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When your arm becomes mine: Pathological embodiment of alien limbs using tools modulates own body representation ☆

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ABSTRACT

Previous evidence has shown that active tool-use can reshape one's own body schema, extend peripersonal space and modulate the representation of related body parts. Here we investigate the effect of tool-use training on length representation of the contralesional forearm in brain-damaged hemiplegic patients who manifested a pathological embodiment of other people body parts. Four patients and 20 aged-matched healthy-controls were asked to estimate the mid-point of their contralesional forearm before and after 15 min of tool-use training (i.e. retrieving targets with a garbage plier). In the case of patients, training was always performed by the examiner's (alien) arm acting in two different positions, aligned (where the pathological embodiment occurs; E+ condition) or misaligned (where the pathological embodiment does not occur; E− condition) relative to the patients' shoulder. Healthy controls performed tool-use training either with their own arm (action condition) or observing the examiner's arm performing the task (observation condition), handling (observation with-tool condition) or not (observation without-tool condition) a similar tool. Crucially, in the E+ condition, when patients were convinced to perform the tool-use training with their own paralyzed arm, a significant overestimation effect was found (as in the Action condition with normal subjects): patients mislocated their forearm midpoint more proximally to the hand in the post- than in the pre-training phase. Conversely, in the E− condition, they did not show any overestimation effect, similarly to healthy subjects in the observation condition (neither in the with-tool nor in the without-tool condition significant overestimation effects were found). These findings show the existence of a tight link between spatial, motor and bodily representations and provide strong evidence that a pathological sense of body ownership can extend to intentional motor processes and modulate the sensory map of action-related body parts.

1. Introduction

When we interact with the world around us, spatial, motor and bodily representations contribute, in different ways, to the conscious experience of the self as an acting body. We can relate this normal bodily experience to the classical concept of "body schema", firstly described by Head and Holmes (1911) as an unconscious, bottom-up, dynamic representation relying on proprioceptive information from the muscles, joints and skin. Considering the motor nature of body schema, a fundamental issue to be clarified is the relationship between body schema and motor and spatial cognition. Head and Holmes suggested that the nature of body schema is not only sensory-motor but also "action-oriented", in the sense that the possibility of action execution, intrinsic to the body function, can modulate how we represent the spatial extension of our body with respect to the external world (Gallese and Sinigaglia, 2010). Action execution, in turn, takes

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place in ‘action space’ which can be coded as ‘near’ or ‘far’ relative to the acting body.

Near (peripersonal) and far (extrapersonal) space are behaviorally defined as the space within and beyond hand reach, respectively (Berti and Frassinetti, 2000). This definition is based upon both neurophysiological evidence in the monkey and behavioural, PET and TMS evidence in humans showing that near and far space representations in the brain are anatomo-functionally dissociated. In the monkey, near space seems to be represented in frontal area 6 and in the rostral part of the inferior parietal lobe, area 7b and area VIP (Colby et al., 1993;), whereas far space is apparently coded in area 8 and area LIP (Colby et al., 1996). Behavioural (Berti and Frassinetti, 2000; Maravita et al., 2003; Farné et al., 2007), PET (Weiss et al., 2000) and TMS (Lane et al., 2013) studies in humans have confirmed this dissociation. Furthermore, recent findings indicate that near and far space representations are not to be considered as static concepts, but as dynamic entities: for example, active tool-use can reshape one's own body schema, remapping near space to include the tool used to reach for objects located in far space (Maravita and Iriki, 2004, for a review). In the monkey, it has been shown that the area of visual receptive fields (vRFs) of bimodal visuo-tactile parietal neurons (known to map the subject's peripersonal space) can be modified by actions performed with tools (Iriki et al., 1996; Ishibashi et al., 2000). Indeed, the vRFs anchored to the paw were shown to encompass the entire length of the tool used to reach food located in far space, as if the tool held by the animal's hand were incorporated into the body schema. A number of studies in humans – both in brain-damaged and in healthy participants – have shown similar changes following practice to reach far visual stimuli with a tool. It has been shown that reaching with a tool a far ipsilesional target may increase the saliency of that stimulus so as to increase extinction of a contralesional tactile stimulus in patients affected by cross-modal extinction (di Pellegrino et al., 1997; see also Farnè and Ladavas, 2000; Farnè et al., 2005). Several line-bisection studies on patients with selective neglect for near or for far space indicated that tool use can reduce or increase neglect according to the sector of space – within or outside reaching distance – where the lines are positioned (e.g., Ackroyd et al., 2002; Berti and Frassinetti, 2000; Neppi-Mòdona et al., 2007; Pegna et al., 2001). Interestingly, such a dynamical spatial remapping was modulated not only by visual and somatosensory feedbacks, but also by the modality of execution. For example, if the context required a pointing action (usually executed in far space), a far space representation was activated; if the context required a reaching action (usually executed in near space), near space was activated irrespective of the absolute spatial position of the object. Note that in this case the extension of body schema was modulated by the intentional action executed. In healthy subjects, it has been shown that the progressive increase in line bisection errors with increasing stimulus distance was abolished if participants used, instead of a laser pointer, a long stick to reach objects in far space (Longo and Luorenco, 2006). It has been also documented that tool-use may increase the impact of a visual distractor on tactile discrimination (Holmes et al., 2008; Maravita et al., 2002a, 2002b). More importantly for the present study, a number of studies suggested that the modulatory effect of tool-use in space coding may be accompanied by a parallel change in the representations of body metrics (e.g., Bonifazi et al., 2007; Farné et al., 2007; Maravita and Driver, 2004). This hypothesis has been confirmed in a recent study (Sposito et al., 2012) showing that, in healthy subjects, active tool-use modulates the representation of related body parts; i.e. after tool-use training, participants showed an increased representation of the length of the arm handling the tool. Taken together, these findings indicate a relationship between body schema, action execution and space representation and that body schema is better conceptualized as the neurocognitive result of implicit sensory monitoring for action in a dynamic space. Although viewed as an unconscious representation, body schema is tightly linked to the representation of both intentional processes and spatial coding, contributing in fundamental ways to the emergence of the conscious experience of the self as an acting body in the space.

