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Research Report

The robot hand illusion: Inducing proprioceptive drift through visuo-motor congruency

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ABSTRACT

The representation of one's own body sets the border of the self, but also shapes the space where we interact with external objects. Under particular conditions, such as in the rubber hand illusion external objects can be incorporated in one's own body representation, following congruent visuo-tactile stroking of one's own and a fake hand. This procedure induces an illusory sense of ownership for the fake hand and a shift of proprioceptive localization of the own hand towards the fake hand. Here we investigated whether pure visuo-motor, instead of visuo-tactile, congruency between one's own hand and a detached myoelectric-controlled robotic hand can induce similar embodiment effects. We found a shift of proprioceptive hand localization toward the robot hand, only following synchronized real hand/robot hand movements. Notably, no modulation was found of the sense of ownership following either synchronous or asynchronous-movement training. Our findings suggest that visuo-motor synchrony can drive the localization of one's own body parts in space, even when somatosensory input is kept constant and the experience of body ownership is maintained.

1. Introduction

The body sets the boundaries between the self and the rest of the world. Furthermore, the body shapes the representation of external space which is not processed in a uniform fashion (Valdés-Conroy et al., 2014). In particular peripersonal space (PPS), extending near the body, benefits from rich properties of multisensory integration (Farnè 2003; Maravita et al., 2002a, 2002b) in order to plan actions for manipulative (Brozzoli et al., 2011) or defensive purposes (Cooke and Graziano 2003; Rossetti et al., 2014). The PPS is critically shaped by the location of body parts and their intrinsic motor properties for action (Makin et al., 2008). Furthermore, the PPS boundary holds dynamic properties, as shown, for example, by its extension following the active use of a tool expanding action space (Canzoneri et al., 2013; Farnè et al., 2005; Maravita et al., 2001; Maravita et al. 2003; Maravita and Iriki 2004). Similarly, also the representation of the body in the brain shows dynamic properties as demonstrated by well-known paradigms in which fake body parts can be incorporated into one's own body representation, inducing either changes in the feeling of ownership felt for that fake body part and/or changes in the perceived location of one's body segment (Botvinick and Cohen 1998; Costantini and Haggard 2007; Ehrsson et al., 2007; Lloyd 2007; Tsakiris et al., 2010). In the seminal paradigm set-up by Botvinick and Cohen (1998), known as the rubber hand illusion (RHI), the tactile stimulation of one's own hidden hand and the congruent visual stimulation of a visible, anatomically compatible fake hand induces the sensation that the fake limb belongs to oneself. Furthermore, when asked to localize the position of their own hidden limb, participants mislocalize it towards the position of the fake limb. Since the original demonstration of this striking illusion, other paradigms have extended the description of similar effects from isolated body parts, namely the hand, to the full body either with real rubber hands (Botvinick and Cohen 1998), mannequins (Petkova and Ehrsson 2008) or in virtual reality (Lenggenhager et al., 2007; Slater et al., 2009).

The dynamic properties of internal body representation and the PPS seem to be connected, since changes of the one can modulate the other. For instance, the active use of a tool, is supposed to extend the boundaries of the PPS (Canzoneri et al., 2013; Farnè et al., 2005; Maravita et al., 2002a), also induces changes of kinematic patterns of grasping movements (Cardinali et al.,

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2009b), body part metric representation (Garbarini et al. 2014; Sposito et al., 2012; Cardinali et al., 2009a) and arousal responses to noxious stimuli on the body (Rossetti et al., 2014), despite many evidences support that these effects are meant because of an extension of the PPS (Canzoneri et al., 2013; Farnè et al., 2005; Maravita et al., 2001, 2003; Maravita and Iriki 2004), it is still debatable whether they could be due to a mere shift in spatial attention (Holmes 2012).

Interestingly, since its first demonstration, the weight of the congruency between proprioceptive, visual, and tactile information has been stressed as the critical determinant of the RHI, and widely investigated (Armel and Ramachandran 2003; Botvinick and Cohen 1998; Costantini and Haggard 2007; Ehrsson et al., 2007; Lloyd et al., 2013; Lloyd 2007; Pavani et al., 2000; Tsakiris and Haggard, 2005), while the contribution of the motor system remains less clear and less studied (Kalckert and Ehrsson 2012, 2014; Newport et al., 2010; Rognini et al., 2013; Tsakiris et al., 2006). Indeed, the embodiment sensations originating after the RHI seem to be multicomponential. Also, different measures, sometimes assumed to be equivalent (Armel and Ramachandran 2003; Guterstam et al., 2011; Moseley et al., 2008; Tsakiris et al., 2010, 2011), might reflect different sub-component of the illusion (Longo et al., 2008; Maselli and Slater 2014; Rohde et al., 2011; Tsakiris et al., 2006).

To date, several methods have been used to induce the embodiment of a fake hand, but rarely the role of the motor system was primarily investigated, especially concerning real prosthetic hands and not virtual hands. First, Botvinick and Cohen (1998) used a visuo-tactile synchronous stimulation of the rubber hand and the participant's biological hand to induce the embodiment of the fake hand; similar effects have been induced through the coupling of tactile and proprioceptive information, without the contribution of vision (Ehrsson et al., 2004; Pozeg et al., 2014). On the other hand, illusory embodiment of a fake hand was induced by using motor imagery in virtual reality and congruent visuo-acoustic stimulations (Hägni et al., 2008); and only recently without any tactile stimulation involving visuo-motor congruency (Sanchez-Vives et al., 2010; Rognini et al., 2013).

