated from the tip of the tool.

Overall, previous studies suggest that the brain uses the available sensory information coming from different modalities to infer the structure of a wielded tool and create a unified, extended representation of the body plus the tool. If tools are treated as part of one's own body representation, one could ask to what extent the representation of the embodied tool shares similar properties with the representation of the body itself? In particular, we asked wether manipulating the multisensory stimuli perceived through the tool can induce a recalibration of this extended body representation, as assessed by the Rubber Hand Illusion. In fact, while it is well established that the manipulation of multisensory stimuli (as in the RHI) can induce a recalibration of the body representation, it is still unknown whether this is also true for the extended representation encompassing the embodied tool.

The current experiments investigated this issue. In particular, we hypothesized the importance of three factors for the modified RHI illusion to occur: (a) the type of tool (and in particular, the match or mismatch between the tool's function and the grip exerted to wield the tool) (b) one's level of proficiency in using the tool, and (c) recency of experience with the tool. These points are explained in greater detail in the following sections. To test these hypotheses, we conducted two experiments.

2. Experiment 1

2.1. Introduction

The main purpose of Experiment 1 was to investigate whether multisensory stimulation (i.e. visual and tactile) would induce a recalibration of the felt position of the body plus the tool. We used a modified version of the Rubber Hand Illusion in which the participant and the rubber hand both held a pair of chopsticks. Rather than applying stimulation to the fingers of the real and fake hand, the experimenter brushed the tip of the chopsticks held by the participant and by the rubber hand. Thus, no stimulation was delivered directly to the participant's hand, though the participant was still able to feel the contact between the brush and chopstick. As controls for multisensory stimulation and visual similarity, we manipulated the synchrony of the visuo-tactile stimulation and used a non-hand shaped object (Fig. 1B), respectively. The participant held the tool while viewing the non-hand shaped object (a block of wood with the outline of a hand) during the visual similarity control conditions. We expected participants to experience the illusion only after receiving synchronous stimulation at the tip of the chopsticks held by the rubber hand.

Our choice to use chopsticks was based on several considerations. First, previous studies have already shown that tools like drumsticks (e.g. Yamamoto & Kitazawa, 2001; Yamamoto et al., 2005), and chopsticks (Rademaker, Wu, Bloem, & Sack, 2014) can be incorporated in the body representation. Furthermore, we hypothesized that the functional characteristics of a non-body shaped tool would be crucial for its incorporation, and therefore for the update of the extended body representation in the RHI. This hypothesis is supported by recent evidence showing that the embodiment of tools is constrained not only by the morphology of the tool, but also by its functionality (Miller, Longo, & Saygin, 2014). Though chopsticks violate the morphological similarity between the participant's hand and the viewed object, they are manipulated using a precision grip and they function to extend the fingers in a precision grip