A normal interaction with the world implies the implicit notion that the body executing actions in the space is mine (not yours, not others'), i.e. it implies a normal sense of body ownership. But what happens when the sense of body ownership is dramatically altered as, for instance, after a brain damage? In brain-damaged patients with motor and somatosensory impairments, body awareness can be pathologically altered. In some cases, patients may feel a sense of strangeness towards their contralesional limbs felt as separated from their own body. The more frequent manifestation of this disorder is characterized by a sense of disownership, which is the delusional belief that the contralesional limbs do not belong to one's own body but to another person (a disturbance called somatoparaphrenia: Vallar and Ronchi, 2009; Gandola et al., 2012; Romano et al., 2014). The possibility of the existence of an opposite behavior, i.e. patients who misidentify other people's limbs as their own, has been rarely considered. However, in recent studies (Garbarini et al., 2013a, 2014; Garbarini and Pia, 2013; Pia et al., 2013a), this behavior has been observed in a sample of patients, who, while not explicitly denying that their contralesional (left) limbs belonged to themselves (as in the somatoparaphrenic delusion of disownership), claimed that the examiner's left hand was their own whenever it was positioned, in egocentric coordinates, next to their left hand. This delusion of ownership, which we called ‘pathological embodiment’, although resembling the “rubber-hand-illusion” (Botvinick and Cohen, 1998), was spontaneous and not induced by any experimental procedure. Patients treated and cared for the experimenter's left arm as if it was their own, showing a consistent embodiment of the alien hand in their own body schema (because of this behavior, we named them ‘E+’ patients). Interestingly, this phenomenon occurs only when the alien hand is located in a position coherent with the patients' higher-order and pre-existing body representation. It is important to consider that in E+ patients the pathological embodiment occurs only when the alien arm is in egocentric coordinates and it is aligned with the patients' contralesional shoulder, exactly where it is expected to be. If the position of the alien arm is misaligned with respect to the patient's shoulder, the pathological embodiment does not occur and patients correctly discriminate their own arm/hand from the alien arm/hand (see Section 2.2.2 for details of how the embodiment is evaluated). Previous studies stressed the crucial role of the alignment of the alien arm with the shoulder in determining embodiment phenomena during the rubber hand illusion. Pavani et al. (2000) have shown that the illusion effect disappears when the fake hand is misaligned with respect to the subject's shoulder (see also Costantini and Haggard 2007, where stimulation and posture of both the real and the fake hand were manipulated, and Lloyd 2007, where the effect of proximity between the fake and the real hand was investigated). Accordingly, Farnè et al. 2007) described, in right-brain damaged patients, a left tactile extinction following visual stimulation of a right rubber hand. Interestingly, this cross-modal extinction was only evident when the rubber hand was aligned with the patients' shoulder; on the contrary, when the rubber hand was misaligned with respect to the patients' shoulder, cross-modal extinction was strongly reduced.

Critically for the present study, the pathological embodiment occurs not only with a static alien hand, but also with a moving hand: when the examiner moved his/her left hand, patients, to their surprise, claimed that they were moving their own (paralyzed) hand. Previous studies demonstrated that this phenomenon

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