Furthermore, the contribution of agency, i.e. the feeling of being the author of an observed action (Moore et al., 2012), in building up the sense of ownership towards the fake hand in the classic RHI appears crucial to achieve a global and coherent embodiment of the entire rubber hand, as compare to a single finger embodiment (Tsakiris et al., 2006). To this mechanism, the congruency of visuo-proprioceptive information seems key, and even more relevant than active vs. passive motor control, as tested in a single-digit visuo-motor congruency paradigm (Walsh et al., 2011).

In the present paper we addressed the role of movement for inducing embodiment effects in a novel paradigm in which a RHI-like illusion was induced through the use of a detached hand prosthetic device. This evidence was sought as a clue for the effect of motor performance in the inclusion of extracorporeal prosthetic devices, typically designed for amputees, in the body representation of the user for optimal performance (see di Pino et al. (2014)). Marasco et al., (2011) have recently found that RHI-like effects are reported in some participants observing a prosthetic limb with tactile sensors that send sensory signals to the neural fibers once serving the lost limb. However, the effect of isolated visuo-motor signals in the induction of a RHI using a prosthetic device remains to be investigated.

In order to do so in our study we used a detached myoelectric robotic hand (Hernandez-Arieta et al., 2005; Marini et al., 2014) to assess any effects induced by the vision of the self-driven robot hand on proprioception and ownership, in a similar fashion to the classic, static RHI, but reducing the possible influence of the visual capture due to the human-like aspect (see e.g. Pavani et al. (2000)) that is usually adopted in the classic RHI (Botvinick and Cohen 1998), and that has recently been used in a virtual reality environment, where virtual hands were shown moving synchronously with the participant's hand (Rognini et al., 2013). In particular, we measured the felt location of the biological hand and the subjective experience of ownership for the fake hand, following a training where participants observed movements executed by the self-controlled robot hand that could move either synchronously to the participant's own hand, or randomly.

We predicted an increased localization error toward the robotic device following the training with the hands moving synchronously, we also expected an increased subjective experience of embodiment following the synchronous training, although this prediction was weaker, due to the notion that the two measures can sometimes dissociate (Rohde et al., 2011; Maselli and Slater 2014).

2. Materials and methods

2.1. Subject

Participants were recruited from students attending the University of Milano-Bicocca; 12 neurologically healthy individuals (2 males; age= 25.33 ± 2.23, range: 23–30; scholarship = 16.67 ± .98, range: 16–18) took part in the experiment and received course credit for their participation. Experimental procedures were in accordance with the Declaration of Helsinki (World Medical Organization, 1996).

2.2. Robot hand apparatus

The robot hand consisted of a forearm and a hand with five mechanical fingers, each one with two degrees of freedom, and it was equipped with pressure sensors on each fingertip and in the palm for delivering touch (for further description of the robot hand see Hernandez-Arieta et al. (2005); Hernandez-Arieta et al. (2008); Nakamura et al. (2009) and Marini et al. (2014)). The hand was controlled by means of the subject's muscular activity through two electrodes capturing electromyographic (EMG) signals from the flexor digitorum superficialis. The calibration of the robot hand was performed at the beginning of the training session by means of a computer-based algorithm using a feed-forward neural network, with an automated procedure extracting EMG signals and then estimating parameters for clustering these signals into a classification unit. A separated supervision unit was used to control movement execution. As a result of these computational steps, the contractions of the subject's muscles resulted in a simultaneous congruent movement of the robot hand, while muscle stretching resulted in a simultaneous relaxation of the robot hand. The pressure sensors producing the afferent signals were switched off for the experiment proposed in this study.

2.3. Procedure

Subjects comfortably sat in front of a table. The robot hand was a right hand, and it was aligned to the mid-sagittal line of the participants. The participant's right arm was placed below the robot hand, 15 cm aside from it on the right side and kept out of view throughout the experiment.

The robot hand was similar to a real hand in size, motor behavior and shape, although the cosmetic aspect of the device was not realistic, since the hand was only covered by a thin semitransparent white glove, leaving some metallic parts and electronics visible.

Participants were divided in two groups (factor Group: congruent/incongruent): for six individuals (age= 26 ± 2.89, range: 23–30, 1 male) the robotic hand moved in a congruent way with the participant's real hand controlling it, so that the real and the robot hands opened and closed synchronously. For the other group (six participants, age= 24.6 ± 1.21, range: 23–26, 1 male) the robot hand motor behavior was not previously calibrated on that of the real hand, so that the robot hand followed the movements of the real hand by generating random movements.

Each participant took part in a 22 min training with the robotic hand (see below). Measurements of embodiment were taken immediately before and after the training session. During these measurements, neither the real hands nor the robotic hand were visible.

2.4. Training

The training was structured as follows. The participant's right hand rested below a wooden board, on top of which the robot hand rested, assuming a posture compatible to that of the hand below (Fig. 1).

To familiarize with and learn to control the robot hand we created different tasks. Participants first had 5 min of free practice, and then were asked to perform